International Atomic Energy Agency



INDC(NDS)-335 Distrib.: G+NM

INTERNATIONAL NUCLEAR DATA COMMITTEE

"DEVELOPMENT OF REFERENCE INPUT PARAMETER LIBRARY FOR NUCLEAR MODEL CALCULATIONS OF NUCLEAR DATA"

Texts of Papers presented at the 1st Research Co-ordination Meeting organized by the International Atomic Energy Agency in co-operation with ENEA, Bologna, Italy, and held at Cervia (Ravenna), Italy,

19 to 23 September 1994

Compiled by

Pavel OBLOŽINSKÝ IAEA Nuclear Data Section Vienna, Austria

May 1995

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

"DEVELOPMENT OF REFERENCE INPUT PARAMETER LIBRARY FOR NUCLEAR MODEL CALCULATIONS OF NUCLEAR DATA"

Texts of Papers presented at the 1st Research Co-ordination Meeting organized by the International Atomic Energy Agency in co-operation with ENEA, Bologna, Italy, and held at Cervia (Ravenna), Italy,

19 to 23 September 1994

Compiled by

Pavel OBLOŽINSKÝ IAEA Nuclear Data Section Vienna, Austria

Abstract

The Report collects scientific and technical papers presented at the IAEA 1st Research Co-ordination Meeting on "Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data". The Library is being developed for use in theoretical calculations of nuclear reactions primarily induced by neutrons in the incident energy range up to about 30 MeV. Two introductory complex papers present regional approach to develop input parameter library. The remaining 7 papers are dealing with those segments of the library that need major attention: discrete level schemes, average neutron resonance parameters, optical model parameters, nuclear level densities (total, partial, fission) and γ ray strength functions.

May 1995

Reproduced by the IAEA in Austria May 1995

Contents

1010	······································
T. Fi	ikahori and T. Nakagawa (Tokai-mura):
"Data	bases for Model Parameters and Integrated Nuclear Data Evaluation
Syste	ms
٠	T. Nakagawa (Tokai-mura), presented by T. Fukahori:
	"Format of Evaluation Data File"
Su Z	ongdi, Ge Zhigang, Zhang Limin, Ma Lizhen, Sun Zhengju, Wang
Chenz	kiang, Zhou Chunmei, Huang Zhongfu, Liu Jianfeng, Yu Ziqiang, Zuo
lixin	and Ma Gonggui (Beijing, Guangxi, Zhengzhou, Nankai and Sichuan):
'Prog	ress and Activities on Reference Input Parameter Library for Nuclear
Mode	l Calculations of Nuclear Data at CNDC"47
٠	Su Zongdi, Ma Lizhen, Zhou Chunmei and Ge Zhigang (Beijing):
	"Atomic Masses and Characteristic Constants of Nuclear Ground States
	(MCC, Part I)"
•	Su Zongdi and Ma Lizhen (Beijing):
	"Atomic Masses and Characteristic Constants of Nuclear Ground States
	(MCC, Part II)"
•	Su Zongdi Zhang Limin Zhou Chunmei and Sun Zhengiun (Beijing):
•	"Discrete Level Schemes, Their γ Radiation and Branching Ratios
	(DLS, Part I)"
-	Co Thisses Su Tongdi Jin Vardi Husse Therefored Dong Lissmon
•	(Beijing and Guangyi).
	"Sub-Library of Nuclear Level Densities (LD, Part I)"
_	
•	Liu Jianieng, Zhang Xizhi, Su Zongdi, Ge Zhigang and Zuo Yixin (Zhenghou, Beijing and Nankai).
	"Library of Giant Dipole Resonance Parameters for α Bays
	(GDP, Part I)"
•	Zuo Yixin, Su Zongdi, Ge Zhigang, Liu Jianfeng and Zhang Xizhi (Nankaj Beijing and Zhanghou):
	"Library of Giant Dipole Resonance Parameters for γ Rays
	(GDP, Part II)"
٠	Linang Limin, Ge Zhigang and Su Zongdi (Beijing): "Library of Figure Provide Department (FDD, Provide IV)"
	LIDIALY OF FISSION DATHER FARAMETERS (FDF, FART 1)"

• Zhang Limin, Ge Zhigang and Su Zongdi (Beijing): "Library of Fission Barrier Parameters (FBP, Part II)"85
• Su Zongdi, Sun Zhengjun, Wang Chenxiang, Ge Zhigang, Yu Ziqiang, Zuo Yixin and Ma Gonggui (Beijing, Nankai and Sichuan): "Optical Model Parameter Sub-Library (OMP, Part I)"
G. Molnár, T. Belgya and B. Fazekas (Budapest): "Complete Spectroscopy of Discrete Nuclear Levels"
G. Reffo (Bologna): "Average Neutron Resonance Parameters"105
P.G. Young (Los Alamos): "Experience at Los Alamos with Use of the Optical Model for Applied Nuclear Data Calculations"
S.B. Garg and Ashok Kumar (Bombay): "Optical Model and Level Density Parameters for Nuclear Data Evaluation"
A.V. Ignatyuk (Obninsk): "Analysis of the Neutron Resonance Densities, Low-Lying Levels and Level Density Parameters"
M.B. Chadwick and P. Obložinský (Livermore and Vienna): "Partial Level Densities for Modeling Continuum Angular Distributions in Nuclear Reactions"
M. Uhl and J. Kopecky (Vienna and Petten): "Gamma-Ray Strength Function Models and Their Parameterisation"157

Foreword

The Report collects scientific and technical papers presented at the IAEA 1st Research Co-ordination Meeting on "Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data (Phase I: Starter File)" held in Cervia near Ravenna, Italy, 19–23 September 1994. The Summary Report of the Meeting can be found in INDC(NDS)-321 (IAEA, Vienna, December 1994).

The Reference Input Parameter Library should be composed of the following 6 segments:

- Atomic masses, shell corrections and deformations
- Discrete level schemes
- Average neutron resonance parameters
- Optical model parameters
- Nuclear level densities (total, partial, fission)
- Gamma-ray strength functions

The Library should be used in model calculations of nuclear reaction data primarily induced by neutrons in the incident energy range up to about 30 MeV. It should preserve an immense knowledge and experience accumulated over years in nuclear reaction model calculations, and it should become an indispensible source of information for future nuclear data evaluators.

Nine chief scientific investigators from 8 countries involved in the Coordinated Research Programme on "Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data (Phase I: Starter File)" presented their papers at the Meeting. The Report is organized as follows. Two introductory papers are rather complex and they deal with results aiming to develop regional input parameter library INDES (Tokai-mura) and CENPL (Beijing). Seven other papers address various parameters and problems related to composing of the Library and they follow, as far as possible, the sequence of the above mentioned segments of the Library.

A major part of papers was collected at the Meeting with the idea to publish the Report soon. However, 2 papers were submitted after substantial delay in April 1995 causing an unforseen delay in publishing the Report. In any case I feel that all papers are important for deeper understanding of this ambitious and valuable project.

Vienna, 19 April 1995

Pavel Obložinský

for the 1st Meeting of IAEA/CRP on Reference Input Parameter Library, on 19–23 Sep., 1994, at Cervia, Italy

Databases for Model Parameters and Integrated Nuclear Data Evaluation System

T. Fukahori and T. Nakagawa Nuclear Data Center, Department of Reactor Engineering, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki, 319-11 Japan (e-mail: J4276@JPNJAERI.bitnet)

ABSTRACT

The integrated nuclear data evaluation system (INDES) is being made in order to support the evaluation work. INDES manages a database; the evaluation data file (EVLDF) storing the basic nuclear physics parameters such as optical model potential parameters, level density parameters, mass excess data, level scheme and gamma transition from excited levels, and various information, for example, names of theoretical calculation codes used in JENDL-3 evaluation work. By using EVLDF and the other databases, INDES automatically creates input data and JCL for several theoretical calculation codes for the nuclear data evaluation. A guidance system in INDES, which is called '*Evaluation Tutor* (ET)', can support users in selecting a set of suitable theoretical calculation codes by applying knowledge engineering technology and the experiences of evaluation work for JENDL-3.

In the present report, the outline of INDES functions and databases in INDES are introduced. The format of EVLDF is also explained.

1. Introduction

Evaluated nuclear data files are necessary for design of nuclear fission and fusion reactors, shielding calculations, etc. Nuclear data evaluation is required to obtain the most reliable data sets for the evaluated nuclear data files. The evaluation must be done by using experimental data and by many complicated theoretical calculations with various basic data such as optical potential parameters, level density parameters, and level scheme. Japanese Evaluated Nuclear Data Library, version 3 (JENDL-3)¹⁾ released in 1989 was accomplished by great efforts of many evaluators with many intricate works. Integrated Nuclear Data Evaluation System (INDES) is being developed to keep their experiences and basic data of nuclear physics used for the evaluation of JENDL-3, and to support new evaluations.

Roughly classified, the INDES functions are of three categories, which are to retrieve basic data described above, to set up input data of theoretical calculation codes automatically, and to select the most suitable set of theoretical calculation codes applying knowledge engineering technology. In this paper, those databases and functions are introduced, especially the model parameter database which is called '*Evaluation Data Files* (EVLDF)'. The format of EVLDF is also explained briefly.

2. Database for Model Parameters

Parameters to be used in theoretical calculations of nuclear data are stored in EVLDF which consists of several parameter files and an index file. The parameters provided in EVLDF are optical potential parameters, level density parameters, level scheme, deformation parameters, and basic information of nuclei. EVLDF stores also such information as theoretical codes used for the JENDL-3 evaluation. This information on the theoretical codes is gathered into a knowledge-base which is used for code selection suitable for evaluation.

3. Function of INDES

INDES is an interactive program available on character display TSS terminals. Figure 1 shows structure of INDES. It consists of several FORTRAN programs called as 'segments' executed by calling them with TSS command procedures from the root segment.

A group of the segments supplies evaluators the useful information for nuclear data evaluation such as existing evaluated data, experimental data, nuclear structure data (from ENSDF), reaction Q-values and threshold energies of the reactions. One segment was prepared for retrieval of the parameters stored in EVLDF. Some segments will be made for evaluation of the level density parameters, the optical model parameters, etc.

Since theoretical calculations take a long CPU time, we have to submit batch jobs for the calculations. The input data and JCL for the theoretical calculation codes are semi-automatically produced in the JCL set-up segments. INDES requires only limited number of input data such as an atomic number and a mass number, name of a parameter set, energies where the calculation will be made, etc. The JCL and input data are set up on a JCL file. The user can submit it as a batch job from INDES.

Selection of the suitable theoretical calculation codes can be made with the aid of ET. In order to support users in selecting a set of suitable theoretical calculation codes, a prototype of a nuclear data evaluation guidance system, named '*Evaluation Tutor* (ET)⁽²⁾, was developed by applying knowledge engineering technology, which is based on the similar method of 'example-base reasoning' called in the society of artificial intelligence. The codes considered in ET are DWUCKY³, ECIS⁴, JUPITOR⁵, CASECIS⁶, EGNASH2³, TNG⁷, PEGASUS⁸, ALICE-F⁹, CASTHY2¹⁰, ELIESE-3¹¹, RESCAL¹² and HIKARI¹³. ET consists of an inference engine, frames, a rule-base, two example-bases and modules calculating certainty factors. A schematic diagram of ET is shown in Fig. 2. The inference engine and modules of ET are written in FORTRAN77, since FORTRAN77 is the most familiar computer language to the evaluators of the nuclear data. The names of codes recommended by ET are shown on the terminal screen. By selecting one of the codes on the screen, one can go into the segment for its JCL and input data setting-up.

4. Format of EVLDF

In this Chapter, basic rules and basic format of EVLDF are described. The current format of EVLDF is capable of storing parameters used for the evaluation work of JENDL-3. An index file of EVLDF which is an auxiliary file for handling EVLDF is also introduced.

4.1 Basic Rules of EVLDF Format

- 1) Each <u>line</u> of EVLDF consists of 80 columns. The columns from 73 to 80 are used for sequential number of lines or other purposes.
- 2) Characters from A to Z should be capital letters.

- 3) The smallest group of lines is a record.
- 4) A record name is given in the columns from 1 to 10. For example, the line with 'DATA' in the columns from 1 to 4 is called as a DATA record. Record names defined are listed in **Table 1**.
- 5) Each record can be continued to the next line. No limitations exist on the number of lines.
- 6) In the case where a record is repeated, "+" is given in the first column of the following records.
- 7) Data in the columns from 11 to 72 depend on the record name. Data type is summarized in **Table 1**. Usually, data in the columns from 11 to 72 are given in a free format.
- 8) In any lines, any comment can be given after a semi-colon (";").
- 9) Some records have corresponding END records. A group of lines from a line with record name to its END record is a <u>section</u>. A section can include other sections inside. Currently defined sections are DATA, MAT and SET sections and parameter sections for basic data on nuclei, level scheme, deformation parameters, level density parameters and optical model parameters.
- 10) In many cases, nuclide is represented with an integer calculated from atomic number, mass number and meta-stable number as (atomic number)×10000 + (mass number)×10 + (meta-stable state number). The mass number and meta-stable state number are 0 for natural elements. This integer is called as a <u>nuclide name</u>.
- 11) Units of numerical data are defined in Table 2.

4.2 DATA Section

The DATA section starts with the DATA record and ends with the ENDDATA record. The DATA section is used to store numerical data in a parameter section. The DATA record indicates parameters whose values are given in the DATA section. Parameter symbols are listed in the columns from 11 to 72, and separated with a comma (",") or blanks. The parameter symbols are listed in **Table 3**. There are no restrictions on the order of parameter symbols. Numerical data in the DATA section should be given under the following rules.

- 1) Data given in the columns from 1 to 9 of each line in the DATA section depend on parameters. Sometimes they are called as <u>DATA-line symbols</u>. The DATA-line symbols defined so far are listed in **Table 4**.
- 2) DATA-line symbols should be left-adjusted except for the case where the DATA-line symbols are nuclide names.
- 3) The column 10 indicates continuation to the next line. If the 10-th column is not blank, the data are continued to the next line. In this case, a DATA-line symbol of the next line is the same as the previous line. It should be noted that this rule of continuation is valid only for the numerical data in the DATA section.
- 4) The numerical data in the columns from 11 to 72 are given in a free format and in the same order of the parameter symbols. They are read with a list-directed READ statement of FORTRAN.

4.3 MAT Section

In the MAT section, parameters used for the evaluation of the material(s) specified on a MAT record are stored. On one MAT record, only one nuclide name is given. If two or more than two nuclide names have to be given, the MAT record should be repeated.

4.4 SET Section

A set of parameters between a pair of SET and ENDSET records is named. A set name is any alphabetic characters and/or integers without any blanks or commas among them. The maximum length of the set name is 20 characters. The SET section is allowed only in parameter sections.

4.5 Basic Data on Nuclei

Basic data of nuclei are stored between a NUCLIDE record and an ENDNUCLIDE record. In the DATA section, the following data can be stored.

EL	level energy (MeV). For the ground state, EL=0.0.
J	spin. If unknown, $J < 0.0$.
PARITY	parity. (1.0 or -1.0). If unknown, PARITY = 0.0.
HL	half-life (sec). For stable states, 0.0 is given. If unknown, HL < 0.0 .
ABN	abundance (%).
MASSEX	mass-excess (MeV).

The data should be stored in the increasing order of level energies. DATA-line symbols in the columns from 1 to 9 are nuclide names. The nuclide names should be given in the increasing order.

4.6. Level Scheme

Level scheme is stored between a LEVEL record and an ENDLEVEL record. In the DATA section, the following data can be stored.

level number. A ground state should be 0.
level energy (MeV).
spin. For the energy above where levels can be assumed to be overlapping, $J=-1.0$.
parity. Parity of + and - is represented by 1.0 and -1.0 , respectively. For the overlapping state, PARITY = 0.0.
half-life (sec).
number of γ -rays emitted from the level.
level number of a final state.
branching ratio.
γ-ray energy (MeV).

In order to store γ -transition data, NG, FLVL, BR and/or EG have to be specified in the form of

DATA ... , NG (FLVL, BR)

Among these parameter symbols, EL, J and PARITY should be always given. For γ -ray transition data, in addition to them, NO, NG, FLVL and BR are obligatory. The data should be stored in the increasing order of level numbers and level energies. In the columns from 1 to 9, nuclide name is given in the increasing order.

4.7 Deformation Parameters

Deformation parameters are stored between a DEFORM record and an ENDDEFORM record. In the DATA section, the following data are stored.

EL	level energy (MeV).
J	spin
PARITY	parity
DL	orbital angular momentum transfer
BETA	deformation parameters (β)
BETA2	deformation parameters (β^2)

The data should be stored in the increasing order of level energies. In the columns from 1 to 9, nuclide name is given. In one DATA section, the deformation parameters for many nuclei can be stored. In such case, the deformation parameters should be stored in the increasing order of the nuclide names.

4.8 Level Density Parameters

Level density parameters are stored between a LDP record and an ENDLDP record. The parameters are model dependent. In the current format, the parameters for Gilbert and Cameron's composite formula can be stored. A FORMULA record identifies a level density formula.

FORMULA XXXXX XXXX = GILBERT-CAMERON: Gilbert and Cameron's composite formula¹⁴)

Gilbert and Cameron's Composite Formula

Level density of levels having spin J, parity π and excitation energy E is written by the following equations:

$$\rho_{J\pi} = p(\pi) R(J) \rho_0(E) , \qquad (4.8.1)$$

where $p(\pi)$ is the normalized parity distribution, and R(J) the normalized spin distribution.

$$R(J) = \frac{2J+1}{2\sigma^2} \exp\left(-\frac{J(J+1)}{2\sigma^2}\right).$$
 (4.8.2)

The energy dependent part $\rho_0(E)$ is written by the Fermi gas model above E_x ,

$$\rho_0(E) = \frac{\exp(2\sqrt{aU})}{12\sqrt{2}\sigma a^{1/4}U^{5/4}}, \qquad (4.8.3)$$

and by the constant temperature model below $E_{\rm r}$,

$$\rho_0(E) = C \exp(U/T) . \qquad (4.8.4)$$

 E_x is a connection energy of these two models. U is given by $U = E - \Delta$, where Δ is a pairing energy. The spin cutoff factor σ^2 in the energy region above E_x is written as:

$$\sigma^2 = C_0 \sqrt{a U A^{2/3}} = \alpha_M U^{1/2}, \qquad (4.8.5)$$

where $\alpha_{\rm M}$ is a spin cutoff parameter. On the other hand, in the constant temperature model region $(E \leq E_x)$, several equations of σ^2 have been proposed. One parameter to be stored is a spin cutoff factor at 0 MeV, $\sigma^2(0)$. For example, the following equation was proposed by Gruppelaar¹⁵:

$$\sigma^{2} = \sigma^{2}(0) + (\sigma^{2}(E_{x}) - \sigma^{2}(0)) \frac{E}{E_{x}}. \qquad (4.8.6)$$

The parameters are stored with the following auxiliary record and the DATA section.

SCOEF

n is a coefficient of spin cut-off factor (C_0 in Eq. (4.8.5)). If the coefficient is 0.146, this record can be omitted.

In the DATA section, the following parameters are stored.

n

Α	$a (MeV^{-1})$ in Eq.(4.8.3).
Т	temperature (MeV) in Eq.(4.8.4).
PAIR	pairing energy $\Delta(MeV)$.
EX	connecting energy E_x of the constant temperature model and
	Fermi gas model (MeV).
SCF	spin cutoff factor at 0 MeV, $\sigma^2(0)$ in Eq.(4.8.6).
SCP	spin cutoff parameter, α_{M} in Eq.(4.8.5).
E0	energy (MeV) where a cumulative number of levels is 1.0.

In the columns from 1 to 9, nuclide name is given. The nuclide name should be given in the increasing order.

4.9 Optical Model Parameters

Optical model parameters are stored between an OMP record and an ENDOMP record. An INCIDENT section has to be used to specify the incident particle. Between an INCIDENT record and an ENDINC record, the optical model parameters of the corresponding incident particle are stored. The following auxiliary records are defined.

> TARGET n1, n2 n1 and n2 indicate a range of nuclei for which the optical potential parameters can be applied.

TYPE

n

defines type of form factors of imaginary parts.

n	Surface term	Volume term
1	Gaussian form	none
2	derivative Wood-Saxon form	none
3	none	Wood-Saxon form
4	Gaussian form	Wood-Saxon form
5	derivative Wood-Saxon form	Wood-Saxon form

COULOMB n

Coulomb radius parameter (fm) for charged particles.

In the DATA section, parameters are stored under the following parameter symbols.

V	real potential depth (MeV)
WV	volume type imaginary potential depth (MeV)
WS	surface type imaginary potential depth (MeV)
VSO	real part of spin-orbit potential depth (MeV)
WSO	imaginary part of spin-orbit potential depth (MeV)
EMIN	lower boundary of incident particle energy (MeV)
EMAX	higher boundary of incident particle energy (MeV)

By some researchers, very complicated formulas have been proposed. However, only the following energy dependent potential p(E) can be stored.

$$p(E) = a_0 + a_1 E + a_2 E^2 + a_5 \sqrt{E} + b \frac{N-Z}{A} + C \frac{Z}{A^{1/3}}.$$
 (4.9.1)

Nuclear radius for each potential is expressed as:

$$R = r_0 + r_a A^{1/3} + r_1 E + r_2 E^2 + \dots + r_s \frac{N-Z}{A}.$$
 (4.9.2)

Diffuseness parameters have almost the same form as nuclear radii.

$$a = a_0 + a_1 E + a_2 E^2 + \dots + a_s \frac{N-Z}{A}$$
. (4.9.3)

DATA-line symbols in the columns from 1 to 9 of the DATA section represent the terms of above expressions as follows:

E0	constant term. a_0 in Eq.(4.9.1).
E1	first order term of energy. a_1 in Eq.(4.9.1).
E2	second order term of energy. a_2 in Eq.(4.9.2).
E5	square root term. a_5 in Eq.(4.9.1).
E9	$Z/A^{1/3}$ term. c in Eq.(4.9.1).
SYM	symmetric term. b in Eq.(4.9.1).
R	nuclear radius parameter. r_a in Eq.(4.9.2).

- RC constant term of nuclear radius. r_0 in Eq.(4.9.2).
 - diffuseness parameter. a_0 in Eq.(4.9.3).

energy dependent terms and symmetric terms of R and A can be represented as R-E1 (= r_1), R-SYM (= r_s), A-E1 (= a_1), A-SYM (= a_s).

4.10 Structure of EVLDF

Α

There are two ways of storing parameters into EVLDF. One is to store the parameters used for evaluation of each material. Another way is to store global parameters or systematically evaluated parameters. A file made for the first purpose is called as a material-wise file and the other a parameter-wise file.

4.10.1 Material-wise File

This file consists of a MAT section. Parameters used for the evaluation of material n_1 is compiled in a MAT section as follows:

 $\begin{array}{c|c} MAT & n_1 \\ EVAL \ record \\ REF \ record \\ CODE \ record \\ COMMENT \ record \\ NUCL \ section \\ LEVEL \ section \\ DEFORM \ section \\ LDP \ section \\ OMP \ section \\ ENDMAT \\ \end{array}$

After this MAT section, another MAT section can be stored. In this case, MAT sections should be stored in increasing order of nuclide names $(n_1 < n_2 < ... < n_n)$.

4.10.2 Parameter-wise File

A parameter-wise file stores global parameters and/or parameters evaluated systematically. In the parameter-wise file, the MAT section cannot be existing. The following is an example of the parameter-wise file for the optical potential parameters.

OMP INCIDENT n_1 SET NN01 REF record TARGET record DATA section (Pairs of the TARGET record and the DATA section can be repeated.)*) ENDSET (SET sections for the incident particle n_1 can be repeated.) ENDINC (INCIDENT sections can be repeated.) ENDOMP

*) Pairs of the TARGET record and the DATA record should be given

in the increasing order of nuclide names.

In the parameter-wise file, parameter sets should be named by SET and ENDSET records. In a file, several kinds of parameters may be stored.

4.11 Index of EVLDF

Parameters are stored in several material-wise files and several parameter-wise files. Those files can be partitioned or sequential files. In order to treat the parameters stored in EVLDF, therefore, an index file is required.

The format of the index file is as follows:

Columns	format	description
1 - 33	A33	Data-set name where the parameters are stored. In the case of a PO file, a member name is specified.
34 - 40	I7	The first position (line number) of record.
41 - 45	I5	Number of lines.
46 - 54	A9	Name of record. One of MAT, LDP, OMP, LEVEL, NUCLIDE.
(for parar	neter-wise file	s)
55 - 74	A20	Name of parameter-set.
(for mate	rial-wise files)	i de la construcción de la constru
55 - 59		blanks
60 - 66	I7	Minimum nuclide name given in MAT record.
67 – 73	I7	Maximum nuclide name given in MAT record.
74		blank
(for both	files)	
75 – 81	17	incident particle for OMP, blanks for other parameters.
82 - 88	I7	Minimum nuclide name of TARGET record or DATA section.
89 – 95	Ι7	Maximum nuclide name of TARGET record or DATA section.

The format of the columns from 55 to 74 for the material-wise file is different from that for the parameter-wise file.

5. Conclusion

The functions of INDES and the format of EVLDF have been described. So far, the formats for the optical model parameters, the level density parameters, the level scheme, the deformation parameters and the basic data on nuclei (such as mass, spin) have been determined. However, they have not been fixed completely yet and they will be modified if some inconveniences are found.

References

- 1) K. Shibata, T. Nakagawa, T. Asami, T. Fukahori, T. Narita, S. Chiba, M. Mizumoto, A. Hasegawa, Y. Kikuchi, Y. Nakajima and S. Igarasi, *JAERI*-1319 (1990).
- 2) T. Fukahori and T. Nakagawa, JAERI-M 92-027 (1992) 214.
- 3) N. Yamamuro, JAERI-M 90-006 (1990).
- 4) J. Raynal, *IAEA* SMR-9/8 (1970).
- 5) T. Tamura, Rev. Mod. Phys. 37 (1965) 679.
- 6) Computer Program CASECIS means CASTHY-ECIS combined code.
- 7) C.Y. Fu, ORNL/TM-7042 (1980).
- 8) S. Iijima, T. Sugi, T. Nakagawa and T. Nishigori, JAERI-M 87-025 (1987) 337.
- 9) T. Fukahori, Computer Program ALICE-F for medium energy preequiliblium process calculation, unpublished (1990).
- 10) S. Igarasi and T. Fukahori, JAERI-1321 (1991).
- 11) S. Igarasi, JAERI-1224 (1972).
- 12) K. Shibata and S. Chiba, Computer Program RESCAL for R-matrix theory calculations, unpublished (1987).
- 13) H. Kitazawa, Computer Program HIKARI for direct-semidirect capture calculations, unpublished (1980).
- 14) A. Gilbert and A.G.W. Cameron, Can. J. Phys. 43 (1965) 1446.
- 15) H. Gruppelaar, ECN-13 (1977).

_	record	functions	11-72 col*	END record
	CODE	specifies a theoretical code used for an evaluation work.	C1	none
	COMMENT	stores any comment.	C2	none
	DATA	defines parameters to be stored. This is a heading line of a DATA section.	C3	ENDDATA
	DEFORM	starts a deformation parameter section.		ENDDEFORM
	EVAL	evaluator's name.	C2	none
	FORMULA	a formalism of level density parameters.	C1	none
	INCIDENT	specifies an incident particle. Used in an OMP section.	n	none
	LDP	starts a level density parameter section.		ENDLDP
	LEVEL	starts a level scheme section.		ENDLEVEL
]	MAT	material name.	n	ENDMAT
	NUCLIDE	starts a section of basic data on nuclei		ENDNUCLIDE
	OMP	starts an optical model parameter section.		ENDOMP
]	REF	references.	C2	none
ŝ	SCOEF	a coefficient for a spin-cutoff factor.	n	none
Ş	SET	names a set of parameters.	C1	ENDSET
	TARGET	a range of target nuclei.	n, n	none
, 	ГҮРЕ	type of an optical potential.	n	none
*	C1: chara C3 Da	acters without blanks and "," C2: a arameter symbols n: ni	ny characters umerical data	

Table 1 Records in EVLDF

Table 2	Units o	of pb	iysical	quantities
---------	---------	-------	---------	------------

unit	quantities
 MeV	energy, mass excess
fm	nuclear radius
barns	cross section
sec	half-life
%	abundance

Symbol	Parameter	description
A	LDP	a (MeV ⁻¹)
ABN	NUCLIDE	abundance (%)
BETA	DEFORM	deformation parameter (β)
BETA2	DEFORM	deformation parameter (β^2)
BR	LEVEL	branching ratio of γ-ray transition
DL	DEFORM	angular momentum transfer
EG	LEVEL	γ-ray energy (MeV)
EMIN	OMP	lower boundary of incident particle energy (MeV)
EMAX	OMP	upper boundary of incident particle energy (MeV)
E0	LDP	an energy where cumulative number of levels is 1.0.
EL	LEVEL DEFORM	level energy (MeV)
EX	LDP	a connection energy between the constant temperature model and the Fermi gas model (MeV)
HL	NUCLIDE	half-life (sec)
J	DEFORM LEVEL NUCLIDE	spin
MASSEX	NUCLIDE	mass excess (MeV)
NG	LEVEL	number of y-rays
PAIR	LDP	pairing energy (MeV)
PARITY	DEFORM LEVEL NUCLIDE	parity
SCF	LDP	spin-cutoff factor at 0 MeV
SCP	LDP	spin-cutoff parameter
Т	LDP	temperature (MeV)
v	OMP	real potential depth (MeV)
VSO	OMP	real part of spin-orbit potential (MeV)
wso	OMP	imaginary part of spin-orbit potential depth (MeV)
WS	OMP	depth of surface type imaginary potential (MeV)
WV	OMP	depth of volume type imaginary potential (MeV)

Table 3 Parameter Symbols used in DATA section

Symbol	Parameter	Description
Α	OMP	diffuseness parameter (fm)
E0	OMP	constant term of potential depth (MeV)
E1	OMP	first order term of potential depth (MeV)
E2	OMP	second order term of potential depth (MeV)
E5	OMP	square root term of potential depth (MeV)
E9	OMP	$Z/A^{1/3}$ term of potential depth (MeV)
R	OMP	nuclear radius parameter (fm)
RC	OMP	constant term of nuclear radius (fm)
SYM	OMP	depth of symmetric term (MeV)
nuclide– name	DEFORM LEVEL LDP NUCLIDE	nuclide name determined as (atomic number)×10000+(mass number)×1000+(meta- stable state number)

Table 4 DATA line symbols

Structure of INDES



Fig. 1 Structure of INDES.

20

Preliminary Version

Format of Evaluation Data File

Tsuneo NAKAGAWA

Nuclear Data Center Japan Atomic Energy Research Institute Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan

Evaluation Data File (EVLDF) is being made to store parameters used in theoretical calculations of nuclear data. EVLDF stores basic data on nuclei, level scheme, deformation parameters, level density parameters and optical model parameters. This report describes a format of EVLDF as of December 1992.

Keywords : Nuclear Data Evaluation, Parameters, Theoretical Calculation, Format

21

Contents

- 1. Introduction
- 2. Basic Rules of EVLDF Format
- 3. Details of Format
 - 3.1 DATA Section
 - 3.2 MAT Section
 - 3.3 SET Section
 - 3.4 Auxiliary Records
- 4. Basic Data on Nuclei
- 5. Level Scheme
- 6. Deformation Parameters
- 7. Level Density Parameters
- 8. Optical Potential Parameters
- 9. Structure of EVLDF
 - 9.1 Material-wise File
 - 9.2 Parameter-wise File
- 10. Index of EVLDF
- 11. Conclusion
- References

1. Introduction

Evaluation Data File (EVLDF) has been designed to store parameters needed for theoretical calculations of nuclear data. EVLDF is mainly used in the Integrated Nuclear Data Evaluation System (INDES)¹⁾ to provide basic parameters that are input data of various theoretical calculation codes. So far, formats for the following parameters are determined.

basic data on nuclei level scheme deformation parameters level density parameters optical model parameters

In Chapters 2 and 3, basic rules and basic formats of EVLDF are described. The formats and some examples of these parameters are given in Chapters from 4 to 8. Among the parameters, the level density parameters and the optical model parameters are model dependent. The current format of EVLDF is capable of storing those parameters used for the evaluation work of JENDL- 3^{2} . Two kinds of file structure of EVLDF are described in Chapter 9; to store the parameters used for the evaluation work and to provide global and systematically evaluated parameters for new evaluation work. Chapter 10 describes an index file of EVLDF which is an auxiliary file for handling EVLDF.

2. Basic Rules of EVLDF Format

- A line of EVLDF consists of 80 columns. The columns from 73 to 80 are used for sequential number of lines or other purposes.
- 2) Characters from A to Z should be capital letters.
- 3) The smallest group of lines is a record.
- 4) In the columns from 1 to 10, a record name is given. For example, a character string DATA is given in the columns 1 to 4, the line is called as a DATA record. Record names defined are listed in Table 1.
- 5) Each record can be continued to next lines. No limitations exist on the number of lines.
- 6) In the case where a record is repeated, "+" is given in the first column of the following records.

Example

CODE	CASTHY
+	ECIS
+	GNASH

- 7) Data in the columns from 11 to 72 depend on the record name. Data type is given in Table 1. Usually, data in the columns from 11 to 72 are given in a free format.
- 8) In any lines, any comment can be given after a semi-colon (";").
- Some records have corresponding END records. A group of lines from a line with record name to its END record is a <u>section</u>.
- 10) In many cases, nuclide is represented with an integer calculated from atomic number, mass number and meta-stable number as (atomic number)×10000 + (mass number)×10 + (meta-stable state number). The mass number and meta-stable state number are 0 for natural elements. This integer is called as a <u>nuclide name</u>.
- 11) Units of numerical data are defined as listed in Table 2.

3. Details of Format

3.1 DATA Section

Parameters are mainly stored in a DATA section. The DATA section starts with the DATA record and ends with the ENDDATA record.

DATA NAME1, NAME2, NAME3,

ENDDATA

NAME1, NAME2, ... are <u>parameter symbols</u> which indicate parameters whose values are given in the DATA section. They are written in the columns from 11 to 72, and separated with a comma (",") or blanks. The parameter symbols are listed in Table 3, and described in Chapters 4 to 8. Actual values of the parameters should be given in the same order of the parameter symbols.

Example

DATA A, T, PAIR, SCF

Parameters of level density (A), nuclear temperature (T), pairing energy (PAIR) and spin cutoff factor (SCF) are given after this DATA record.

In the case of repetition, symbol of number of repetition is followed by a group of symbols to be repeated in "()".

Example

DATA EL, J, PARITY, NG (FLVL, BR) Level scheme is given after this DATA record. Parameters are given in the order of level energy (EL), spin (J), parity (PARITY) and NG sets of level number of final states (FLVL) and branching ratios (BR).

There are no restrictions on the order of parameter symbols. Numerical Data in the DATA section should be given under the following rules.

- Data given in the columns from 1 to 9 of each line in the DATA section depend on parameters. Sometimes they are called as <u>DATA-line symbols</u>. The DATA-line symbols defined so far are listed in Table 4.
- DATA-line symbols should be left adjusted except for the case where the DATA-line symbols are nuclide names.
- 3) The column 10 indicates continuation to the next line. If the 10-th column is not blank, the data are continued to the next line. In this case, a DATA-line symbol of the next line is the same as the previous line. It should be noted that this rule of continuation is valid only for the numerical data in the DATA section.

Example

DATA	EL, J, PARITY, NG (FLVL, BR)
0431010	0.0 , 4.5, 1.0, 0
0431010	+ 1.028, 1.5, 1.0, 5
0431010	3, 0.30, 4, 0.25, 6, 0.14, 8, 0.13
0431010	1.23, 3.5, -1.0, 0

4) The numerical data in the columns from 11 to 72 are given in a free format. They are

read with a list-directed READ statement of FORTRAN.

5) Units of the numerical data are given in Table 2.

3.2 MAT section

MAT n (auxiliary records) (DATA section) ENDMAT

"n" is a nuclide name. In the MAT section, parameters used for the evaluation of the material(s) are stored. On one MAT record, only one nuclide name is given. If two or more than two nuclide names have to be given, the MAT record should be repeated.

Example

MAT	922350
+	922360

3.3 SET section

SET xxxxx (auxiliary records) (DATA section) ENDSET

Any set of parameters between a pair of SET and ENDSET records is named as xxxxx. A set name xxxxxx is any alphabetic characters and/or integers without any blanks or commas among them. The maximum length of the set name is 20 characters.

3.4 Auxiliary Records

Auxiliary records commonly used are described here. Other auxiliary records, which are dependent on parameters, are explained in Chapters from 4 to 8.

1) CODE record

A CODE record is used in the MAT section only. A name of theoretical calculation code is given in the columns from 11 to 72. If several codes are used in the evaluation, the CODE records are repeated as follows:

Example

 CAPTURE AND INELASTIC SCATTERING CROSS SECTION WERE BASED ON THIS CALCULATION. + ECIS + GNASH 	CODE	CASTHY ; OPTICAL AND STATISTICAL MODEL CALCULATION
 WERE BASED ON THIS CALCULATION. + ECIS + GNASH 		CAPTURE AND INELASTIC SCATTERING CROSS SECTIONS
+ ECIS+ GNASH		WERE BASED ON THIS CALCULATION.
+ GNASH	+	ECIS
	+	GNASH

2) EVAL record

Evaluator's names are given. This record is used only in the MAT section.

Example

EVAL	K.SHIBATA	, T.NAKAGAWA, T.	ASAMI, T.FUKAHO	RI, T.NARITA,
	S.CHIBA,	M.MIZUMOTO,	A.HASEGAWA,	Y.KIKUCHI,
	Y.NAKAJIM	A AND S.IGARASI	[

3) REF record

References of the evaluation or parameters are given.

Example

REF JAERI 1319 (1990)

4) COMMENT record

Any comment can be given in the columns from 11 to 72.

Example

COMMENT THE LEVEL DENSITY PARAMETERS STORED HERE WERE MAINLY TAKEN FROM THE EVALUATION BY JNDC FP NUCLEAR DATA WORKING GROUP. THOSE OF NUCLEI

OUTSIDE OF THE FP REGION WERE EVALUATED BY ...

4. Basic Data on Nuclei

Basic data of nuclei are stored between a NUCLIDE record and an ENDNUCLIDE record.

NUCLIDE

ENDNUCLIDE

In the DATA section, the following data can be stored.

EL	level energy (MeV). For the ground state, EL=0.0.
l	spin. If unknown, SPIN < 0.0.
PARITY	parity. (1.0 or -1.0). If unknown, PARITY = 0.0.
HL	half-life (sec). For stable states, 0.0 is given. If unknown, $HL < 0.0$.
ABN	abundance (%).
MASSEX	mass-excess (MEV).

The data should be stored in the increasing order of level energies. DATA-line symbols in the columns from 1 to 9 are nuclide names. The nuclide names should be given in the increasing order.

Example

NUCLIDE	
SET	NUCL92
COMMENT	BASED ON ENSDF AS OF 1992.06
	- EL : LEVEL ENERGY (MEV).
	– J : TOTAL SPIN. IF UNKNOWN, –1.0 IS GIVEN.
	– PARITY : PARITY. IF UNKNOWN, 0.0 IS GIVEN.
	- MASSEX : MASS-EXCESS(MEV): WAPSTRA-AUDI(1985).
	- HL : HALF-LIFE (SEC). IF UNKNOWN, -1.0 IS GIVEN.
	– ABN : ABUNDANCE (%).
DATA	EL, J, PARITY, MASSEX, HL, ABN

0000010	0.00000E+00, 0.5, 1.0, 8.07137E+00, 6.24000E+02, 0.0
0010010	0.00000E+00, 0.5, 1.0, 7.28903E+00, 0.00000E+00, 99.985
0010020	0.00000E+00, 1.0, 1.0, 1.31358E+01, 0.00000E+00, 0.015
0010030	0.00000E+00, 0.5, 1.0, 1.49491E+01, 3.89098E+08, 0.0
0010040	0.00000E+00, 2.0,-1.0, 2.58400E+01,-1.00000E+00, 0.0
0020030	0.00000E+00, 0.5, 1.0, 1.49310E+01, 0.00000E+00, 0.000137
0020040	0.00000E+00, 0.0, 1.0, 2.42409E+00, 0.00000E+00, 99.999863

0.00000E+00, 1.5,-1.0, 1.13900E+01, 1.09703E-13, 0.0

ENDDATA ENDSET

0020050

ENDNUCLIDE

5. Level Scheme

Level scheme is stored between a LEVEL record and an ENDLEVEL record.

LEVEL

ENDLEVEL

In the DATA section, the following data can be stored.

NO	level number. A ground state should be 0.
EL	level energy (MeV).
1	spin. For the level energy above where levels can be assumed to be
	overlapping, J=-1.0.
PARITY	parity. Parity of + and - is represented by 1.0 and -1.0, respectively.
	For the overlapping state, $PARITY = 0.0$.
HL	half-life (sec).
NG	number of γ -rays emitted from the level.
FLVL	level number of final state.
BR	branching ratio.
EG	γ-ray energy (MeV).
If y tra	nsition data are given, NG, FLVL, BR and/or EG have to be specified

in the form of	
DATA	, NG (FLVL, BR)

Among these parameter symbols, EL, J and PARITY should be always given. For γ -ray transition data, in addition to them, NO, NG, FLVL and BR are obligatory. The data should be stored in the increasing order of level numbers and level energies. In the columns from 1 to 9, nuclide name is given in the increasing order.

Example

LEVEL	
SET	J3FPLVL
COMMENT	USED FOR THE EVALUATION OF FP NUCLEAR DATA FOR
	JENDL-3.
DATA	EL, J, PARITY
0330750	0.0 , 1.5, -1.0 ; LVL70
0330750	1.98600E-01, 0.5, -1.0
0330750	2.64660E-01, 1.5, -1.0
0330750	2.79540E-01, 2.5, -1.0
0330750	3.03920E-01, 4.5, 1.0
0330750	8.65000E-01, -1.0, 0.0
0340740	0.0 , 0.0, 1.0 ; LVL70
0340740	6.34780E-01, 2.0, 1.0
0340740	8.53800E-01, 0.0, 1.0
0340740	1.26890E+00, 2.0, 1.0
0340740	1.36320E+00, 4.0, 1.0
0340740	1.60000E+00, 2.0, 1.0
ENDDATA	
ENDSET	
ENDLEVEL	

The following is an example of level scheme with γ -transition data.

LEVEL

SET		YAMAMURO91; FOR 504 NUCLIDES.	
COMMENT		EVALUATED BY N.YAMAMURO FOR SINCROS (199	1).
DATA		NO, EL, J, PARITY, NG (FLVL, BR)	
0050100		0, 0.00000E+00, 3.0, 1.0, 0	
0050100		1, 7.18300E-01, 1.0, 1.0, 1, 0, 1.00000	
0050100		2, 1.74010E+00, 0.0, 1.0, 2, 1, 0.99800, 0, 0.00200	
0050100		3, 2.15430E+00, 1.0, 1.0, 3, 2, 0.51600, 1, 0.27300	
0050100	+	4, 3.58710E+00, 2.0, 1.0, 4, 3, 0.14000, 2, 0.00300	
0050100		1, 0.66800, 0, 0.18900	
0050100		5, 4.77400E+00, 3.0, 1.0, 2, 1, 0.99500, 0, 0.00500	
0050100		6, 5.11030E+00, 2.0, -1.0, 3, 2, 0.05000, 1, 0.31000	
0050100	+	7, 5.16390E+00, 2.0, 1.0, 5, 4, 0.07700, 3, 0.64800	
0050100		2, 0.00700, 1, 0.22400, 0, 0.04400	
ENDDATA			
ENDSET			
ENDLEVEL			

6. Deformation Parameters

Deformation parameters are stored between a DEFORM record and an ENDDEFORM record.

DEFORM

ENDDEFORM

In the DATA section, the following data are stored.

EL	level energy (MeV).
J	spin
PARITY	parity
DL	orbital angular momentum transfer
BETA	deformation parameters (β)

BETA2 deformation parameters (β^2)

The data should be stored in the increasing order of level energies. In the columns from 1 to 9, nuclide name is given. In one DATA section, the deformation parameters for many nuclei can be stored. In such case, the deformation parameters should be stored in the increasing order of the nuclide names.

Example

DEFORM			
COMMENT	EVALUATEI) BY	N.YAMAMURO FOR SINCROS (1990).
DATA	EL,	DL,	BETA,
0140280	1.77880E+00,	2,	0.47000
0140280	4.61690E+00,	4,	0.20000
0140280	6.69140E+00,	0,	0.08000
0140290	1.27330E+00,	2,	0.41000
0140290	2.02820E+00,	2,	0.41000
0140290	4.08020E+00,	4,	0.20000
0140290	4.74100E+00,	4,	0.20000
0140300	2.23540E+00,	2,	0.32000
0140300	5.27950E+00,	4,	0.20000
0140300	6.64110E+00,	0,	0.08000
0230510	9.28700E-01,	2,	0.25000

ENDDATA

ENDDEFORM

7. Level Density Parameters

Level density parameters are stored between a LDP record and an ENDLDP record. The parameters are model dependent. In the current format, the parameters for Gilbert and Cameron's composite formula can be stored.

_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

ENDLDP

A FORMULA record identifies a level density formula.

FORMULA XXXXX

xxxxx = GILBERT-CAMERON: Gilbert and Cameron's composite formula³⁾

Gilbert and Cameron's Composite Formula

Level density of levels having spin J, parity π and excitation energy E is written by the following equations:

$$\rho_{J\pi} = p(\pi) R(J) \rho_0(E), \qquad (7.1.1)$$

where $p(\pi)$ is the normalized parity distribution, and R(J) the normalized spin distribution.

$$R(J) = \frac{2J+1}{2\sigma^2} \exp\left(-\frac{J(J+1)}{2\sigma^2}\right).$$
 (7.1.2)

The energy dependent part $\rho_0(E)$ is written by the Fermi gas model above E_x ,

$$\rho_0(E) = \frac{\exp(2\sqrt{aU})}{12\sqrt{2}\sigma a^{1/4}U^{5/4}},$$
(7.1.3)

and by the constant temperature model below E_x ,

$$\rho_0(E) = C \exp(U/T).$$
(7.1.4)

 E_x is a connection energy of these two models. U is given by $U = E - \Delta$, where Δ is a pairing energy. The spin cutoff factor σ^2 in the energy region above E_x is written as:

$$\sigma^2 = C_0 \sqrt{aU} A^{2/3} = \alpha_M U^{1/2}, \qquad (7.1.5)$$

where α_M is a spin cutoff parameter. On the other hand, in the constant temperature model

region $(E \le E_x)$, several equations of σ^2 have been proposed. One parameter to be stored is a spin cutoff factor at 0 MeV, $\sigma^2(0)$. For example, the following equation was proposed by Gruppelaar⁴:

$$\sigma^{2} = \sigma^{2}(0) + (\sigma^{2}(E_{x}) - \sigma^{2}(0)) \frac{E}{E_{x}}.$$
 (7.1.6)

The parameters are stored with the following auxiliary record and the DATA record.

SCOEF n n is a coefficient of spin cut-off factor (C_0 in Eq. (7.1.5)). If the coefficient is 0.146, this record can be omitted.

In the DATA section, the following parameters are stored.

Α	$a (MeV^{-1})$ in Eq.(7.1.3).
Т	temperature (MeV) in Eq.(7.1.4).
PAIR	pairing energy Δ (MeV).
EX	connecting energy E_x of the constant temperature model and Fermi gas
	model (MeV).
SCF	spin cutoff factor at 0 MeV, $\sigma^2(0)$ in Eq.(7.1.6).
SCP	spin cutoff parameter, α_{M} in Eq.(7.1.5).
E0	energy (MeV) where a cumulative number of levels is 1.0.

In the columns from 1 to 9, nuclide name is given as the DATA-line symbol. The nuclide name should be given in the increasing order.

Example

LDP	
SET	J3FPLDP; FOR JENDL-3 FP NUCLEAR DATA
COMMENT	MAIN PART OF THIS LDP SET WAS DETERMINED BY JNDC FP
	NUCLEAR DATA WG FOR EVALUATION WORK OF JENDL-3.
FORMULA	GILBERT-CAMERON
SCOEF	0.146
0320780	1.2340+1, 8.6990-1, 2.930, 9.3949+0, 9.3628+0, 5.0000+0
---------	--
0320790	1.3620+1, 7.5230-1, 1.360, 6.5668+0, 9.9203+0, 5.0000+0
0330740	1.1320+1, 9.4750-1, 0.000, 7.0329+0, 8.6583+0, 5.0000+0
0330750	1.2500+1, 9.5100-1, 1.880, 1.0084+1, 9.1801+0, 3.5000+0
0330760	1.3300+1, 7.8600-1, 0.000, 5.6109+0, 9.5533+0, 5.0000+0
0330770	1.3000+1, 8.4400-1, 1.470, 7.9511+0, 9.5276+0, 5.0000+0
0330780	1.1500+1, 7.5000-1, 0.000, 3.8937+0, 9.0385+0, 5.0000+0
0330790	1.2900+1, 8.2300-1, 1.570, 7.5852+0, 9.6546+0, 5.0000+0
0330800	1.1500+1, 7.2500-1, 0.000, 3.5351+0, 9.1924+0, 5.0000+0
0340730	1.4040+1, 8.2500-1, 1.430, 8.2876+0, 9.5555+0, 5.0000+0
0340740	1.2900+1, 8.6200-1, 2.860, 9.6116+0, 9.2428+0, 3.9250+0
0340750	1.3910+1, 8.5000-1, 1.430, 8.7066+0, 9.6841+0, 5.0000+0
0340760	1.3150+1, 8.9000-1, 3.310, 1.0819+1, 9.4993+0, 6.7802+0
0340770	1.4380+1, 8.0000-1, 1.430, 8.0145+0, 1.0021+1, 6.5179+0
0340780	1.2870+1, 8.7500-1, 2.900, 9.8819+0, 9.5618+0, 4.8750+0
0340790	$1.4120+1,\ 8.0000-1,\ 1.430,\ 7.8422+0,\ 1.0101+1,\ 4.6724+0$

ENDDATA ENDSET ENDLDP

8. Optical Model Parameters

Optical model parameters are stored between the OMP record and the ENDOMP record.

OMP

ENDOMP

An INCIDENT section has to be used to specify the incident particle. Between an INCIDENT record and an ENDINC record, the optical model parameters of the corresponding

incident particle are stored.

INCIDENT n

ENDINC

"n" represents the incident particle in the same rule as nuclide name.

 10
 neutron

 10010
 proton

 10020
 deuteron

 10030
 triton

 20040
 α

The following auxiliary records are defined.

n

TARGET n1, n2

n1 and n2 indicate a range of nuclei for which the optical potential parameters can be applied.

TYPE

defines type of form factors of imaginary parts.

n Surf	face term	Volume term
1 Gaussia	n form	none
2 derivativ	ve Wood-Saxon form	none
3 none		Wood-Saxon form
5 none		WOOd Saxon Ionn
4 Gaussia	n form	Wood-Saxon form

COULOMB n

V

Coulomb radius parameter (fm) for charged particles.

In the DATA section, parameters are stored under the following parameter names.

real potential depth (MeV)

WV	volume type imaginary potential depth (MeV)
ws	surface type imaginary potential depth (MeV)
VSO	real part of spin-orbit potential depth (MeV)
WSO	imaginary part of spin-orbit potential depth (MeV)
EMIN	lower boundary of incident particle energy (MeV)
EMAX	higher boundary of incident particle energy (MeV)

By some researchers, very complicated formula have been proposed. For each type, however, only the following energy dependent potential p(E) can be stored.

$$p(E) = a_0 + a_1 E + a_2 E^2 + a_5 \sqrt{E} + b \frac{N-Z}{A} + c \frac{Z}{A^{1/3}}.$$
(8.1)

Nuclear radius for each potential is expressed as:

$$R = r_0 + r_a A^{1/3} + r_1 E + r_2 E^2 + \dots + r_s \frac{N-Z}{A}.$$
 (8.2)

Diffuseness parameters have almost the same form as nuclear radii.

$$a = a_0 + a_1 E + a_2 E^2 + \dots + a_s \frac{N-Z}{A}.$$
 (8.3)

DATA-line symbols in the columns from 1 to 9 of the DATA section represent the terms of above expressions as follows:

E0	constant term. a_0 in Eq.(8.1).
E 1	first order term of energy. a_1 in Eq.(8.1).
E2	second order term of energy. a_2 in Eq.(8.2).
E5	square root term. a_5 in Eq.(8.1).
E9	$Z/A^{1/3}$ term. c in Eq.(8.1).
SYM	symmetric term. b in Eq.(8.1).
R	nuclear radius parameter. r_a in Eq.(8.2).
RC	constant term of nuclear radius. r_0 in Eq.(8.2).

Α

diffuseness parameter. a_0 in Eq.(8.3).

energy dependent terms and symmetric terms of R and A can be represented

as

R-E1 (=
$$r_1$$
), R-SYM (= r_s),
A-E1 (= a_1), A-SYM (= a_s).

10; neutron

130000, 239999

Example

OMP INCIDENT TARGET TYPE

TYPE	1					
DATA	V,	WS,	VSO,	EMIN,	,	EMAX
E0	48.46,	4.94,	6.0,	0.0,	11.0	
E0	51.87,	7.14	6.0,	11.0,	20.0	
E1	0.0,	0.20,	0.0,	0.0,	11.0	
E1	-0.31,	0.0,	0.0,	11.0,	20.0	
R	1.18,	1.26,	1.01,	0.0,	20.0	
A	0.64,	0.58,	0.5,	0.0,	20.0	

ENDDATA

ENDINC

ENDOMP

This example stores the following potential parameters:

V = 48.46 for $E_n < 11$ MeV, and = 51.87 - 0.31× E_n for $E_n > 11$ MeV, WS = 4.94 + 0.2× E_n for $E_n < 11$ MeV, and = 7.14 for $E_n > 11$ MeV, VSO = 6.0 MeV R (real term) = $1.18 \times A^{1/3}$ fm, R (surface term) = $1.26 \times A^{1/3}$ fm, R (volume term) = $1.01 \times A^{1/3}$ fm, Diffuseness parameter of the real term = 0.64 fm, Diffuseness parameter of the surface term = 0.58 fm, Diffuseness parameter of the volume term = 0.50 fm.

9. Structure of EVLDF

There are two ways of storing parameters into EVLDF. One way is to store the

parameters used for evaluation of each material. Another way is to store global parameters or systematically evaluated parameters. A file made in the first way is called as a materialwise file and the file in the second way a parameter-wise file.

9.1 Material-wise File

This file consists of only MAT sections. Parameters used for the evaluation of material n_1 is compiled in a MAT section as follows:

MAT n₁ EVAL record REF record CODE record COMMENT record NUCL section LEVEL section DEFORM section LDP section OMP section

If no data are existing, some records and/or sections may be omitted. After this MAT section, another MAT section can be stored. In this case, MAT sections should be stored in increasing order of nuclide names $(n_1 < n_2 < ... < n_n)$.

9.2 Parameter-wise File

A parameter-wise file stores global parameters and/or parameters evaluated systematically. In the parameter-wise file, the MAT section cannot be existing. The following is an example of the parameter-wise file for the optical potential parameters.

OMP INCIDENT n₁ SET NN01 REF record TARGET record DATA section (other pairs of the TARGET record and the DATA section)^{*)} ENDSET (other SET sections for the incident particle n₁) ENDINC (other INCIDENT sections) ENDOMP

*) Pairs of the TARGET record and the DATA record should be given in the increasing order of nuclide names.

In the parameter-wise file, parameter sets should be named by SET and ENDSET records. In a file, several kinds of parameters may be stored.

10. Index of EVLDF

Parameters are stored in several material-wise files and several parameter-wise files. Those files can be partitioned or sequential files. In order to treat the parameters stored in EVLDF, therefore, an index file will be quite useful. A small program, EVLDFIND, was made to create the index file.

The format of the index file is as follows:

Columns	format	description
1 - 33	A33	Data-set name where the parameters are stored. In the
		case of a PO file, a member name is specified.
34 - 40	I7	The first position (line number) of record.
41 - 45	I5	Number of lines.
46 - 54	A9	Name of record. One of MAT, LDP, OMP, LEVEL,
		NUCLIDE.
(for para	neter-w	vise files)
55 - 74	A20	Name of parameter-set.
(for mate	rial-wis	se files)
55 – 59		blanks
60 - 66	I 7	Minimum nuclide name given in MAT record.
67 - 73	I7	Maximum nuclide name given in MAT record.

74		blank
(for bot	th files)	
75 - 81	I7	incident particle for OMP, blanks for other parameters.
82 - 88	I7	Minimum nuclide name of TARGET record or DATA section.
89 - 95	I7	Maximum nuclide name of TARGET record or DATA section.

The format of the columns from 55 to 74 for the material-wise file is different from that for the parameter-wise file.

The outputs of EVLDFIND in the above format are merged into one sequential file.

11. Conclusion

The format of EVLDF has been described. So far, the formats for the optical model parameters, the level density parameters, the level scheme, the deformation parameters and the basic data on nuclei (such as mass, spin) have been determined. However, they have not been fixed completely yet and they will be modified if some inconveniences are found. The formats for other parameters will be defined too.

References

- Nakagawa T., and Fukahori T.: "Integrated Nuclear Data Evaluation System", proc. 1992 Symposium on Nuclear Data, Tokai, 1992 Nov. 26-27, published as JAERI-M report.
- Shibata K., Nakagawa T., Asami T., Fukahori T., Narita T., Chiba S., Mizumoto M., Hasegawa A., Kikuchi Y., Nakajima Y., and Igarasi S.: "Japanese Evaluated Nuclear Data Library, version-3", JAERI 1319 (1990).
- 3) Gilbert A., and Cameron A.G.W.: Can. J. Phys., 43, 1446 (1965).
- 4) Gruppelaar H.: ECN-13 (1977).

record	functions	11-72 col*	END record
CODE	specifies a theoretical code used for an evaluation work.	C1	none
COMMENT	stores any comment.	C2	none
DATA	defines parameters to be stored. A heading line of a DATA section.	C3	ENDDATA
DEFORM	starts a deformation parameter section.		ENDDEFORM
EVAL	evaluator's name.	C2	none
FORMULA	a formalism of level density parameters.	C1	none
INCIDENT	specifies an incident particle. Used in a OMP section.	n	none
LDP	starts a level density parameter section.		ENDLDP
LEVEL	starts a level scheme section.		ENDLEVEL
MAT	material name.	n	ENDMAT
NUCLIDE	starts a section of basic data on nuclei.		ENDNUCLIDE
OMP	starts an optical model parameter section.		ENDOMP
REF	references.	C2	none
SCOEF	a coefficient for a spin-cutoff factor.	n	none
SET	names a set of parameters.	C1	ENDSET
TARGET	a range of target nuclei.	n, n	none
TYPE	type of an optical potential.	n	none

Table 1 Records in EVLDF

- * C1 characters without blanks and ","
 - C2 any characters
 - C3 parameter symbols
 - n numerical data

Table 2	Units	of physical	quantities
	Onico	or physical	Anamercie 2

unit	quantities	
MeV	energy, mass excess	
fm	nuclear radius	
barns	cross section	
sec	half-life	
%	abundance	

Symbol	Parameter	description
A	LDP	a (MeV ⁻¹)
ABN	NUCLIDE	abundance (%)
BETA	DEFORM	deformation parameter (β)
BETA2	DEFORM	deformation parameter (β^2)
BR	LEVEL	branching ratio of γ-ray transition
DL	DEFORM	angular momentum transfer
EG	LEVEL	γ-ray energy (MeV)
EMIN	OMP	lower boundary of incident particle energy (MeV)
EMAX	OMP	upper boundary of incident particle energy (MeV)
E0	LDP	an energy where cumulative number of levels is 1.0.
EL	LEVEL DEFORM	level energy (MeV)
EX	LDP	a connection energy between the constant temperature model and the Fermi gas model (MeV)
HL	NUCLIDE	half-life (sec)
1	DEFORM LEVEL NUCLIDE	spin
MASSEX	NUCLIDE	mass excess (MeV)
NG	LEVEL	number of y-rays
PAIR	LDP	pairing energy (MeV)
PARITY	DEFORM LEVEL NUCLIDE	parity
SCF	LDP	spin-cutoff factor at 0 MeV
SCP	LDP	spin-cutoff parameter
Т	LDP	temperature (MeV)

Table 3 Parameter Symbols used in DATA section

.....

Symbol	Parameter	description
v	OMP	real potential depth (MeV)
VSO	OMP	real part of spin-orbit potential (MeV)
wso	OMP	imaginary part of spin-orbit potential depth (MeV)
ws	OMP	depth of surface type imaginary potential (MeV)
wv	OMP	depth of volume type imaginary potential (MeV)

Symbol	Parameter	Description							
A	OMP	diffuseness parameter (fm)							
E0	OMP	constant term of potential depth (MeV)							
E1	OMP	first order term of potential depth (MeV)							
E2	OMP	second order term of potential depth (MeV)							
E5	OMP	square root term of potential depty (MeV)							
E9	OMP	$Z/A^{1/3}$ term of potential depthy (MeV)							
R	OMP	nuclear radius parameter (fm)							
RC	OMP	constant term of nuclear radius (fm)							
SYM	OMP	depth of symmetric term (MeV)							
nuclide– name	DEFORM LEVEL LDP NUCLIDE	nuclide name determined as (atomic number)×10000+(mass number)×1000+(meta- stable state number)							

Table 4 DATA line symbols

PROGRESS AND ACTIVITIES ON REFERENCE INPUT PARAMETER LIBRARY

FOR NUCLEAR MODEL CALCULATIONS OF NUCLEAR DATA

AT CNDC *

Su Zongdi Ge Zhigang Zhang Limin Ma Lizhen Sun Zhengju Wang Chenxiang Zhou Chunmei (Chinese Nuclear Data Centre, CHINA INST. OF ATOMIC ENERGY)

Huang Zhongfu Liu Jianfeng (Dept.of Phys., Guangxi Univ.) (Dept.of Phys., Zhengzhou Univ.)

Yu Ziqiang Zuo Yixin Ma Gonggui (Dept.of Phys.,Nankai Univ.)(Inst.Nucl.Sci.& Tech.,Sichuan Univ.)

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

ABSTRACT

The reference input parameter library for nuclear model calculations of nuclear data, i.e. Chinese Evaluated Nuclear Parameter Library (CENPL), which consists of six sub-libraries, is being set up at Chinese Nuclear Data Center (CNDC). Most of the data files for this library have been set up, and the management-retrieval codes of these sub-libraries are being developed. These sub-libraries have been applied to retrieve the required data for nuclear model calculations of neutron data and other fields widely.

I. INTRODUCTION

Over time, theoretical understanding of nuclear phenomena has reached a considerable degree of reliability, therefore an important trend in evaluations of nuclear reaction data is the increasing use of nuclear model theories and related codes to calculate the required cross sections and spectra. In fact the experimental measurement program could never supply all of the needed data, so the results of theoretical programs have been assimilated in order to supplement the experimental data.Due to the widespread use of nuclear models in generating evaluated nuclear data, there are some difficulties for requirements of a large volume of nuclear basic data and model parameters, as well as for the lack of reliable parameters needed to perform such calculations. As we know, the confidence of the calculated results depends on not only used model but also the reliability of the relevant parameters. Hence, it will be very useful and convenient if the user could retrieve all of the needed nuclear basic data and reliable parameters from a computer library and make a primary analysis to a studied nuclear reaction. Based on above considering, a Reference Input Parameter Library(RIPL) for Nuclear Model Calculations of Nuclear Data, i.e. the CENPL, has been setting up at CNDC.

II. SCOPE AND COMPOSITION

At present, CENPL includes the following six sub-libraries: (1) THE SUB-LIBRARY OF ATOMIC MASSES AND CHARACTERISTIC CONSTANTS FOR NUCLEAR GROUND STATES (MCC);

(2) THE SUB-LIBRARY OF DISCRETE LEVEL SCHEMES AND GAMMA RADIATION BRANCHING RATIOS (DLS);

(3) THE SUB-LIBRARY OF LEVEL DENSITY (LD);

(4) THE SUB-LIBRARY OF GIANT DIPOLE RESONANCE PARAMETERS FOR GAMMA-RAY STRENGTH FUNCTION (GDP);

(5) THE SUB-LIBRARY OF FISSION BARRIER PARAMETERS (FBP);

(6) THE SUB-LIBRARY OF OPTICAL MODEL PARAMETERS (OMP).

Each sub-library consists of two parts : the data file and the management-retrieval code.

The data file stores the compiled nuclear basic data and model parameters according to certain format of computer, which can be printed out with table format for reading easily. In order to satisfy the demands of different users for model parameters, which were obtained and recommended by different authors. Hence, the data files contain various kinds of popular model parameters as far as possible.

The management-retrieval code can provide the related information on the nuclear basic data and model parameters stored in the data files, and retrieve the required data. Besides the functions mentioned above, there are other functions, such as, deriving new data, supplementing the deficient parameters, making some nuclear model calculations and comparing the calculated results from different model parameters with the experimental values etc. to help users to choose and obtain the required parameters.

The management-retrieval code provides two retrieval ways. One is a retrieval for a single nucleus(SN) or channel(SC), another is one for all relevant residual nuclei or reaction channels in a neutron induced reaction(NR). The later contains four kinds of retrieval types corresponding four types of fast neutron computation codes respectively, which make differences including reaction channels. They are as follows:

	(1) The first	type (e.g. FUP code, 4	i channels),
	1st process	2nd process	3rd process
(n	, G)(Z , A+1)	(n, 2n)(Z, A-1)	(n,3n)(Z , A-2)
(n	, n)(Z , A)		

(2) The second type (emitted particles without deutron , triton and He-3, 16 channels), 2nd process 3rd process 1st process (n, 2n)(Z, A-1)(n, 3n)(Z, A-2)(n , G)(Z , A+1)(n, n)(Z, A)(n, n p)(Z-1, A-1)(n, 2n p)(Z-1, A-2)(n , p)(Z-1,A) (n, n He4) (Z-2, A-4)(n, 2n He4)(Z-2, A-5)(n, He4) (Z-2, A-3)(n, p n)(Z-1, A-1)(n, 2p)(Z-2, A-1)(n,p He4)(Z-3,A-4)(n, He4 n) (Z-2, A-4)(n, He4 p)(Z-3, A-4)(n, 2He4)(Z-4, A-7)(3) The third type (e.g. UNF code, 14 channels), 1st process 2nd process 3rd process (n , G)(Z , A+1)(n, 2n)(Z, A-1)(n, 3n)(Z, A-2)(n, n)(Z, A)(n, n p)(Z-1, A-1)(n, p)(Z-1, A)(n, n He4) (Z-2, A-4)(n, d)(Z-1, A-1)(n, p n)(Z-1, A-1)(n, t)(Z-2, A-2)(n, 2p)(Z-2, A-1)(n, He3)(Z-2, A-2)(n, He4 n) (Z-2, A-4)(n, He4)(Z-2, A-3)(4) The fourth type (e.g. MUP code, 49 channels), 3rd process 1st process 2nd process (n, G)(Z, A+1)(n, n x) (n, 3n) (Z , A-2) (n, 2n p)(Z-1,A-2)(n, n)(Z, A)(n, p x) (n, p)(Z-1, A)(n, d x) (n, 2n d)(Z-1, A-3)(n, t x) (n, d)(2-1, A-1)(n, 2n t)(Z-1, A-4)(n, t)(Z-2, A-2)(n,He3 X) (n, 2nHe3)(Z-2, A-4)(n, He3)(Z-2, A-2)(n,He4 x) (n, 2nHe4)(Z-2, A-5)

(n,He4)(Z-2,A-3) (x=n,p,d,t,He3,He4)The nuclear basic data and model parameters of relevant residual

nuclei or reaction channels can be retrieved by using the management-retrieval code simultaneously.

III. CONTENTS AND PROGRESS

Up to now, most of the data files for six sub-libraries have been set up, and the management-retrieval code systems are being developed. Their contents and progress are as follows:

(1) THE MCC Sub-Library

The MCC data file[1] consists of calculated , systematics, and in most cases also measured mass excess ME, atomic mass M, total binding energy B, half-life T/2 or abundance AB , spin J and parity P of nuclear ground state , etc. of 4800 nuclides ranging from Z=0, A=1 to Z=122 , A=318. Most of these data were taken from Ref. [2-5], the few were collected and compiled by us, and M, B were derived from ME.

The MCC management-retrieval code, which could provide two retrieval ways, SN and NR, has been finished . For SN , besides the data listed in the MCC data file, the separation energies of

some particles and particle groups , as well as the decay energies of beta+ and beta- could be derived. For NR retrieval, the code can first calculate the reaction energies Q and threshold energies Et of 49 reaction channels for the fourth retrieval type. User may choose a retrieval type from four kinds of retrieval types according to the calculated threshold energies and user's needs, and obtain the required data for the related residual nuclei simultaneously.

(2) The DLS Sub-Library

The DLS data file contains the data and information on the discrete levels and their gamma radiations. The data and information of this file were translated from the Evaluated Nuclear Structure Data File (ENSDF)[4]. A transforming code from ENSDF to DLS had been written, and the transformation of the data has been finished. The data have further been checked and corrected, the levels undetermined energies and their gamma radiations have been deleted. Finally, the DLS data file, which contains the data and information of 79456 levels and 100411 gamma radiations for 1908 nuclides, has been set up, and the managementretrieval code is being written.

At present, the data file includes the energy, spin, parity and half-life of each measured level, as well as the order numbers to the final levels, branching ratios and multiporalities for gamma-radiations of level, if they existed.

(3) The LD Sub-Library

This sub-library includes the following two data files: A. The data relative to level density (LRD)

The LRD data file including S-wave average level spacing Do, strength function So and radioactive capture width at neutron separation energy, as well as the cumulative number No of low-lying levels for about 300 nuclides has been set up. The Do, So and No values are further being analysed and checked, a new set of Do, So, and No values will be recommended.

B. The level density parameters (LDP)

The LDP data file contains eight sets of level density parameters for three popular used level density formulae. They are three sets of parameters for the composed four-parameter formula(i.e.Gilbert-Cameron[6], Cook et al.[7] and ours[8]), three sets of parameters for back-shifted Fermi gas formula (i.e. parameters of the rigid and half-rigid body of Dilg et al.[9] and ours[10]), as well as two sets of parameters for the generalized superfluid model (Ignatyuk et al. [11] and ours[12]). The LDP data file has been set up.

The management-retrieval code of this sub-library including two retrieval ways SN and NR, is being developed.

(4) The GDP Sub-Library[13]

The GDP data file storing the giant dipole resonance parameters of 102 nuclides ranging from V-51 to Pu-239 compiled by Dietrich and Berman[14] has been set up. The management-retrieval code including two retrieval ways SN and NR has been finished. Since there are no giant dipole parameters for most nuclides, we presented a treatment method including replacement, interpolation and calculation of systematics formula, which could supplement the giant dipole resonance parameters for lack of ones in the GDP data file by using the management retrieval code.

(5) The FBP Sub-Library[15]

There are three data tables in the FBP data file, which contain fission barrier parameters recommended by Lynn[16] (for 50 nuclides ranging from Th-230 to Cf-255), Back et al.[17](for 46 nuclides ranging from Th-229 to Cf-253), and Ohsawa[18] (for 24 nuclides ranging from Pa-232 to Cf-253), respectively.

The related management-retrieval code system including two retrieval ways SN and NR has been finished.

(6) OMP Sub-Library

The OMP data file includes the following two parts:

In the first part, the global and regional optical model potentials of six type projectiles (n, p, d, t, He-3 and alpha) have being collected and compiled. There is a brief information table for each type of projectile, and there is an entry for each potential parameter set in this part. The basic information about each global and regional optical model parameter set are compiled in the table and entry.

In the second part, We have determined a standard optical potential form for nucleus-specific optical model potential, which not only can cover most of the popular optical potential parameter sets, but also is suited for future possible development tendency of optical model potential. A related computer format has also been fixed for setting up the part. About 75 sets of optimum optical model parameters for neutron only,which were used in the calculations of complete neutron data in CENDL -1, 2, have been compiled at present.

IV. CONCLUSIONS

As mentioned above, the work of constructing the six sublibraries have got a remarkable progress and the following conclusions could be obtained.

(1) Three sub-libraries (the first edition) , MCC, GDP and FBP , including their data files and management-retrieval codes have all been finished.

(2) For the DLS and LD sub-libraries, their data files have been set up, and the related management-retrieval codes are being developed.

(3) For the OMP sub-library , the data file compiled the global and regional optical model potential has had an initial scope, and the data file including the nucleus-specific optical model parameters appeared in an embryonic form yet. As the next step, we will further expand and perfect the OMP data file, that will include more optical model parameter sets from the optimized nucleus-specific ones of ENDF/B6, JENDL-3, etc., especially,

as well as others . The management-retrieval code of this sublibrary will be developed.

(4) These sub-libraries have widely been used in nuclear model computations, nuclear data evaluations and other fields in China. The applied results show that our evaluated nuclear parameter library is satisfactory and convenience, as well as this project is great worth.

(5) As the next step, the management-retrieval codes of the LD, DLS and OMP sub-libraries will be finished in the first place, the data files for OMP sub-library, in particular, and others will be expanded and updated. The management-retrieval codes should further be developed and perfected for wider applications.

V. ACTEVITIES ON CENPL AT CNDC

The project of setting up CENPL was presented at June 1990 meeting of the Chinese Nuclear Data Committee and was rated at its Nov. 1990 specialist meeting on theory work programme of nuclear data at CNDC for the period from 1991 to 1995.Our group started to bring the plan of setting up CENPL into effect in May 1991. We only collected the related data then .

Two Consultants' Meetings (Vienna, Nov. 1991 and Sirolo, June 1993) and the activities (e.g. 1992 Trieste workshop) organized by the IAEA, as well as the Agency Research Contract give much support to our project. Our project has been brougt into the programme on "Development of Reference Input Parameter Library(RIPL) for Nuclear Model Caculations of Nuclear Data" of the IAEA.

In order to review the work progress during the past period, discuss some problems in constructing CENPL, propose and arrange the tasks for the next period, we held the 1st and 2sd Working Meetings on CENPL (Nov. 26-29, 1992, Tianjin and July 17-19, 1994, Chengde), as well as two Workshops on the OMP and LD sub-libraries (Oct. 18-20,1993, Beijing and June 8-10, 1994, Nanni). The work of setting up CENPL has got a remarkable progress since 1992, and we submited the data files and managementretrieval codes of three sub-libraries(MCC, GDP, FBP) to the NDS, IAEA in April 1994.

In addition, three working groups have been organized in our group in order to perform well the Co-ordinated Research Programme (CRP) on RIPL of the IAEA and make the studies of relevant model parameters. Three working groups and their tasks are as follows.

The working group of optical model parameters consists of members from CNDC, Nankai Univ. and Sichuan Univ. And its most important task is to set up the OMP sub-library, because it will be more difficult then others. The sub group will also make the studies on optical model parameter systematics and applications of some new research achievement (e,g. dispersion relation) to the relevant codes and nuclear data calculations.

The second working group , which consists of members from CNDC and Guangxi Univ., takes on setting up the level density sub-library . And it is going to analyse and intercompare four

sets of available average resonance data (BNL, Bologna, Obninsk and CNDC) No values further, and recommend a new set of data relative to level density(LRD) . Based on the new LRD, we will analyse and compare various level density formulae and parameters(LDP) , and recommend three new sets of LDP corresponding three kinds of popularly used level density formulae (the composed four-parameter formula, back-shifted Fermi gas formula and generalized superfluid model) respectively.

The ather working group, including the members from CNDC and Zhengzhou Univ., studies mainly the giant resonance parameters of Gamma-ray strength function.We are extracting the giant dipole parameters for the more nuclei espicilly the nuclei with A<50 by using the photonuclear cross-sections, and will develop the systematics of GDP.

Finally, it will be studied that these sub-libraries are assembled a unified Reference Input Parameter Library, in order to perform the retrieval for needful various nuclear basic data and nuclear model parameters in Nuclear model Calculations at the same time.

ACKNOWLEDGMENT

The authors would like to thank NDS/IAEA and NNDC/BNL for providing us the data tapes with mass excesses, ENSDF and so on.

Reference

- [1] Su Zongdi, Ma Lizhen, Zhou Chunmei et al., CNDP, 11, 103 (1994).
- [2] A.H.Wapstra et al., At. Nucl. Data Tables, 39,281(1988).
- [3] P.Moller et al., At. Nucl. Data Tables, 39,225(1988).
- [4] Evaluated Nuclear Structure Data File a computer file of evaluated nuclear structure data maintained by the National Nuclear Data Center, Brookhaven National Laboratory.
- [5] N.E.Holden,"Table of the Isotopes", CRC Handbook of Chemistry and Physics 71st edition(1990).
- [6] A.Gilbert et al., Can.J.Phys., 43,1446(1965).
- [7] J.L.Cook et al., Auist.J.Phys., 20,477(1967).
- [8] Su Zongdi et al., INDC(CPR)-2,1985.
- [9] W.Dilg et al., Nucl. Phys., A217,296(1973).
- [10] Huang Zhongfu et al., Chinese J. Nucl. Phys., 13,147(1991).
 [11] A.V.Ignatyuk et al., Sov. Nucl. Phys., 1979, v.29, P.450.
- [12] Dong Liaoyuan et al., to be published.
- [13] Zuo Yixin, Liu Jianfeng, Zhang xizhi et al., CNDP, 11, 95 (1994).
- [14] S.S.Dietrich et al., At. Nucl. Data Tables, 38,199(1988).
- [15] Zhang Limin, Su Zongdi and Ge Zhigang, CNDP, 10,88(1994).
- [16] J.E.Lynn, AERE-R7468,1974.
- [17] B.B.Back et al., Phys.Rev., C9,1924(1974); C10,1984(1974).
- [18] T.Ohsawa, IAEA-TECDOC-483, 1988, P.134

ATOMIC MASSES AND CHARACTERISTIC CONSTANTS OF NUCLEAR GROUND STATE (CENPL.MCC)(I)*

(The first edition, Data file)

Su Zongdi Ma Lizhen Zhou Chunmei Ge Zhigang (Chinese Nuclear Data Center, CIAE, Beijing)

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

Atomic masses and data relative to nuclear ground states are nuclear basic data, and these data are also the fundamental and necessary ones in basic researches of nuclear physics, nuclear model calculations of nuclear data, and other many applied researches. A computer data file(MCC), in which the atomic masses and characteristic constants of nuclear ground states have been collected and compiled in brief table format, has been set up. Some recent measured data, such as the mass excesses and half-lives for some new nuclides etc., have been collected, and put into MCC data file.

CONTENTS

The MCC data file, which is a sub-library of Chinese Evaluated Nuclear Parameter Library(CENPL), consists of calculated, systematics, and in most cases also measured, mass excess ME, atomic mass M, total binding energy B, half-life T / 2 and abundance, spin J and parity P of nuclear ground state, etc. of 4800 nuclides ranging from Z=0, A=1 to Z=122, A=318. Most of these data were took from Ref.[1-4], the few were collected and compiled by us, and M,B were derived from ME.

FORMAT

Each record of the file contains Z, EL, A, ME, M,B and T / 2 or AB, J, P, as defined below :

Z : Charge number, column 1–3.

EL : Element symbol, column 5–6.

A : Mass number, column 8–10.

ME : Mass excess M-A and its uncertainty, column 13-28.

Most of mass excesses are the experimental data, compiled by A.H.Wapstra et al. (Ref.[1]). An appended "s" denotes that the value is from systematics(see the contribution of Ref.[1]). An appended "t" denotes that the value is the mass excess calculated by P.Moller et al.(Ref.[2]), using a nuclear mass formula with a finite-range droplet model and a folded-Yukawa single particle potential.

M : Atomic mass and its uncertainty, column 31-48. "s", "t": see above.

B : Total binding energy, column 51–60.

T / 2 or AB: Half-life and abundance, column 63-80.

These data are given followed by units ("%" symbol in case of abundance)which are followed by the uncertainty. The uncertainty given is in the last significant figures . For some very short-lives nuclei, level widths rather than half-lives are given, followed by units (e.g., eV, keV, or MeV) which are followed by the uncertainty if known.

J,P: Spin and parity of ground state, column 83–92.

ACKNOWLEDGMENT

The authors would like to thank NDS, IAEA and NNDC, BNL for providing us the data tapes with mass excesses, ENSDF and so on.

References

[1] A.H.Wapstra, G.Audi, R.Hoekstra, At. Nucl. Data Tables, 39, 281 (1988).

[2] P.Moller, M.J.Swiatecki and J.Treiner, At. Nucl. Data Tables 39, 225 (1988).

[3] Evaluated Nuclear Structure Data File – a computer file of evaluated experimental nuclear structure data maintained by the National Nuclear Data Center, Brookhaven National Laboratory. (File as of March 1991).

[4] N.E.Holden, Table of the Isotopes, 71st edition(1990).

Z	ZEL A ME(MeV)		MeV)	M(micr	o-u)	B(MeV)	T/2 0	R AB	J		
0	n	1	8.071	0	1008665	0	0.000	10.4	m	2	1/2+
1	н	1	7.289	0	1007825	0	0.000	99.985	96	1	1/2+
1	Н	2	13.136	0	2014102	0	2.224	0.015	8	1	1+
1	н	3	14.950	0	3016049	0	8.482	12.33	У	6	1/2+
1	H	4	25.840	380	4027740	410	5.663		-		2-
2	He	3	14.931	0	3016029	0	7.718	0.000137	%	3	1/2+
2	He	4	2.424	0	4002602	0	28.297	99.999863	8	3	0+
2	He	5	11.390	50	5012228	50	27.402	0.60	MeV	2	3/2-
	•		-		•		•	•			·
	•		•		•		•				
26	Fe	54	-56.250	1	53939614	0	471.763	5.9	%	2	0+
26	Fe	55	-57.476	1	54938297	0	481.060	2.73	a	3	3/2-
26	Fe	56	-60.603	1	55934941	0	492.259	91.72	%	15	0+
	•		•		•		•	•			
77	Ir	198	-25.830	s 200 s	3 197972271	s 210 s	1563.721 s	8	S	1	
77	Ir	199	-24.424	34	198973780	37	1570.339				
77	Ir	200	-22.412	t	199975940	t	1576.446 t				
77	Ir	201	-20.332	t	200978173	t	1582.437 t				
	٠		•		٠		•				
	•		•		•		•				
92	U	234	38.141	2	234040946	0	1778.584	0.0055	8	5	0+
92	U	235	40.915	2	235043924	0	1783.882	0.720	8	1	7/2-
. 92	U	236	42.441	2	236045562	0	1790.427	2.3415E7	a	14	0+
92	U	237	45.387	2	237048725	0	1795.552	6.75	đ	1	1/2+
92	U	238	47.305	2	238050784	0	1801.706	99.2745	%	15	0+
	•		•		•		•				
	•		•		•		•				
122		316	252.146	t	316270688	t	2202.961 t				
122		317	255.372	t	317274151	t	2207.807 t				
122		318	257.518	t	318276455	t	2213.732 t				

Table

·

58

ATOMIC MASSES AND CHARACTERISTIC CONSTANTS OF NUCLEAR GROUND STATE (CENPL.MCC) (II) *

(The first edition, Management-retrieval code)

Su Zongdi Ma Lizhen (Chinese Nuclear Data Center, CIAE,P.O.BOX 275-41, BEIJING)

* This project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

The management-retrieval code of the sub-library of atomic masses and characteristic constants for nuclear ground state (MCC) is used for showing the basic information on the MCC sublibrary on the screen, and retrieving the required data through code's running procedure and man-computer interaction. The retrieved results are put into the data file OUTMCC.DAT. The code has been finished at the Chinese Nuclear Data Center(CNDC), and has widely been used in nuclear model calculations of nuclear data and other fields at present.

1. Basic Information

The MCC management-retrieval code could retrieve the following data :

ME: Mass excess (M-A). Most of mass excesses are the experimental data compiled by A.H. Wapstra et al. [1] . An appended "s" denotes that the value is from systematics [1]. An appended "t" denotes that the value is calculated by P.Moller et al.[2].

J, P and T/2: Spin , parity and half-life of ground state. Most of these values are took from the Evaluated Nuclear Structure Data File(ENSDF)[3].

AB: Abundance. The abundance values are from Ref. [4].

The others, such as atomic mass M, total binding energy B; separation energies of some particles and particle groups and beta-decay energies; nuclear reaction energies Q and the corresponding threshold energies Et for some reaction channels including in up to the third reaction process could also be obtained as combinations of different mass excesses.

The retrieving data are from a computer file, MCC data file[5], which contains the data of 4800 nuclides ranging from Z=0, A=1 to Z=122, A=318. Most of these data are from the documents mentioned above, and the few are collected and complied by us.

2. Running Procedure and Examples

This code provides two retrieval ways . One is a retrieval for a single nucleus(SN), and another is one for a neutron reaction(NR). The latter contains four kinds of retrieval types corresponding four types of different neutron calculation codes respectively. The atomic masses and characteristic constants of nuclear ground states for all relevant residual nuclei including in the four kinds of retrieval types can be retrieved . We take Bi-208 and Fe-N as examples for SN, as well as Ni-58 as example doing NR retrieval respectively.

There are two ways for retrieving: _______ 1. retrieving for a single nucleus; (SN) 2. retrieving for possible residual nuclei in a neutron induced reaction. (NR) Choosing the retrieval way, SN or NR ? (ex=stop) sn SHOWING ON THE SCREEN : The following data could be retrieved for a single nucleus(Z,A): Atomic mass M and mass excess ME; Total binding energy B; Spin J and parity P of nuclear ground state; Half-life T/2 or abundance AB. If retrieving a natural isotopic composition, then the above mentioned data for all stable isotopes will be retrieved. If need be, this code could also provide the separation energies S(n), S(p), S(d), S(t), S(He3), S(He4), S(2n), S(2p); beta-decay energies Q(Beta+) and Q(Beta-). The charge number Z=? 83 The mass number A=?(For natural isotopic composition A=0) 208 **** Retrieving MCC of nucl. ground state in SN **** J, PZ, A T/2 or AB M(u) ME (MeV) B(MeV) 207.979706 -18.894 1632.805 3.68E+5 (5)+ (83,208)Y If retrieving separation energies and beta-decay energies ? (Y OR N)

У

* Retrieved separation energies and beta-decay energies * S(n) (MeV) S(p) (MeV) S(D) (MeV) S(t) (MeV) S(He3) (MeV) S(He4) (MeV) -- ------.. 6.886 3.707 8.221 10.051 9.979 -3.050 S(2n) (MeV) S(2p) (MeV) Q(B+) (MeV) Q(B-) (MeV) Z , A...................... 14.985 11.194 2.878 (83,208) Retrieving for other nucleus in the way? (y/n)Y The charge number Z=? 26 The mass number A=?(For natural isotopic composition A=0) ٥ Retrieving and showing retrieved data on the screen (be omitted, see section 3) If retrieving separation energies and beta-decay energies ? (Y OR N) Y Retrieving and showing retrieved data on the screen (be omitted, see section 3) Retrieving for other nucleus in the way? (y/n)n Choosing the retrieval way, SN or NR ? (ex=stop) nr SHOWING ON THE SCREEN : The following data could be retrieved for a neutron induced reaction: The nuclear reaction energies Q(n,x), Q(n,xy), Q(n,2nx)(here x,y denote n, p, d, t, He3 and He4) and the corresponding threshold energies Et(n,x), Et(n,xy), Et(n,2nx); Mass excess ME (or atomic mass M), abundance AB, and spin J, parity P of the ground state for target nucleus and all possible residual nuclei in the following retrieval type selected by user. There are four possible retrieval types corresponding to four kinds of fast neutron calculation codes in the managementretrieval code. The information on the residual nuclei for four retrieval types is as follows: 1) The first type (FUP code) 1st process 2nd process 3rd process (n,gamma)(Z,A+1) (n,2n) (Z,A-1) (n,3n) (Z,A-2)

(n,n) (Z,A)

61

2) The second type (emitted particles without d, t, He-3) 1st process 2nd process 3rd process (n,gamma)(Z,A+1)(n,2n) (Z, A-1)(Z, A-2)(n,3n) (n,n) (Z,A) (n,np) (2-1, A-1)(n,2np) (Z-1, A-2)(n,p) (Z-1,A)(n,n He4) (Z-2, A-4)(n, 2nHe4)(Z-2, A-5)(n,He4) (Z-2,A-3) (n,pn)(Z-1, A-1)(n,2p) (Z-2, A-1)(n,p He4) (Z-3, A-4)(n,He4 n) (Z-2, A-4)(n,He4 p) (Z-3,A-4) (Z-4,A-7) (n,2 He4) 3) The third type (UNF code) 1st process 2nd process 3rd process (n,gamma)(Z,A+1)(n,2n) (Z, A-1)(n,3n) (Z,A-2) (n,n) (Z,A) (n,np)(Z-1, A-1)(n,p) (Z-1,A) (n,n He4) (Z-2, A-4)(n,pn) (n,d) (Z-1, A-1)(Z-1, A-1)(n,t) (Z-1, A-2)(n,2p) (Z-2,A-1) (n,He3) (Z-2, A-2)(Z-2, A-4)(n,He4 n) (n,He4) (Z-2, A-3)4) The fourth type (MUP code, 49 kinds of channel) 1st process 2nd process 3rd process (n,gamma)(Z,A+1)(n,nx) (Z, A-2)(n,3n) (n,n) (n, px)(Z-1, A-2)(Z,A) (n,2np) (n,dx) (n,p) (Z-1, A)(n,2nd) (Z-1, A-3)(n,d) (Z-1, A-1)(n,tx) (n,2nt) (Z-1, A-4)(Z-1,A-2) (n,He3 x) (n, 2nHe3)(Z-2, A-4)(n,t) (n,He3) (Z-2, A-2)(n,He4 x) (n, 2nHe4)(Z-2, A-5)(Z-2,A-3) (n,He4) (x=n,p,d,t,He3,He4)The charge number Z=? 28 The mass number A=? 58 Retrieving reaction energies Q and threshold energies Et ? (Y or N) Y * Reaction energies Q and threshold energies Et for n+(28,58) * 1st reaction process: (n, t) (n, d) (n,He3) (n,He4) (n, n) (n, p) -5.948 -11.067 2.897 Q (MeV) 0.000 0.401 -6.482 Et(MeV) 0.000 0.000 6.052 11.260 6.595 0.000

2 n	d reaction	n process	:			
	(n,2n)	(n,np)	(n,nđ)	(n,nt)	(n,nHe3)	(n,nHe4)
Q (MeV)	-12.219	-8.172	-17.324	-21.150	-17.680	-6.400
Et(MeV)	12.432	8.314	17.626	21.518	17.988	6.511
	(n,pn)	(n,2p)	(n,pd)	(n,pt)	(n,pHe3)	(n,pHe4)
Q (MeV)	-8.172	-6.554	-11.976	-16.917	-16.666	-6.315
Et(MeV)	8.314	6.668	12.185	17.212	16.956	6.425
	(n,dn)	(n,dp)	(n,2d)	(n,dt)	(n,dHe3)	(n,dHe4)
Q (MeV)	-17.324	-11.976	-20.950	-23.990	-24.668	-13.029
Et (MeV)	17.626	12.185	21.315	24.408	25.097	13.256
	(n,tn)	(n,tp)	(n,tđ)	(n,2t)	(n,tHe3)	(n,tHe4)
Q (MeV)	-21.150	-16.917	-23.990	-31.111	-27.349	-18.827
Et (MeV)	21.518	17.212	24.408	31.653	27.825	19.155
	(n,He3n)	(n,He3p)	(n,He3d)	(n,He3t)	(n,2He3)	(n,He3He4)
Q (MeV)	-17.680	-16.666	-24.668	-27.349	-26.734	-14.096
Et(MeV)	17.988	16.956	25.097	27.825	27.199	14.341
	(n,He4n)	(n,He4p)	(n,He4d)	(n,He4t)	(n,He4He3) (n,2He4)
Q (MeV)	-6.400	-6.315	-13.029	-18.827	-14.096	-5.557
Et (MeV)	6.511	6.425	13.256	19.155	14.341	5.654
3 n (d reaction	n process	:			
	(n,3n)	(n,2np)	(n,2nd)	(n,2nt)	(n,2nHe3)	(n,2nHe4)
Q (MeV)	-22.466	-19.548	-27.407	-35.239	-26.977	-19.778
Et (MeV)	22.857	19.888	27.884	35.853	27.447	20.122

```
Choosing the retrieval way (1/2/3/4)?

2

selecting ME or M ? 1=ME, 2=M

1

selecting unit (u/MeV)? 1=u, 2=MeV

2

Retrieving and showing retrieved data on the screen(be omitted,

see section 3)

Retrieving for other nucleus in the way?(y/n)

n

Choosing the retrieval way, SN or NR ? (ex=stop)

ex
```

3. Retrieved Results

The retrieved results in data file "OUTMCC.DAT" are as follows: **** Retrieving MCC of nucl. ground state in SN ****

M(u)	ME (MeV)	B(MeV)	T/2 or AB		J, P	Z , A
207.979706	-18.894	1632.805	3.68E+5	 y	(5)+	(83,208)
53.939617	-56.250	471.763	5.9	~	0+	(26, 54)
55.934940	-60.603	492.259	91.72	%	0+	(26, 56)
56.935394	-60.178	499.905	2.1	%	1/2-	(26, 57)
57.933281	-62.151	509.950	0.28	%	0+	(26, 58)

* Retrieved separation energies and beta-decay energies *

S(n)(MeV)	S(p)(MeV)	S(D)(MeV)	S(t)(MeV)	S(He3)(MeV)	S(He4)(MeV)
6.886	3.707	8.221	10.051	9.979	-3.050
13.378	8.853	18.684	22.962	19.734	8.418
11.198	10.184	18.186	20.867	20.252	7.614
7.646	10.560	15.606	19.575	18.179	7.321
10.044	11.953	18.380	19.393	21.977	7.646
S(2n)(MeV)	S(2p)(MeV) Q(B+)(Me	≥V) Q(B-)(1	MeV)	Z , A
14.985	11.194	2.878			3,208)
24.062	15.414			(2	6, 54)
20.496	18.251			(2	6, 56)
18.845	19.651			(2	6, 57)
17.691	21.439			(2	6, 58)

* Retriev ME(MeV)	ed ME J,P J,P	and T/2(or T/2	AB) for or AB	n+(28, Z,	58) A	in 2nd type * Re.Channel
-61.153	3/2-	7.5E+4	у	(28,	59)	(n,gamma)
-60.225	0+	68.077	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	(28,	58)	(n,n)
-59.844	2+	70.82	đ	(27,	58)	(n,p)
-57.476	3/2-	2.73	У	(26,	55)	(n,He4)
-56.077	3/2-	35.65	ĥ	(28,	57)	(n,2n)
-59.342	7/2-	271.80	đ	(27,	57)	(n,np)
-56.250	0+	5.9	%	(26,	54)	(n,nHe4)
-59.342	7/2-	271.80	đ	(27,	57)	(n,pn)
-60.178	1/2-	2.1	%	(26,	57)	(n,2p)
-55.553	3+	312.12	đ	(25,	54)	(n,pHe4)
-56.250	0+	5.9	%	Ć	26,	54)	(n,He4n)
-55.553	3+	312.12	đ	Ć	25,	54)	(n,He4p)
-51.447	7/2-	27.702	đ	(24,	51)	(n,2He4)
-53.901	0+	6.10	đ	(28,	56)	(n,3n)
-56.037	4+	77.12	đ	Ć	27,	56)	(n,2np)
-50.943	7/2-	8.51	m	(26,	53)	(n,2nHe4)
	-						

* Reaction energies Q and threshold energies Et for n+(28,58) * (be omitted, see section 2)

4. Discussion

The MCC sub-library (Version 1) has been set up at CNDC, and used to retrieve the atomic masses and characteristic constants of nuclear ground states for the nuclear model calculations, nuclear data evaluations and other fields.

There are the mass excesses of 4800 nuclides including exotic nuclei quite far from the valley of stability in the MCC data file, therefore this sub-library could satisfy requirements of different users.

This code can also derive the separation energies of some particles and particle groups, beta-decay energies, nuclear reaction energies and corresponding threshold energies for 49 reaction channels mentioned above by the combinations of different mass excesses. Therefore, besides the data listed in the MCC data file, the derived data could also be retrieved by using this code.

It is very simple and convenient to retrieve atomic masses and related data by using the management retrieval code, because of adopting the man-computer interaction and providing various choice.

As the next step, the data of the MCC sub-library, such as ME and the data relative to ME, will be updated, and the management-retrieval code should further be perfected for wider applications.

Acknowledgment

The authors would like to thank NDS, IAEA and NNDC, BNL for providing us the data tapes with mass excesses, ENSDF and so on.

References

- [1] A.H.Wapstra, G.Audi, R.Hoekstra, At. Nucl. Data Tables, 39, 281 (1988).
- [2] P.Moller, M.J.Swiatecki and J.Treiner, At. Nucl. Data Tables 39, 225 (1988).
- [3] Evaluated Nuclear Structure Data File a computer file of evaluated experimental nuclear structure data maintained by the National Nuclear Data Center, Brookhaven National Laboratory. (File as of March 1991).
- [4] N.E.Holden, Table of the Isotopes, 71st edition(1990).
- [5] Su Zongdi and Ma lizhen, "Atomic Masses and Characteristic Constants of Nuclear Ground State (CENPL.MCC)(I)

DISCRETE LEVEL SCHEMES AND THEIR GAMMA RADIATION BRANCHING RATIOS (CENPL-DLS)(I)*

(The first edition, Data file)

Su Zongdi Zhang Limin Zhou Chunmei Sun Zhengjun (Chinese Nuclear Data Center, CIAE, P.R.China)

The DLS data file, which is a sub-library (Version 1) of Chinese Evaluated Nuclear Parameter Library (CENPL), consists of data and information of discrete levels and gamma radiations. The data and information of this data file are translated from the Evaluated Nuclear Structure Data File (ENSDF)[1], which is maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory based on evaluation from the International Nuclear Structure and Decay Data network co-ordinated by the IAEA. The transforming code from ENSDF to DLS has been written, and the transformation of the data and information has been finished. The data have further been checked and corrected, and the levels, which are of undetermined energy, and their gammas have been deleted. Finally, the DLS data file has been set up. The data format is suitable for computer reading and listing table.

CONTENTS

In the DLS data file, there are the data on both discrete levels with determinate energy and their gamma radiations. For each measured level, its order number, energy,spin, parity and half-life, as well as the order numbers to the final levels, branching ratios and multipolarities for gamma radiations are listed. At present, this file contains the data of 79456 levels and 100411 gammas for 1908 nuclides.

FORMAT

The records of the first line for each nuclide are as follows:

Z : the charge number, column 1-3.

EL : the element symbol, column 4–6.

A : the mass number, column 7-10.

The records of the line marked "L" in 13 column contain the level data NL, E, dE, J, P, IS UL and T / 2, as defined below:

NL : the order number of level, column 14–16.

E : the level energy in keV, column 17-27.

dE : the standard uncertainty of E, column 28-30.

J,P: the level spin and parity, column 31–49.

IS : the isomer state is denoted by "M", column 50.

UL : the character "?" denotes an uncertain or questionable level, column 51.

T / 2: the level half–life, column 66-83.

The records of the line marked "G" in 52 column contain the data of the gamma radiation for the level listed above, NG, Br, dBr, MP and UG, as defined below:

NG : the order number to final level for gamma transition, column 53-55.

Br : the branching ratio or relative photo intensity for gamma radiation, column 56–61.

dBr: the standard uncertainty of Br, column 62–65.

Mp : the multipolarity of gamma radiation, column 66–83.

UG : the character "?" denotes an uncertain placement of the transition in the level scheme; letter "s" denotes an expected, but as yet unobserved transition, column 84.

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

ACKNOWLEDGMENT

The authors would like to thank NNDC,BNL for providing us the data tapes with ENSDF and so on.

REFERENCE

[1] Evaluated Nuclear Structure Data File – a computer file of evaluated experimental nuclear structure data maintained by the National Nuclear Data Center, Brookhaven National Laboratory, (File as of 1991).

Example:

Z	EL	A	N	IL	E	đE	J	•	, P	ISUL	J	NG	Br	dBr	Т/2 с	r M	p	UG
21	8c	46	L	1	0.0		4+			· · · · · · · · · · · · · · · · · · ·					83.810	D	10	
			L	2	52.011	1	6+	•							9.4	US	8	
										G	ł	1	100.0		E2			
			L	3	142.528	7	1-	•		M					18.75	8	4	
										G	ł	1	100.0		E3			
			\mathbf{L}	4	227.767	9	3+	•							270	PS	LT	
										G	}	1	100.0		Ml			
			L	5	280.701	13	5+	•							270	PS	LT	
										G	;	1	5.8	7	M1			
										G	;	2	94.2	7	Ml			
					•								•					
					•								•					
			_		•	-							•					
			L	16	1141	6												
			L	17	1270.46	3	4-	•			_	_						
										G		1	40.6	11				
										G		8	21.2	10	Ml			
			_			_				G	i	9	38.2	11	Ml			
			L	18	1298	5												
			Г	19	1321.12	3	34	•	(4+)	_		-						
										G	ł	1						
			-	~ ~			<u>.</u>			G	i	11	100.0		Ml			
			Ъ	20	1394.18	4	24	•				~						
										G	ř	3	70 0	• • •	EI Mi			
										G	ř L	4	79.2	13	MI			
			т	~ 1	1427 00		10		`	G	Ì	13	20.8	13	MI			
			L	21	142/.90	4	(2	T)	~		2	100 0					
			-	~ ~	1596 74	F	10		2 41)	G	Ì	3	100.0					
			L	22	1520./4	5	(2		,3,47)	~		7	50 C	10				
										G	r •	0	50.0	19				
										6		0		10				
										G		У	47.4	19				
					•								•					
					•								•					
					•								•					

70
A SUB-LIBRARY OF NUCLEAR LEVEL DENSITY (CENPL-LD)(I)*

Ge Zhigang Su Zongdi Jin Yongli (Chinese Nuclear Data Centre, CIAE)

Huang Zhongfu Dong Liaoyuan (Phys. Dept. Guangxi University)

1. Introduction

As we know the nuclear level densities are crucial ingredient in the statistical models and the nuclear model calculations of nuclear data. Many kinds of the level density formulae have been accumulated in the past which are being used today, and there are so many sets of related level density parameters for each formula . For the convenient using we have collected the level density parameters for the popularly used four level density formulae(Gilbert-Cameron, Back-Shifted, and Generalized Superfliud Model). We also collected the data relative to level density from experimental data, the S-wave average level spacing Do, strength function So and the cumulative number No etc. Users could account these values with one of level density formula mentioned above. To make a comparison with the experimental information to help users to make the choice for level density parameters.

2. The Data File

The data file of the library consists of two parts , there are the data relative to the level density which is named as LRD and the level density parameters named as LDP.

In the LRD file the following values relative to the experimental information have been collected.

Do :	S-wave average level spacing at Bn[1],
	321 nuclei ranging from 17-0 to 253-Cf;
No :	cumulative number of low-lying level[1];
GWo:	S-wave average radiative capture width at Bn[2]
	208 nuclei ranging from 35-S to 250-Bk.

The LDP data file consists of three tables which includes several sets relevant level density parameters.

Table 1. contains three sets of parameters recommended by Gilbter-Cameron[3],Cook et al.[4] and Su et al.[5]respectively, for the composed four-parameter level density formula. The file includes the following parameters;

S(N), P(N): shell correction and paring energy for neutron unmber; S(Z), P(Z): shell correction and paring energy for charge unmber;

the parameters recommended by Gilbter-Cameron are ranging from Z=11, N=11 to Z=98, N=150, the parameters recommended by Cook et al. are ranging from Z=28, N=28 to Z=95, N=150. Su et al. recommended the parameters are ranging from Z=11, N=11 to Z=98, N=150.

Table 2.includes three sets of parameters for Back-Shifted level density formula recommended by Dilg et al.[6] and Huang et al.[7] respectively. The parameters are as follows;

as : level density parameter in 1/MeV, BSE: back shift energy.

The parameters recommended by Dilg et al for half-rigid body and rigid body are ranging from 41-Ar to 248-Cm for 220 nuclei. Huang et al. recommended the parameters for 318 nuclei ranging from 17-0 to 253-Cf.

Table 3.collected the parameters for Generalized Superfluid Model(GSM) recommended by Ignatuky et al[8] and Dong[9], respectively. The parameters are as follows;

as: asymptotic values of the level density parameter a in 1/MeV, ES: energy shift in MeV.

3. Retrieval Code System

The retrieval code system for G-C , B-S formulae has been finished and the retrieval for GSM will be provided use before long. The system could provide two ways to retrieve the parameters, i.e. retrieval for single nucleus(SN) and retrieval for a neutron introduce reaction which is four retrieval types corresponding four types of different neutron calculation code respectively. The retrieval code system can also compare the calculated results of Do, No etc. from different sets of parameter with the experimental information, in order to help users to make the choices.

4. Parameters Renewal and System Completion

As a part of Chinese Evaluated Nuclear Parameter Library, the library has been used in nuclear data calculations in China It is very convenient and useful for users. The data file will be updated and renewed if there are new parameters and the retrieval system will be perfect and complete according to users' suggestions and requirements. * The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

References

- [1] Huang Zhongfu, At. Energy Sci. Technol., 22, 321(1988)
- [2] BNL, the fourth edition, 325(1981 & 1984)
- [3] A.Gilbert et al., Can. J. Phys., 43, 1446(1965)
- [4] J.L.Cook et al., Auist. J. Physi., 20, 477(1967)
- [5] Su Zongdi et al., INDC(CRP)-2, 1985
- [6] W.Dilg et al., Nucl. Phys., A217, 269(1973)
- [7] Huang Zhongfu et al., Chinese J. Nucl. Phys., 13, 147(1991)
- [8] A.V.Ignatyuk et al., Sov. Nucl. Phys., 1979, v.29, P.450
- [9] Dong Liaoyuan, Thesis of Master "Research on GSM Level Density Formula and Comparison With Other Formulae", to be published.

A LIBRARY OF GIANT DIPOLE RESONANCE PARAMETERS FOR GAMMA-RAY(CENPL-GDP)(I)* (The first edition, the data file)

Liu Jianfen Zhang Xizhi Su Zongdi Ge Zhigang (Dept. of Phys. Zhenzhou Univ). (Chinese Nuclear Data Centre)

> Zuo Yixin (Dept. of Mathematics, Nankai Univ.)

1. Introduction

The giant resonance parameter of gamma-ray strength function characterize the average electromagnetic properties of excited nuclei. Besides their fundamental importance for nuclear structure, gamma-ray strength function is an indispensable component for nuclear reaction model calculations too. The giant dipole resonance parameters are necessary and important in the calculations of average radiation widths, radiative capture cross sections, gamma-ray production cross sections and gammaray spectra. A computer data file(GDP), in which the giant dipole resonance parameters for gamma-ray have been compiled in brief table format, has been set up. It is a sub-library of Chinese Nuclear Parameter Library (CENPL).

2. Contents

The GDP data file contains the giant dipole resonance parameters for gamma-ray strength function. These parameters of Lorentz Curves fitted to the total photoneutron cross section data compiled by S. S. Dietrich and B.L.Berman for 102 nuclides ranging from V-51 to Pu-239 in 1987.

3. Format

Each record of the file contains Z, EL, A, NL, NG, E1, CS1 E2, CS2, REF, LAB and No as defined below:

- Z : the charge number, column 1-3.
- EL : the element symbol, column 4-6.
- A : the mass number, column 7-10.
- NL : the number of sets of data for same nucleus, column 11-13.
- NG : for NG=1, single peak; for NG=2, double peaks, column 14-16.
- E1 : the peak energy of the first peak, column 17-23.

CS1:	the peak cross section of the first peak,
	column 24-30.
GW1:	the peak full width of the first peak at half-
	maximum, column 31-36.
E2 :	the peak energy of the second peak, column 37-43.
CS2:	the peak cross section of the second peak,
	column 44-50.
GW2:	the peak full width of the second peak at half-
	maximum, column 51-56.
REF:	the publication reference, bibliographic informa-
	tion is given in a chronological listing following
	the table, column 57-63.
LAB:	the laboratory at which the data were obtained and
	the experimental method employed, column 64-67.
	L Livermore, annihilation photons,
	S Saclay, annihilation photons,
	GA General Atomic, annihilation photons,
	I Illinois, tagged bremsstrahlung.

No : the order number, column 68-71.

The units for the listed quantities are given with the respective subunits headings.

The table A is an example of the data file.

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

References

[1]. S.S.Dietrich and B.L.Berman, Atomic Data and Nuclear Data Tables 38, 199(1988)

Authors for setting up this file: Liu Jianfeng, Zhang Xizhi Department of Physics, Zhenzhou Univ., Ge Zhigang, Zhou Chunmei and Su Zongdi CIAE, Chinese Nuclear Data Centre, P.O.BOX 275-41, Beijing, P.R. China, Zuo Yixin Department of Mathematics Nankai Univ.

Time of establishment: May 10, 1992. Time of correction: June 18, 1993. A LIBRARY OF GIANT DIPOLE RESONANCE PARAMETERS FOR GAMMA-RAY(CENPL-GDP)(II)* (The first edition, the management-retrieval system)

Zuo Yixin Su Zongdi Ge Zhigang (Dept.of Math.,Nankai Univ.) (Chinese Nuclear Data Centre)

> Liu Jianfeng Zhang Xizhi (Dept. of Physics, Zhenzhou Univ.)

1. Introduction

The management-retrieval system of the sub-library of the giant dipole resonance parameters for gamma-ray (GDP) is used for showing the basic information on GDP sub-library, and retrieving the giant dipole resonance parameters through code's running procedure with a conversational model way. There are no the giant dipole resonance parameters for many nuclei in GDP data file, which only contains the giant dipole resonance parameters compiled by Dietrich and Berman[1] and these parameters are necessary in a practical nuclear model calculation. A treatment method including replacement interpolation and calculation of systmatics formula, which could supplement the giant dipole resonance parameters for lack of ones in the GDP data file, was present [2]. The code has been finished at Chinese Nuclear Data Centre (CNDC), and has been used in nuclear model calculations of nuclear data.

2. Basic Information

The code is used for retrieving the giant dipole resonance (GDR) parameters for gamma-ray strength function. They are:

- E1 : the peak energy of the first peak;
- CS1: the peak cross section of the first peak;
- GW1: the peak full width of the first peak at halfmaximum;
- E2 : the peak energy of the second peak;
- CS2: the peak cross section of the second peak;
- GW2: the peak full width of the second peak at halfmaximum;

These parameters are taken from Ref[1]. The parameters retrieved from above document denoted by "E". If there are no the GDR parameters for retrieved nucleus, the code system will give ones, that are replaced with values its natural isotopic composition or other nucleus of same isotope and denoted by "R", or given by the interpolation obtained from values of other nuclei and denoted by "I", or given by the calculated values by systematic formula and denoted by "S". This file consists of the GDR parameters of 102 nuclei ranging from V-51 to Pu-239. 3. Running Process and Examples

This code system provides two retrieval ways. One is a retrieval for one single nucleus(SN), another is one for a neutron reaction(NR). The latter contains four kinds of retrieval types corresponding four types of different neutron calculation codes respectively. The GDR parameters of relevant residual nuclei including in up to the third reaction process can be retrieved. We take V-51, Sm-N and Ca-40 as examples for SN, as well as Y-89 as examples doing NR retrieval respectively.

There are two ways for retrieving: 1. retrieving for a single nucleus; (SN) 2. retrieving for possible residual nuclei in a neutron induced reaction. (NR) Choosing the retrieving way SN or NR ? (EX=stop) sn The charge number Z=? 23 The mass number A=? (For natural isotopic composition A=0) 51 ****** Retrieved G D R parameters for SN: Z=23 A= 51 ******* E1(MeV) CS1(mb) GW1(MeV) E2(MeV) CS2(mb) GW2 (MeV) Z A 53.3 7.15 E(23, 51) 17.93 3.62 20.95 40.7 Showing the reference? (Y or N) Y A. Veyssiere, H. Beil, R. Bergere, P. Carlos, A. Lepretre, A. De Miniac; Nucl. Phys. A227, 513(1974). Retrieving for other nuclei? (Y or N) Y The charge number Z=? 62 The mass number A=? (For natural isotopic composition A=0) 0 ****** Retrieved G D R parameters for SN: Z=62 A= 0 ******* CS1(mb) GW1(MeV) E2(MeV) CS2(mb) GW2(MeV) Z A E1(MeV) E(62, 144)15.32 383.0 4.45 339.0 5.09 E(62, 148)14.82 312.0 5.97 E(62, 150)14.61 E(62, 152)12.38 176.0 2.97 15.74 234.0 5.22 181.0 2.95 15.94 215.0 5.70 E(62,154) 12.27 No GDR parameters for retrieved natural isotopic composition (Z = 62),list ones of all corresponding isotopes in this data file.

Retrieving for other nuclei? (Y or N) Y The charge number Z=? 20 The mass number A=? (For natural isotopic composition A=0) 40 Showing retrieved data on the screen (be omitted, see section 4) Retrieving for other nuclei? (Y or N) n Continue to retrieve? (Y or N) Y There are two ways for retrieving: 1. retrieving for a single nucleus; (SN) 2. retrieving for possible residual nuclei in a neutron induced reaction. (NR) Choosing the retrieving way SN or NR ? (EX=stop) nr The information on the residual nuclei for four retrieval types is as follows: 1) The first type (FUP code) 3rd process 1st process 2nd process (n,gamma)(Z,A+1)(n,2n) (Z,A-1) (n,3n) (Z,A-2) (n,n) (Z,A) 2) The second type (EMISSION PARTICLES WITHOUT d,t,He-3 TYPE) 3rd process 1st process 2nd process (n,gamma)(Z,A+1)(n,2n) (Z,A-1) (n,3n) (Z,A-2) (Z-1,A-1) (n,n) (Z,A) (n,np) (n,2np) (Z-1, A-2)(Z-1,A) (n,n He4) (Z-2,A-4) (n, 2n He4) (Z-2, A-5) (n,p) (Z-2,A-3) (n,He4) (n,pn) (2-1, A-1)(n,2p) (Z-2, A-1)(n, p He4) (2-3, A-4) (n,He4 n) (2-2, A-4)(n,He4 p) (Z-3, A-4)(n,2 He4) (Z-4, A-7)3) The third type (UNF code) 3rd process 1st process 2nd process (n,gamma)(Z,A+1)(n,2n) (Z,A-1) (n,3n) (Z,A-2) (n,n) (Z,A) (n,np) (2-1, A-1)(Z-1,A) (n,n He4) (Z-2, A-4)(n,p) (n,d) (2-1, A-1)(n,pn) (Z-1, A-1)(Z-1,A-2) (n,t) (n,2p) (Z-2, A-1)(n,He3) (Z-2,A-2) (n,He4 n) (Z-2,A-4) (n, He4) (Z-2, A-3)

4) The fourth type (MUP code, 49 kinds of channel) 1st process 2nd process 3rd process (n,gamma)(Z,A+1)(n, nx)(n,3n) (Z,A-2) (n,n) (Z,A) (n,px) (n, 2np)(Z-1, A-2)(n,p) (Z-1,A) (n,dx) (n,2nd) (Z-1, A-3)(Z-1, A-1)(n,tx)(n,d) (n,2nt) (2-1, A-4)(n,t) (Z-1,A-2) (n,He3 x) (n, 2nHe3) (Z-2, A-4) (n,He3) (Z-2,A-2) (n,He4 x) (n, 2nHe4) (Z-2, A-5) (n,He4) (Z-2, A-3) (x=n,p,d,t,He3,He4) Retrieving for other reaction in this way? (Y/N) Y The charge number of target Z=? 39 The mass number of target A=? 89 Choosing the retrieving type (1/2/3/4)? Showing retrieved data on the screen (be omitted, see section 4)

4. Retrieved Results

The retrieved GDR parameters in data file "OUTGDP.DAT" are as follows:

***** Retrieved G D R parameters for SN ***** E1(MeV) CS1(mb) GW1(MeV) E2(MeV) CS2(mb) GW2 (MeV) Z A 53.3 3.62 40.7 7.15 E(23, 51) 17.93 20.95 15.32 383.0 4.45 E(62, 144)14.82 339.0 5.09 E(62, 148)14.61 312.0 5.97 E(62,150) 12.38 176.0 2.97 15.74 234.0 5.22 E(62,152) 12.27 181.0 2.95 15.94 215.0 5.70 E(62,154) No GDR parameters for retrieved natural isotopic composition (Z = 62),list ones of all corresponding isotopes in this data file. 5.00 19.94 107.0 S(20, 40)******* Reference: ******* A. Veyssiere, H. Beil, R. Bergere, P. Carlos, A. Lepretre, A. De Miniac; Nucl. Phys. A227, 513(1974).

Retrieved GDR parameters for NR: n+(39, 89) in 2nd type 1st reaction process: E1(MeV)CS1(mb)GW1(MeV) E2(MeV) CS2(mb) GW2(MeV) Z A Re-Chan. 16.83 205.0 R(39,90)(n,g) 3.69 16.83 205.0 E(39,89)(n,n) 3.69 16.84 206.0 4.50 R(38,89)(n,p) R(37,86) (n,He4) 16.80 190.0 4.47 2nd reaction process: E1(MeV)CS1(mb)GW1(MeV) E2(MeV) CS2(mb) GW2(MeV) Z A Re-Chan. R(39,88)(n,2n)16.83 205.0 3.69 16.84 206.0 4.50 R(38,88)(n,np) R(37,85) (n,nHe4) 16.80 190.0 4.47 16.84 206.0 4.50 R(38,88)(n,pn) 16.80 190.0 4.47 R(37,88)(n,2p) 17.02 222.0 S(36,85)(n,pHe4) 5.00 R(37,85) (n,He4n) 16.80 190.0 4.47 17.02 222.0 5.00 S(36,85) (n,He4p) 17.15 214.6 5.00 S(35,82)(n,2He4) 3rd reaction process: E1(MeV)CS1(mb)GW1(MeV) E2(MeV) CS2(mb) GW2(MeV) Z A Re-Chan. 16.83 205.0 3.69 R(39,87)(n,3n) 16.84 206.0 4.50 R(38,87)(n,2np) 16.80 190.0 4.47 R(37,84) (n,2nHe4)

The retrieved results are put into the file "OUTGDP.DAT".

5. Discussion

This sub-library has been used in the nuclear model calculations for nuclear data. It is very useful and simple for users to retrieve the giant dipole resonance parameters with the conversational model. The treatment methods in the sub-library for the lack experimental parameters are available, but they will be needed to improve for future works. We will also perfect the the systematics formula the sub-library including, since it is only for single peak and can not give double peak at present.

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

References

[1]. S.S.Dietrich and B.L.Berman, At. Nucl. Data Tables 38,199(1988) [2]. Zuo Yixin et al., CNDP, 11,95(1994)

A LIBRARY OF FISSION BARRIER PARAMETERS(CENPL-FBP)(I)* (The first edition, data file)

Zhang Limin Ge Zhigang Su Zongdi (Chinese Nuclear Data Centre, CIAE)

1. Introduction

The fission barrier parameters are important to determine the fission character of a nucleus. In addition, an important trend in the evaluation of the neutron reaction data is the increasing use of nuclear reaction theory codes to compute the complete neutron data. The fission barrier parameters (FBP) are needed in the calculations of various cross sections and spectra for the fissile nuclides, even heavy nuclides at higher incident energies, and the requirement of the accuracy is even higher in the practical calculation. Therefore FBP have played a special role both in fundamental nuclear physics and in the field of applications.Some valuable FBP obtained in the studies of various fission phenomena are being coolected and compiled in the FBP sub-library, which is one part of Chinese Evaluated Nuclear Parameter Library(CENPL).

2. Contents

The data file contains three sets of the fission barrier parameters. They are listed in Tables 1, 2 and 3 respectively.

Table 1 includes the fission barrer parameters recommended by J. E. Lynn [1] in 1974 from analysis of the neutron cross sections by using Hauser-Feshbach theory with the double-humped barrier for 50 actinide nuclei ranging from 229-Th to 255-Cf.

B.B.Back et al. [2,3] had measured the fission probability distributions of several fission reactions induced by direct reaction and analyzed by using a statistical model involving resonant penetration of the double--humped fission barrier in 1974. Table 2 lists the fission barrier parameters and their deviations estimated by B.B.Back et al. for 46 actinide nuclei ranging from 229-Th to 253-Cf.

Table 3 including the fission barrier parameters obtained by T. Ohsawa [4] in 1988 for 24 actinide nuclei ranging from 232-Pa to 253-Cf. The barrier heights were obtained from the fission cross section analysis based on the double-humped barrier concept and by best use of information available on the fission barriers to reduce the number of adjustable parameters. The barrier curvature parameters can were taken three constants for odd-odd, odd-A and even-even nuclei respectively, which were determined by fission isomer half-lives and fission probability data.

3. Format

Each record of these data file contains Z, EL, A, V1, DV1, W1, DW1, V2, DV2, W2, DW2, REF and No, as defined below:

: the charge number, column 1-3. : the element symbol, column 4-6. EL : the mass number, column 7-10. A V1 : the height of the first barrier, column 14-19. DV1 : the deviation of V1, column 20-23. : the curvature of the first barrier, column 27-32. W1 DW1 : the deviation of W1, column 33-36. : the height of the second barrier, column 40-45. ₹2 DV2 : the deviation of V2, column 46-49. : the curvature of the second barrier, column 53-58. W2 DW2 : the deviation of W2, column 59-62. REF : the reference, column 65-69. No : the order number, column 73-74.

The tables 1-3 give the examples of the data file.

The data file of this library will be updated when we get the new paramters.

* The project supported in part by the Internationl Atomic Energy Agency and National Natural Science Foundation of China.

References

[1] J. E. Lynn, AERE-R7468, 1974
[2] B. B. Back et al., Phys. Rev. C9, 1924(1974)
[3] B. B. Back et al., Phys. Rev. C10, 1948(1974)
[4] T. Ohsawa, IAEA-TECDOC-483, 1988, P.134

Author for setting up this file: Zhang limin, Ge Zhigang, Su Zongdi Chinese Nuclear Data Centre, CIAE P.O. Box 275(41), Beijing 102413 P.R.CHINA

Time of establishment: Aug. 15, 1992.

A LIBRARY OF FISSION BARRIER PARAMETERS(CENPL-FBP)(II)* (The first edition, The management-retrieval code)

> Zhang Limin Ge Zhigang Su Zongdi (Chinese Nuclear Data Centre, CIAE)

1. Introduction

This code system is used to retrieve the fission parameter data file of the fission barrier parameter sub-library [1] by the code's running procedure with man-computer interaction.

2. Basic Information

This code is used for retrieving the fission barrier parameters, which come from following authors; J.E. Lynn [2], for 50 actinide nuclei ranging from Th-229 to Cf-255; B.B. Back et al.[3] for 46 actinide nuclei ranging from 229-Th to 253-Cf; T. Ohsawa [4], for 24 actinide nuclei ranging from 232-Pa to 253-Cf.

The parameters come from above authors are denoted by the appended symbols "L", "B" and "O", respectively.

The used symbols and retrieved parameters in this code are as follows:

Z : the charge number.
A : the mass number.
V1 : the height of the first barrier.
W1 : the curvature of the first barrier.
V2 : the height of the second barrier.
W2 : the curvature of the second barrier.

3. Running Process and Examples

This code system provides two retrieval ways. One is retrieval for a single nucleus (SN), another is retrieval for the related nuclei with (n,f), (n,nf), (n,2nf) reaction processes in a neutron induced reaction(NR). We take 232-Pa,240-Pu as SN retrieval examples and 238-U as NR retrieval example. The running process is as follows.

There are two ways for retrieving: ------------1.retrieving for a single nucleus; (SN) 2. retrieving for the related nuclei with (n,f), (n,nf), (n,2nf) and (n,3nf) reaction processes in a neutron induced reaction.(NR) Choosing the retrieving way, SN or NR ? (EX=stop) SN The charge number Z=? 90 The mass number A=? 232 **Retrieving FB parameters for single nucleus (90,232) in SN** V1 (MeV) W1(MeV) V2(MeV) W2(MeV) Z Ά ____ --------5.82 1.0 6.22 0.75 L (90,232) 5.50 0.50 6.15 B (90,232) Choosing the required parameters, L/B/O/All or N (Not) ? L **Retrieving FB parameters for single nucleus (90,232) in SN** V1(MeV) W1(MeV) V2(MeV) W2(MeV) Z A -------------5.82 1.0 6.22 0.75 L (90,232) Retrieving for other nucleus in this way, (Y or N) ? Y The charge number Z=? 94 The mass number A=? 240 **Retrieving FB parameters for single nucleus (94,240) in SN** V1(MeV) W1(MeV) V2(MeV)W2 (MeV) Z Α -----5.57 5.07 0.6 L (94,240) 1.04 B (94,240) 5.45 0.60 5.80 0.82 0 (94,240) 0.70 5.99 1.0 5.22

86

Choosing the required parameters, L/B/O/All or N (Not) ? 0 **Retrieving F B parameters for single nucleus (94,240) in SN** V1(MeV) W1(MeV)V2 (MeV) W2 (MeV) 7 A 0.70 1.0 5.22 0 (94,240) 5.99 Retrieving for other nucleus in this way , (Y or N) ? N Continue to retrieve , (Y or N) ? Y Choosing the retrieving way, SN or NR ? (EX=stop) NR The charge number of the target Z=? 92 The mass number of the target A=? 238 **Retrieving FB parameters for target nucleus (92,238) in NR** V1(MeV) W1(MeV) V2(MeV) W2(MeV) Z A Re-Channel 1st fission process: L (92,239) (n, f) 6.46 0.8 6.16 0.52 6.55 0.90 6.30 0.6 B (92,239) (n, f) 0.55 O (92,239) (n, f) 0.8 5.75 6.31 2nd fission process: L (92,238) (n,nf) 5.68 1.0 5.68 0.6 1.00 0.62 B (92,238) (n,nf) 5.90 6.12 3rd fission process: 0.52 6.28 0.8 6.08 L (92,237) (n,2nf) B (92,237) (n,2nf) 6.35 0.85 5.95 0.55 6.38 0.8 5.85 0.55 O (92,237) (n,2nf) 4th fission process: 5.63 1.04 5.53 0.6 L (92,236) (n,3nf) 5.70 0.90 5.68 0.50 B (92,236) (n,3nf) O (92,236) (n,3nf) 5.86 1.0 5.70 0.70 Choosing the required parameters, L/B/O/All or N (Not) ?

Retrieving FB parameters for target nucleus (92,238) in NR

B

87

Retrieving FB parameters for target nucleus (92,238) in NR V1(MeV) W1(MeV) V2(MeV) W2(MeV)Z A Re-Channel 1st fission process: 6.55 0.90 6.30 0.65 B (92,239) (n, f) 2nd fission process: 5.90 1.00 B (92,238) (n,nf) 6.12 0.62 3rd fission process: 0.55 B (92,237) (n,2nf) 6.35 0.85 5.95 4th fission process: 5.70 0.90 5.68 0.50 B (92,236) (n,3nf) Retrieving for other nucleus in this way , (Y or N) ? N Continue to retrieve , (Y or N) ? N * Retrieved results have been put into data file: OUTFBP.DAT; * * Retrieving procedure has been written the file: OUTFBP.TXT. *

The NR retrieval model in the code will be improv so that it could be used for FBP retrieving for all kinds of neutron introduced reaction.

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

References

[1]. Ge Zhigang et al., present for the meeting
[2]. J.E. Lynn, AERE-R7468(1974)
[3]. B.B. Back et al. Phys.Rev., C9,1924 and C10,1948(1974)
[4]. T. Ohsawa, IAEA TECDOC-483, P134,1988

OPTICAL MODEL PARAMETER SUB-LIBRARY(CENPL-OMP)* (The first edition, Data file)

Su Zongdi Sun Zhengjun Wang Chenxiang Ge Zhigang (Chinese Nuclear Data Centre, CHINA INST. OF ATOMIC ENERGY)

> Yu Ziqiang Zuo Yixin (Dept. of Phys., Nankai Univ.)

Ma Gonggui (Inst. Nucl. Sci. & Tech., Sichuan Univ.)

* The project supported in part by the International Atomic Energy Agency and National Natural Science Foundation of China.

The optical model is the most fundamental and important one in nuclear physics, and the optical model parameters (OMP) play very crucial role in the nuclear model calculations of nuclear data and many theoretical analyses. The OMP table compiled by Perey in 1976 is significant and useful . It is very necessary and valuable to set up a new OMP data file, in which the OMP sets should be collected and compiled in a suitable format.But it would be more difficult to set up this file than others, because there have been the tremendous amount of information on optical model potential buried in the literature, as well as many different types of optical potentials (such as different incident particle types, local vs. nonlocal, spherical vs. deformed , different geometry shape etc.) , and different types of OMP sets (such as global, regional, nucleus-specific, different E-dependence and A-dependence types of the potential parameters etc.). Here , our idea and progress on the OMP sublibrary at Chinese Nuclear Data Centre(CNDC) will be presented.

This file is the data file of OMP sets, which is a sublibrary of Chinese Evaluated Nuclear Parameter Library(CENPL). In fact, there are two types of OMP sets, i.e. the global and regional OMP sets, as well as the nucleus-specific ones existing in literature. They are different in fundamental requirements and complexity of parameter sets. The former aims at maximum generality and a developing trend is adopting more complex expression, while the latter aims at maximum accuracy in reproducing the experimental data and its expression is simpler in general.For convenience of setting up data file and retrieval, we divide the OMP sets into two parts, in which two types of OMP sets mentioned above are compiled respectively.

I. Global and Regional Optical Model Potential Parameter Sets

The global and regional optical model Potential parameter (OMPP) sets for six types of projectiles, i.e. neutron, proton, deutron, triton, He-3 and He-4 are collected and compiled in (1) - (6) of this data file respectively, which is one part of the OMP Sub-library(OMP-1). There is a brief information table, which includes authors, published date, mass region of target nucleus, energy region of incident particle, spherical or deformed (S/D), local or nonlocal (L/N) and fitted experimental data types, for each type of projectile. The fitted experimental data in this table are listed with the following symbols.

So	:	the neutron S-wave strength function;	
T-CS	:	the total cross section;	
E-DCS	:	the elastic differential cross section;	
E-CS	:	the elastic scattering cross section;	
NE-CS	:	the non-elastic cross section;	
Pol	:	the polarization;	
Ay	:	the analyzing power;	
i T 11	:	the vector analyzing power;	
X2	:	Some tensor analyzing powers and combinations	of
		them	
		-(1/2)T20-[(3/2)**(1/2)]T22,	
		$-(1/2)T20-\Gamma(3/2)**(1/2)T22,$	
		T22 - [(3/2) * * (1/2)]T20.	

There is an entry for each set of OMPP, and each entry contains 13 subjects denoted by different keywords. They are "Entry", "Tital", "Authors", "Affil.", "Ref.", "Projectile", "Nucleus Region", "Energy Region", "Potential", "Parameters", "Primary Data", "Optim. Method" and "Comments".

(1) Neutron Optical Model Potential Parameter Sets

A brief information table for neutron global and regional OMPP

Authors	Date	Nucleus Region	Ene Regio	rgy S/D n(MeV)	L/N	Fitted Expt. Data
Moldauer	1963	40-150	<	1 S	 L	So,T-CS,E-DCS
•	•	•	•			•
•	•	•	•			•
Varner et al.	1991	40-209	10 - 2	6 S	L	E-DCS, Ay
	•			•		•
	•			•		•
Entry : Wilm	ore and	l Hodgson	Neutron	OMPP		
Title : The	Calcula	ation of	Neutron	Cross S	ectio	ns from Optical
Pote	ntials					
Authors : D.	Wilmore	e and P.E.	Hodgson			
Affil. : Atom	mic Ene	ergy Resea	rch Est	ablishme	nt, H	arwell
Ber	kshire;					
Nuc	lear Ph	ysics Lab	., Oxfo	rd, U.K.		
Ref. : Nucl	. Phys.	, 55, 673	(1964)	•		
Projectile :	Neutro	n n				
Nucleus Regi	on : A	28 -	238			
Energy Regio	n: E	1 -	15	(MeV)		

(Note: All potentials in MeV, all lengths in fm)

Primary Data : Fitting total cross sections, elastic differential cross sections for Si, S, Ca, Ti, Fe, Ba, Pb and U. Optim. Method : Using a least-squares parameter search routine so that it can systematically adjust parameters of non-local potential to give the best fit for a given set of experimental data . A program was used to obtain local-potential from nonlocal potential and then to calculate the cross sections.

Comments : Used potential is the local potential equivalent to the non-local potential of Perey and Buck as it is more convenient for practical calculations;

This potential is able to fit a wide range of neutron data.

٠

٠

(2) Proton Optical Model Potential Parameter Sets

A brief information table for proton global and regional OMPP

Author	:s		Date	Nucleus Region	R	E: eg:	nergy ion(M	S/D eV)	L/N	Fitted Exp Data	pt.
Becchei Greenle	ti.	, ,	1969	56-208	1	-	24	8	L	E-DCS	
•			•	•		•				•	
•			•	•		•				•	
Varner	et	al.	1991	40-209	10		26	8	L	E-DCS, Ay	
			•				•			•	
			•				•			•	
Entry	: 1	Walte	er and	Guss Prot	on (DMI	PP				
Title	: 1	A Glo and :	obal Op 10 MeV	otical Mod < E < 80	el : MeV	Eog	r Neu	tron S	catt	ering for 1	A>53
Author	s:	: R.J	L.Walte	er and P.P	.Gu	55					
Affil	: 1	Duke	Unive	rsity and	Tria	ang	gle V	nivers	itie	s Nuclear)	Lab.

: Proc. of Intern. Conf. on Nuclear Data for Basic and Ref. Applied Science, Santa Fe, 1985; In: Radiation Effects, 1986, P.1079 **Projectile :** Proton p Nucleus Region : A 54 -208 Energy Region : E 10 -80 (MeV) Potential : -U(r,E)=Vr*fr(r,rr,ar) +i{Wv*fv(r,rv,av)-4*ad*Wd*[dfd(r,rd,ad)/dr]} -2/r*(l*s)*{Vso* [dfso(r,rso,aso)/dr] +iWso*[dfso(r,r'so,a'so)/dr]} -Vc(r,rc)+V'c+i4*Wcd*[dfd(r,rd,ad)/dr]fi(r,ri,ai)=1/[1+exp(Xi)]Xi=(r-Ri)/ai Ri=ri*A**(1/3) i=r, v, d, so Vc=[Zp*Zt*e*e/(2*Rc)]*[3-r*r/(Rc*Rc)] r < RC or Zp*Zt*e*e/r r > & = RcRc=rc*(A**1/3)Parameters : Vr=52.56-0.310*E+(16.5-0.081*E)*(N-Z)/A (E<40 MeV) or 52.56-12.40*[1+ln(E/40)]+{16.5-3.24* [1+ln(E/40)] * (N-Z)/A(E>40 MeV) rr=1.219 ar=0.688 Wd=10.85-0.157*E+14.94*(N-Z)/A (E>9.9 MeV) rd=1.282 ad=0.512 Wv=-0.963+0.153*E (E<39.4 MeV) or -0.963+0.153*E*[1-0.33*ln(E/39.4)] (E>39.4 MeV) rv=1.38+3.76/A av=0.557-0.462/[A**(1/2)] $V_{SO}=5.767-0.015 * E + 2 * (N-Z) / A$ rso=1.103 aso=0.560 Wso=0.791-0.018*E r'so=1.364 a'so=0.632 rc=1.219 V'c=0.4*Z/A (E<40 MeV) or 0.4*(Z/A)*678/E (E>40 MeV) Wcd=1.30 (Note: All potentials in MeV, all lengths in fm) Primary Data : fitting proton elastic differential cross sections E-DCS and analyzing powers Ay between 20-85 MeV

Optim Metho obtail	od : Using a modi: ned from F.Perey (fied version of the of ORNL	e search code GENOA
Comments :	Proton global, sp Containing an ima	pherical, local OMI aginary part of the	P set; spin-orbit interac
tion;	-		-
	Contain coulomb o More complex E-do In comparison with	correction terms V ependence in the hi th the others , thi	c and Wcd; gher energy range; s potential para-
meter	can give the bett	ter agreement with	experimental data
in gen	neral.		
	•	•	•
	•	•	•
((3) Deuteron Optic	cal Model Potential	. Parameter Sets
	•	•	•
	•	•	•
	(4) Triton Optica	L Model Potential H	Parameter Sets
	•	•	•
	•	•	•
	(5) Helium-3 Optic	cal Model Potential	. Parameter Sets
	•	•	•
	•	•	•
((6) Helium-4 Optic	cal Model Potential	. Parameter Sets
	•	•	•
	•	•	•

II. Nucleus-Specific Optical Model Potential Parameter Sets

The nucleus-specific OMPP sets for neutron projectile only are collected and compiled in this data file, which is one part of the OMP Sub-library(OMP-2). The brief information on each set of OMPP and potential parameters are listed in OMP-2 data file (see appendix). The brief information contains target nucleus, neutron incident energy, spherical or deformed(S/D), fitted experimental data types and made model calculations, deformed parameter and standard abbreviation of reference.

A standard OMPP form has been determined . It not only can cover most of the OMPP sets existing in the literature at present, but also is suited for future possible development tendency of OMPP. The standard OMPP formula for neutron case is as follows.

-U(r,E)=Vr*fr(r,rr,ar) +i{-4*ad*Wd*[dfd(r,rd,ad)/dr]+Wg*exp[-Xg**2] +Wv*fv(r,rv,av)} -2/r*(l*s)*{Vso*[dfso(r,rso,aso)/dr] +iWso*[dfso(r,r'so,a'so)/dr]} Vi=Vi0+Vi1*E+Vi2*E*E+(Vi3+Vi4*E)*(N-Z)/A, i=r, so Wi=Wi0+Wi1*E+Wi2*E*E+(Wi3+Wi4*E)*(N-Z)/A, i=d, g,v,so

```
fi(r,ri,ai)=1/[1+exp(Xi)],
```

Xi=(r-Ri)/ai,

Ri=(ri0+ri1*E) *A**(1/3)+Ci,

ai=ai0+ai1*E

i=r, g, d, v, so

The first line for each set of OMPP in the file contains the following information:

Z : the charged number, column 1-3. EL : the element symbol, column 4-5. A : the mass number, column 6-22. Energy region : in MeV, column 23-44. Spherical or deformed(S/D) : column 45-46.

The fitted experimental data and made model calculations : They include total cross section, elastic differential cross section, non-elastic cross section, polarization, Hauser-Feshbach theory, DWBA, coupled channel theory, and indicate by "*" in proper order in 49th-55th columns.

Deformed parameter : column 56-60. Standard abbreviation of reference : column 61-66.

The line marked "Vr"in 7th-10th columns contains the depth parameters of real potential: Vr0(column 12-22), Vr1(column 23-33), Vr2(column 34-44), Vr3(column 45-55), Vr4(column 56-66), and the sign for requiring annotation(column 67-74).

The line marked "rr" in 7th-10th columns and "ar" in 75th-78th columns contains the geometry parameters of real potential rr0(column 12-22), rr1(column 23- 33), Cr(column 34-44), ar0 (column 45-55), ar1(column 56-66), and the sign for requiring annotation(column 67-74).

The rest may be deduced by analogy, the lines contain the data for Wd, rd, ad; Wg, rg, ag; Wv, rv, av; Vso, rso, aso;Wso, r'so, a'so, and notes for non-standard optical potential parameters

The format examples of this part are given in appendix.

III. Management Retrieval Code

The management-retrieval code of the OMP sub-library is being developed at CNDC. The its basic functions have been decided. The code not only could retrieve the required optical model parameter sets for a single reaction channel and several related channels in a neutron induced reaction respectively, but also could calculate the optical model cross sections. Therefore this management-retrieval code should include two optical model codes for the spherical and deformed potential respectively, and could compare the results of the optical model calculation from different parameter sets with input experimental data. Appendix

۰.

72 Hf 0	NZ72	0.001	-20	S *** *	0 86Su1	
Vr:	54.0300	-0.6745	-0.0050	-24.0000	0.0000 *	:Vr
rr:	1.1710	0.0000	0.0000	0.7010	0.0000	** :ar
Wd:	10.4650	-0.3957	0.0000	-12.0000	0.0000	:Wd
rd:	1.3510	0.0000	0.0000	0.5753	0.0000	:ad
Wv:	-1.6190	0.2120	0.0000	0.0000	0.0000	:Wv
rv:	1.3510	0.0000	0.0000	0.5753	0.0000	:av
Vso:	6.2000	0.0000	0.0000	0.0000	0.000	:Vso
rso:	1.1710	0.0000	0.0000	0.7010	0.0000	:aso
:	Vr=Vr0+Vr1	[1-(1+E*(A**	1/3)/82)**	(-2)]+Vr2*E*I	=+Vr3*(N-Z)/A	۱.
**:	ar=ar0/{1+e	kp(-5*E)]				
Ref.:	86Su1 Su Zor	ngdi, Wang Sl	hunuan, Li	Cha et al.,	CNDC-85011, P	ag. 124,
	(1986)).				
	(1986)).				
74 W 184	(1986) NA183,184). 0.15-:	3	D ** **(0.24 80Zh1	
74 W 184 Vr:	(1986) NA183,184 52.9450). 0.15-: -0.3000	3 0.0000	D ** * * (-24.0000	0.24 80Zh1 0.0000	:Vr
74 W 184 Vr: rr:	(1986) NA183,184 52.9450 1.2100). 0.15-: -0.3000 0.0000	3 0.0000 0.0000	D ** * * (-24.0000 0.6200	0.24 802h1 0.0000 0.0000	:Vr :ar
74 W 184 Vr: rr: Wd:	(1986) NA183,184 52.9450 1.2100 5.4237). 0.15-: -0.3000 0.0000 0.4000	3 0.0000 0.0000 0.0000	D ** * * (-24.0000 0.6200 -12.0000	0.24 802h1 0.0000 0.0000 0.0000	:Vr :ar :Wd
74 W 184 Vr: rr: Wd: rd:	(1986) NA183,184 52.9450 1.2100 5.4237 1.2300). 0.15-: -0.3000 0.0000 0.4000 0.0000	3 0.0000 0.0000 0.0000 0.0000	D ** * * (-24.0000 0.6200 -12.0000 0.5800	0.24 802h1 0.0000 0.0000 0.0000 0.0000 0.0000	:Vr :ar :Wd :ad
74 W 184 Vr: rr: Wd: rd: Vso:	(1986) NA183,184 52.9450 1.2100 5.4237 1.2300 7.5000	0.15- -0.3000 0.0000 0.4000 0.0000 0.0000	3 0.0000 0.0000 0.0000 0.0000 0.0000	D ** * * (-24.0000 0.6200 -12.0000 0.5800 0.0000	0.24 802h1 0.0000 0.0000 0.0000 0.0000 0.0000	:Vr :ar :Wd :ad :Vso
74 W 184 Vr: rr: Wd: rd: Vso: rso:	(1986) NA183,184 52.9450 1.2100 5.4237 1.2300 7.5000 1.2100). 0.15- -0.3000 0.0000 0.4000 0.0000 0.0000 0.0000 0.0000	3 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000	D ** ** (-24.0000 0.6200 -12.0000 0.5800 0.0000 0.6200	0.24 802h1 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000	:Vr :ar :Wd :ad :Vso :aso
74 W 184 Vr: rr: Wd: rd: Vso: rso: Ref.:	(1986) NA183,184 52.9450 1.2100 5.4237 1.2300 7.5000 1.2100 802h1 Zhou 2	0.15- -0.3000 0.0000 0.4000 0.0000 0.0000 0.0000 2.0000 2.0000	3 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 g Zhesheng	D ** **(-24.0000 0.6200 -12.0000 0.5800 0.0000 0.6200 , Col.of Theo	0.24 802h1 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000	:Vr :ar :Wd :ad :Vso :aso :1.
74 W 184 Vr: rr: Wd: rd: Vso: rso: Ref.:	(1986) NA183,184 52.9450 1.2100 5.4237 1.2300 7.5000 1.2100 802h1 Zhou Z Reacti). -0.3000 0.0000 0.4000 0.0000 0.0000 0.0000 2hining, Yang ion and Their	3 0.0000 0.0000 0.0000 0.0000 0.0000 g Zhesheng, r Applicat	D ** **(-24.0000 0.6200 -12.0000 0.5800 0.0000 0.6200 , Col.of Theo ion [hsj-7824	0.24 802h1 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.Meth.on Nuc 62(lljs)],Pag	:Vr :ar :Wd :ad :Vso :aso :L.

COMPLETE SPECTROSCOPY OF DISCRETE NUCLEAR LEVELS

G. Molnár, T, Belgya and B. Fazekas Institute of Isotopes, H-1525 Budapest, Hungary

Abstract

Nuclear reaction model calculations require the complete knowledge of discrete level schemes. This information is also necessary for the direct test of level density models describing the continuum. The notion of completeness is reexamined from the viewpoints of nonselectivity of excitation mechanism and power of spectroscopic technique. Several examples are given to illustrate the capabilities of "complete" spectroscopic methods, especially neutron-induced reactions. Some conclusions are attempted concerning the present situation.

1. Introduction

Nuclear reaction model calculations require the complete knowledge of discrete nuclear level schemes. The term "completeness" means here that for a given nucleus all discrete levels are observed in a specified energy and spin window, and they are all characterized by unique energy, spin and parity values. The knowledge of particle and gamma-ray decay branchings may also be required in addition, especially when isomers are populated.

Discrete levels of the residual nucleus specify the possible competing output channels for statistical reaction model calculations. Complete knowledge of levels at higher energies, where the level density is high, is also useful for a direct test of global level density models describing the continuum regime. The gamma-ray branching fractions are needed for gammacascade calculations, and especially for the calculation of isomer feedings.

Completeness can be guaranteed only if a proper reaction mechanism is used to excite the nuclear levels. A compound nuclear reaction is the suitable choice because it statistically populates <u>all</u> states — in a certain energy and spin window — irrespective of their microscopic origin. "Cold" reactions are the best because they populate all states up to a spin cutoff, not only the yrast bands. For neutron projectiles averaged resonance capture (ARC) and low-energy neutron inelastic scattering or $(n,n'\gamma)$ reaction belong to this category. For charged particles heavy ion fusion-evaporation reactions just above the Coulomb barrier, typically low-energy (p,n) and (α,n) reactions, have proved most promising. Naturally, a proper combination of various selective methods may also be fruitful but it usually requires much more experimental effort.

Finally, proper spectroscopic tools are required to determine the quantum characteristics of nuclear levels. Gamma-ray spectroscopy, combined with conversion electron spectroscopy is the most powerful technique in this respect. Beside the high precision of level energy measurement and various ways to determine spins and parities it has a further advantage of automatically providing the gamma-branchings as well.

In the present paper the most commonly used techniques of complete spectroscopy are discussed and illustrated by a few characteristic examples. In chapter 2 the ARC technique while in chapter 3 the $(n,n'\gamma)$ method are described, whereas in chapter 4 a comparison between the two is made invoking two well-studied cases. Finally, some recommendations are formulated in chapter 5.

2. Averaged resonance capture

Radiative capture or (n,γ) reaction of thermal neutrons is the coldest reaction in that the residual nucleus is excited essentially at the neutron binding energy, typically at about 8 MeV by the capture of an s-wave neutron. Bound discrete levels are populated directly by primary capture-gamma dipole transitions of several MeV energy. In addition, many more states are fed by subsequent lower energy gamma-ray cascades of dipole and/or quadrupole multipolarity. Thus the observed primary gamma rays, usually detected by a pair-spectrometer (Figure 1), immediately yield the level energies. On the other hand, by studying the lowenergy cascade transitions one can determine level spins, parities and branching ratios.

Unfortunately, in the thermal neutron case only a single resonance is contributing, hence statistical fluctuations of the radiative widths render random population of final states by the primary dipole transitions. Completeness is not guaranteed, nor can spin/parity information be derived from the observed intensities². This shortcoming can be circumvented when neutrons of higher energy (typically kev or more) are captured and averaging over many individual resonances is performed³. As in different neutron energy regions different partial waves dominate the cross section, resonances of different spin and parity will populate all states in a given spin window. Hence, by averaging the decay widths obtained from a sufficient number of resonances of the same kind complete sets of states can be observed.

Studying a large number of resonances with combined neutron time-of-flight and gamma-spectroscopic techniques is extremely complicated, however⁴. The easiest way to perform such an averaging is to use monochromatic beams of epithermal neutrons with an energy spread sufficient to cover a large enough number of resonances. This can be accomplished by beam filters⁵. For instance, a set of Sc, Fe and Si filters provides monochromatic beams of 2 keV, 24 keV and 144 keV energy, respectively. For A~100 mass nuclei this corresponds to predominantly s-wave, p-wave and d-wave resonance contributions, respectively². The averaged resonance capture (ARC) method has extensively been used at



Figure 1. Gamma-ray spectra from thermal neutron capture by ¹¹⁵Sn, obtained in pair-spectrometer mode¹.

Brookhaven to obtain complete level schemes at low excitation energies.

The best example of a complete level scheme established by ARC is that of the deformed nucleus ¹⁶⁸Er. Davidson and co-workers⁶ performed thermal neutron capture as well as averaged resonance capture at 2 keV and 24 keV, using sophisticated gamma-ray and electron spectroscopic techniques. A comprehensive level scheme was constructed where 128 levels were arranged into 33 rotational bands and four isolated bandheads. As the ¹⁶⁷Er target spin is as high as $7/2^+$, the set of spin 2-5 levels below about 2.2 MeV in ¹⁶⁸Er is nearly complete.

3. Neutron inelastic scattering

Neutron inelastic scattering with monoenergetic neutrons is an ideal tool to excite lowlying discrete levels in a truly statistical manner. The population of a level is predominantly determined by the penetrability of neutrons going into and then out of the nucleus. (For neutrons with energies up to a few MeV partial waves with $l\leq 6$ contribute.) Only in welldeformed nuclei are collective enhancements expected, due to single- or multistep direct reaction contributions. Thanks to the lack of a Coulomb barrier the level thresholds are sharp, hence the excitation functions rise steeply. While the observation of scattered neutrons provide information on the reaction mechanism, nuclear levels (and their decays) are best studied by observing the de-exciting gamma-rays. Even in the latter case the use of monoenergetic neutrons has an advantage, as complications associated with the presence of radiation from higher-lying levels are avoided. The $(n,n'\gamma)$ reaction technique has been explored at the University of Kentucky Van-de-Graaff facility for many years, partly in cooperation with the Budapest group⁷.

In contrast with the (n,γ) reaction where capture gamma-rays populating the states are observed, it is the <u>depopulating gamma-rays</u> which are measured in the $(n,n'\gamma)$ reaction. Hence only the ground-state transitions give the level energies directly. A typical spectrum is shown in Figure 2 where a number of such ground-state transitions can be seen at the high-energy end of the spectrum.



Figure 2. Gamma-ray spectra from the ${}^{116}Sn(n,n'\gamma)$ reaction¹ at an incident neutron energy of 4.5 MeV

Gamma-rays deexciting the same level should have a common threshold, as illustrated

In Figure 3. Thus by varying the beam energy gamma-rays can be placed confidently on the basis of threshold energy with an uncertainty of about 20 keV. In addition, application of the Ritz-combination allows level energy determinations with highest precision, limited only by the gamma-ray energy uncertainties. This is especially important for isomeric levels where all feeding branches from higher levels should be determined.

Gamma-ray excitation functions, when properly normalized, can be used to infer energydifferential inelastic scattering reaction cross sections. For this the balance of incoming and outgoing gamma-ray intensities should be taken for each level at each bombarding energy. The inferred cross sections can than be compared with reaction model calculations to assist spin assignments, as shown in Figure 4.

The main source of information concerning level spins and parities is the multipolarity of deexciting gamma-rays. This can be determined from an angular distribution measurement. Examples are shown in Figure 5 for pure as well as mixed multipolarity transitions. For the latter type the chi-square minima give the mixing ratio



Figure 3. Excitation functions of γ -rays from three levels of the ⁹⁶Zr nucleus⁸

values. For both types of transitions the comparison with theoretical distributions has to be made using alignment factors from reaction theory, in this case Hauser-Feshbach theory.

Using the techniques described above a scheme of 33 levels, extending to 4.2 MeV, could be determined for the ⁹⁶Zr doubly-closed subshell nucleus⁸. In particular, all levels observed from other reactions and beta decay could be identified up to 3.4 MeV and the scheme is believed to be complete up to about 3.2 MeV excitation energy. Many other



Figure 4. Inferred experimental (n,n') reaction cross sections (symbols), compared with Hauser-Feshbach theoretical cross sections (lines) for some 96 Zr levels⁸

examples exist for spherical nuclei, e.g. ⁸⁸Sr and ⁹⁰Zr for which 97 and 104 levels could be determined, respectively, up to about 6.5 MeV excitation energy⁹. As to heavier nuclei away from shell closures, the example of ¹⁴⁶Nd is given here, where over 130 states were observed, up to an excitation energy of 3.5 MeV in ref.¹⁰.



Figure 5. Experimental angular distributions of 96 Zr γ -rays compared with theoretical $(n,n'\gamma)$ distributions⁸.

One way to assess the degree of completeness of a level scheme is to compare the experimental data with a theoretical level scheme. This is done the single-closed shell for nucleus ¹⁴⁴Sm in Figure 6 where all states with spin less than 7 are included. There is an excellent agreement between calculated and observed levels up to an excitation energy of about 3.3 MeV. Hence, the level scheme is complete as far as shell model states are concerned. At higher energies there are more states observed than



Figure 6. Comparison of the experimental (triangles) and shell model (squares) level distributions for ¹⁴⁴Sm nucleus¹¹.

predicted. This is due to the fact that neutron states have not been included in the calculation. On the other hand, many experimental states are possibly missing above 4 MeV.

4. Complete schemes from (n,γ) and $(n,n'\gamma)$ reactions combined

It is interesting to see the benefits of combined (n,γ) and $(n,n'\gamma)$ reaction experiments from the point of view of attaining completeness. Here two cases will be examined, a heavy and a medium-heavy nucleus, both vibrational like, in order to illustrate the nonselectivity of these neutron-induced reactions.

The closed proton-shell nucleus ¹¹⁶Sn has been extensively studied by thermal neutron capture (no ARC!) as well as inelastic neutron scattering by Raman and co-workers¹. From the (n,n' γ) reaction 100 levels were found below 4.3 MeV energy, and for 48 of them at least tentative spin-parity assignments were made. An additional 55 levels with J≤4 were observed above 4.3 MeV excitation energy. With the two experiments combined, all levels with J≤6 up to 4 MeV and J≤3 up to 4.3 MeV may have been experimentally identified. Five different types of excitation can account for all but one of the observed levels; conversely, up to 4 MeV excitation energy almost no predicted level is missing if separately observed high spin states are also included¹.

Finally, we consider ¹⁹⁶Pt. As the first example of the O(6) symmetry it was extensively studied¹² using thermal neutron capture and ARC on a ¹⁹⁵Pt target having spin-parity $1/2^{-}$. A level scheme has been established consisting of 58 levels below 2.5 MeV. In particular,

ARC measurements with a 2 keV filtered beam have led to the identification of all 0^+ , 1^+ or 2^+ states up to this energy. In a recent $(n,n'\gamma)$ reaction work¹³ many previously unidentified states have been observed as illustrated in Figure 7, where the difference between the cumulated number of levels obtained in $(n,n'\gamma)$ and (n,γ) is also shown as a solid line. When the comparison is restricted to states with $J \leq 2$, however. this difference fluctuates about zero, and close to 2.5 MeV the ARC data even provide more states than observed in the $(n,n'\gamma)$ reaction



Figure 7. Comparison of level distributions obtained from the $(n,n'\gamma)$ and (n,γ) reactions on ¹⁹⁶Pt. From top to bottom: $(n,n'\gamma)$, (n,γ) , difference, difference for J ≤ 2 .

work. From this we conclude that the scheme of lowest spin states is possibly complete up to an excitation energy of 2.5 MeV, as expected from s-wave ARC on a low-spin target¹².

5. Conclusions

We have shown that complete level schemes can be obtained only from complete spectroscopy using nonselective reactions. Neutron-induced reactions, like the $(n,n'\gamma)$ reaction and averaged resonance capture, are especially suitable from the viewpoints of nonselectivity of the excitation mechanism and completeness of information obtained with the rich arsenal of gamma-ray spectroscopy.

It is recommended that the best-studied nuclei be used for extracting level density parameters in various mass regions. For the vast majority of nuclei discrete level schemes, compiled in ENSDF should be used with reservation. Experimental data on discrete levels may be complemented and/or cross-checked with theoretical level schemes and level density model predictions. There is an important interconnection between nuclear reaction model calculations and discrete level spectroscopy that should be explored in an iterative way.

References

- 1 S. Raman et al., Phys. Rev. C43 (1991) 521.
- 2 Neutron Radiative Capture, ed. R. E. Chrien (Pergamon Press, Oxford, 1984).
- 3 J. E. Lynn, Theory of Neutron Resonance Reactions (Clarendon Press, New York, 1968)
- 4 C. Coceva, in: *Capture Gamma-Ray Spectroscopy and Related Topics*, ed. J. Kern (World Scientific, Singapore, 1994) p. 550, and references therein.
- 5 R. E. Chrien, in: *Capture Gamma-Ray Spectroscopy*, IOP Conf. Ser. No. 62 (The Institute of Physics, Bristol, 1982) p. 342; Trans. New York Acad. Sci., Ser. II, Vol. 40 (1980) 40, and references therein.
- 6 W. F. Davidson et al., J. Phys. G7 (1981) 455, 843; J. Phys. G17 (1991) 1683.
- 7 S. W. Yates and G. Molnár, in: *Nuclear Structure, Reactions and Symmetries*, eds. R. A. Meyer and V. Paar (World Scientific, Singapore, 1986) p. 624.
- 8 G. Molnár et al., Nucl. Phys. A500 (1989) 43.
- 9 E. Baum et al., in: Capture Gamma-Ray Spectroscopy and Related Topics, ed. J. Kern (World Scientific, Singapore, 1994) p. 244.
- 10 D. P. DiPrete et al., in: Capture Gamma-Ray Spectroscopy and Related Topics, ed. J. Kern (World Scientific, Singapore, 1994) p. 162.
- 11 R. A. Gatenby et al., Nucl. Phys. A560 (1993) 633.
- 12 J. A. Cizewski et al., Nucl. Phys. A323 (1979) 349.
- 13 D. P. DiPrete, Thesis (University of Kentucky, 1994)

Average Neutron Resonance Parameters^{*}

G. Reffo ENEA, I-40138 Bologna, Italy

Abstract.

Results from neutron resonance parameters analysis performed at Bologna for stable isotopes are compared to similar files produced at Obninsk and at Beijing.

1. METHODS AND RESULTS.

The analysis of neutron resonances has been performed for all isotopes for which resonance scheme were available to us.

The present effort is oriented to produce a table of recommended resonance parameters which includes s- and pwawe strength functions, average resonance spacings, total radiative widths.

1.1 Strength functions and mean resonance spacing.

In order to determine mean resonance spacings and s-wawe strength functions we have adopted several different statistical analysis including: staircase of resonance energies, staircase of cumulative reduced neutron widths, integrated Porter-Thomas, truncated Porter-Thomas, segmented Porter-Thomas distrubution, missing level estimator etc.

The final results has been obtained after iterations over all methods until a reasonable convergence was found. The error bar quoted represents the spread of the results from the different methods.

*

Progress report in the frame of the IAEA CRP on "Reference Input Parameter Libraries". 1.2. Total radiative widths.

In order to estimate average total radiative widths, for each isotope, we have compared the distribution of total radiative width for the different resonances, with the corresponding chi-square distribution. The width of such distribution in general is larger than the gaussian distribution of statistical errors, so that the spread of experimental total radiative width is representative of the width of their chi-square distribution rather than of the spread of inherent statitistical errors. This being an important distinction which helps in estimating uncertainties in total radiative widths

2. Contents of the other files considered.

In addition we have collected the files available, from $Obninsk^1$, and $Beijing^2$. Not many details have been given about the methods used by the Obninsk and Beijing groups, as to determine the filed average resonance parameters.

Obninsk file contains average resonance spacings strength functions and total radiative widths, both for s- and pwawes. Beijing files contains s-wawe average resonance spacings. Bologna file contains s-wawe mean resonance spacings, strength functions and total radiative widths per spin state; in particular the number of resonances adopted for each isotope is given.

Our results are compared to the others two files in table 1, and 2, where all available information on the subject is lumped together in order to provide a comprehensive map of the present status of the subject matter.

3. Results and conclusions

From table 1, and 2 it appears that the Beijing file is the one which covers the largest number of isotopes. From the tables it appears also that in most cases, within the quoted uncertainties, there is agreement among the different files.

In a 15-20% of cases, however, one observes discrepancies at the limit of the uncertainty overlap interval and beyond it.

The work will continue. This, infact, is an intermediate step, the final objective being to produce a file of neutron resonance parameters, useful for both level density parametrization and cross-section calculations.
Next step will be to remove discrepancies. To this end a careful reanalysis will be performed of all isotopes for which the discrepancy among different files is comparable or exceeds the quoted uncertainties.

This work proved very useful both because the discrepancies found has put in evidence unsuspected doubtful cases. and because several neutron resonance schemes for new isotopes have been made available by Chinese group.

References

- 1. A. V. Ignatyuk, private communications, 1994 and report to this CRP.
- 2. Ge Zhigang, private communications, 1994.

Note added by the editor:

Three tables of average neutron resonance parameters were distributed in a printed form by G. Reffo at the CRP Meeting (19-23 September 1994) in Cervia. The tables compare the Bologna file with the files from Obninsk and Beijing, and they are available at the IAEA Nuclear Data Section in its original printed form. Furthermore, the tables were converted into the computerized ASCII format in Bologna, brought to Obninsk by A. Ignatyuk on diskettes, and transferred electronically by him to IAEA NDS in December 1994. They are stored in the VAX computer under UD4:[RIPL.RESONANCES] as file names:

1) BOLOGNA_RES_COMPAR1.DAT	(Resonance spacings)
2) BOLOGNA_RES_COMPAR2.DAT	(Radiative widths)
3) BOLOGNA_RES_COMPAR3.DAT	(Strength functions)

EXPERIENCE AT LOS ALAMOS WITH USE OF THE OPTICAL MODEL FOR APPLIED NUCLEAR DATA CALCULATIONS

P. G. Young Los Alamos National Laboratory

ABSTRACT

While many nuclear models are important in calculations of nuclear data, the optical model usually provides the basic underpinning of analyses directed at data for applications. An overview is given here of experience in the Nuclear Theory and Applications Group at Los Alamos National Laboratory in the use of the optical model for calculations of nuclear cross section data for applied purposes. We consider the direct utilization of total, elastic, and reaction cross sections for neutrons, protons, deuterons, tritons, ³He and alpha particles in files of evaluated nuclear data covering the energy range of 0 to 200 MeV, as well as transmission coefficients for reaction theory calculations and neutron and proton wave functions in direct-reaction and Feshbach-Kerman-Koonin analyses. Optical model codes such as SCAT and ECIS and the reaction theory codes COMNUC, GNASH, FKK-GNASH, and DWUCK have primarily been used in our analyses. A summary of optical model parameterizations from past analyses at Los Alamos will be given, including detailed tabulations of the parameters for a selection of nuclei.

I. INTRODUCTION

The optical model frequently provides the basis for theoretical analyses and/or data evaluations that are used in providing nuclear data for applied purposes. In addition to offering a convenient means for calculation of reaction, shape elastic, and (neutron) total cross sections, optical model potentials are widely used in quantum-mechanical preequilibrium and direct-reaction theory calculations and, most importantly, in supplying particle transmission coefficients for Hauser-Feshbach statistical-theory analyses used in nuclear data evaluations. This paper collects and reviews optical model potentials developed over the last several years for applied nuclear data analyses in the Nuclear Theory and Applications Group at Los Alamos National Laboratory.

Section II outlines the methodology used for determining many of the potentials described here. Section III includes tabulations of a selection of spherical optical model potentials that have been utilized at Los Alamos in nuclear data calculations, and Section IV gives a similar summary for coupled-channels optical model potentials. Finally, conclusions and recommendations are given in Section V.

II. METHODOLOGY

In the sections that follow a standard form is used for the optical model potential and the various components of the potential.¹ In particular, the potential is represented by a combination of Woods-Saxon volume and surface derivative terms with (V_R, r_R, a_R) , (W_V, r_V, a_V) , (W_D, r_D, a_D) , and (V_{SO}, r_{SO}, a_{SO}) indicating the real central, volume imaginary, surface derivative imaginary, and real spin-orbit components. In the parameterizations given below, the abbreviations

$$\eta = \frac{N-Z}{A} = 1 - \frac{2Z}{A} \tag{1}$$

and

$$\Delta V_c = 0.4 \frac{zZ}{A^{1/3}}$$
 (2)

are employed in the isospin and coulomb correction terms, respectively. In Eqs. (1) and (2) the quantities N, Z, and A are the neutron, proton, and atomic mass numbers of the target nucleus, respectively, and z is the charge number of the projectile. Note that when plus or minus signs are used with the isospin terms in general expressions for proton or neutron potentials, the minus sign is used for neutrons and the positive sign for protons.

For our calculations we typically use the spherical optical model codes SCAT2 by Bersillon² or SNOOPY8 by Schwandt.³ In the case of SCAT2, we have extended the option to call built-in parameterizations to include many additional global and regional parameterizations. For coupled-channels calculations we use either the ECIS code by Raynal⁴ or the JUPITOR code, as modified by Rebel et al.⁵ In cases where detailed neutron optical model analyses are required, we typically combine the SPRT method⁶ (fitting experimental values of s- and p-wave neutron strengths, potential scattering radii, and low energy neutron total cross sections) with fits to differential elastic scattering data at higher energies. We often combine analyses of neutron and proton data using a simple Lane model. In cases where accuracy requirements are not too demanding, we use existing global or regional parameterizations in calculations.

III. SPHERICAL OPTICAL MODEL POTENTIALS

A. Global Potentials at Incident Energies Below 50 MeV

A number of global optical model potentials have been developed for nuclear physics calculations at incident energies below ~ 50 MeV, especially for neutrons. A review of neutron global parameters is given in Ref. 1, and the older review by Perey and Perey⁷ is still useful for charged-particle potentials. A global neutron potential developed since the 1985 review that has proven useful for calculations of nuclear data for fusion reactions is a modification by Yamamuro⁸ of the surface imaginary term in the Walter and Guss⁹ potential below an incident neutron energy of 20 MeV, as follows:

$$W_{D} (MeV) = 5.0 - 14.94 \eta + 0.271 E_{n} \qquad 0 \le E_{n} \le 10 \text{ MeV}$$

$$= 7.71 - 14.94 \eta \qquad 10 \le E_{n} \le 20 \text{ MeV}$$
(3)

All other parameters are taken from the Walter and Guss potential, and that potential is used intact at neutron energies above 20 MeV. We have found the Yamamuro/Walter potential to be quite useful in cases where detailed optical model analyses are not available.

B. Global Potentials at Incident Energies Above 50 MeV

NEUTRONS

Possibilities for global optical model parameterizations above 50 MeV are considerably more restricted. Starting from a global proton potential by Schwandt et al.,¹⁰ Madland¹¹ developed a potential that covers a wider energy range and that is generalized for neutrons and protons through the Lane model. The Madland potential was developed by analyzing data for 3 nuclides in the mass range $27 \le A \le 208$ and the energy range 50 MeV $\le E_{n,p} \le 400$ MeV. We have incorporated a form of the Madland potential¹² modified for nonrelativistic calculations over the range 50 MeV $\le E_{n,p} \le 140$ MeV into the SCAT2 code; this potential is listed in Table 1.

Table 1.	Global spherical optical model potentials for incident neutrons and protons over the
	incident energy range 50 MeV $\leq E_{n,p} \leq 140$ MeV and for the mass range $24 \leq A \leq 208$

Well Depth (MeV)	Geometry (fm)
$V_R = 105.5 - 16.5\eta - 0.4 Z/A^{1/3} - 17.14375 \ln(E_n)$	$r_{\rm R} = 1.125 + 0.001 E_{\rm n}$
$W_{\rm D} = 0.0$	$a_R = 0.675 + 0.00031 E_n$
$W_V = 2.4346 + 0.1016 E_n - (9.288E-4) E_n^2 + (3.87E-6) E_n^3$	$r_V = 1.650 - 0.0024 E_n$ $a_V = 0.328 + 0.00244 E_n$
$V_{SO} = 19.0 + 3.75\eta - 3.154 \ln(E_n)$	$r_{SO} = 0.920 + 0.0305 \text{ A}^{1/3}$
	= 0.98 (A ≤ 40)
<u>PROTONS</u> ($r_c = 1.25 \text{ fm}$)	$a_{SO} = 0.768 - 0.0012 E_n$
Well Depth (MeV)	Geometry (fm)
$V_R = 105.5 + 16.5\eta - 17.14375 \ln(E_p)$	$r_{\rm R} = 1.125 + 0.001 E_{\rm p}$
$W_D = 0.0$	$a_R = 0.075 + 0.00051 E_p$
$W_V = 2.4346 + 0.1016 E_p - (9.288E-4) E_p^2 + (3.87E-6) E_p^3$	$r_V = 1.650 - 0.0024 E_p$ $a_V = 0.328 + 0.00244 E_p$
$V_{SO} = 19.0 - 3.75\eta - 3.154 \ln(E_p)$	$r_{SO} = 0.920 + 0.0305 \text{ A}^{1/3}$ $= 0.98 \text{ (A} \le 40)$
	$a_{SO} = 0.708 - 0.0012 E_p$

For deuterons, tritons, ³He and alpha particles, we have modified the SCAT2 code to include a simplified Watanabe model¹³ to derive potentials at medium energies. Details of the Watanabe transformation are also described by Madland.¹¹

Other techniques for simplifying and facilitating development of optical model potentials are summarized in Ref. 1. These include the method of approximating an odd-A rotational nucleus in coupled-channels calculations by using appropriately chosen fictitious levels in an adjacent even-A (K=0) nucleus.¹⁴ This procedure can reduce the computer time required to perform coupled-channels calculations for odd-A rotational nuclei, although some penalty in accuracy and setup time must be paid. Another technique that has good potential but that has had little use is the method outlined by Madland and Young¹⁵ that permits the adaptation of spherical optical model potentials for coupled-channels calculations by simply scaling the imaginary surface potential by the relation

$$\frac{W_D a_D}{W_D a_D} = \alpha \quad , \tag{4}$$

where the primed and unprimed quantities refer to the spherical and deformed potentials, respectively, and α is a constant that can be optimally adjusted but which is typically $\approx 0.7.1$

- C. Regional and Local Potentials
 - 1. Neutron, Proton, and Alpha Potentials for Analysis of n + 27Al Reactions

A reaction theory analysis of neutron cross sections on 27 Al has been carried out with the FKK-GNASH code in some detail to 40 MeV for a planned update of the ENDF/B-VI data file, and in less detail to 100 MeV for comparison with high-resolution γ -ray measurements.¹⁶ In this study the neutron potential of Petler et al.¹⁷ was found to reproduce the available experimental data up to 60 MeV or so, and at higher energies the Madland potential¹¹ appeared to reliably track the total and reaction cross sections to above 100 MeV. For proton channels a form of the Perey proton potential¹⁸ was used for proton energies below 30 MeV, with the following modification to the imaginary surface potential:

$$W_D(MeV) = 13.5 - 0.15 E_p$$
. (5)

In the energy range 30 MeV $\leq E_p \leq 100$ MeV, the Madland global potential¹¹ was employed for protons. The alpha-particle potential was taken from an analysis of n + ^{54,56}Fe reactions¹⁹ (see next section) and was used up to 100 MeV.

These potentials produce good agreement with elastic scattering, (n,p), (n,n'), (n,α) , and nonelastic cross sections over the range of available data, and give reasonable agreement with neutron, proton, and alpha-particle emission spectrum measurements at 14 MeV. Additionally, reasonable agreement is observed in calculations of discrete gamma-ray production cross sections for $(n,n'\gamma)$ and $(n,2n\gamma)$ reactions to 60 MeV.¹⁶ The optical model potentials for neutrons and alpha particles are given in Table 2. Table 2. Spherical optical model potentials for ${}^{27}Al + n$ calculations over the incident neutron energy range 1 keV $\leq E_n \leq 100$ MeV. For $E_n > 60$ MeV, the global potential of Madland¹¹ was used for neutrons (Table 1).

NEUTRONS

Well Depth (MeV)	Range (MeV)	Geome	<u>try (fm)</u>
$V_{R} = 51.55 - 0.308 E_{n}$	$0 < E_n < 60$	$r_{R} = 1.18$	$a_{R} = 0.64$
$W_{\rm D} = 6.07 = 6.07 - 0.10 (E_{\rm n} - 15)$	$\begin{array}{l} 0 < E_n < 15 \\ 15 \le E_n \le 60 \end{array}$	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.58$
$W_V = 0.00$ = -2.625 + 0.175 E _n	$\begin{array}{l} 0 < E_n < 15 \\ 15 \leq E_n \leq 60 \end{array}$	$r_{V} = 1.26$	$a_{V} = 0.58$
$V_{SO} = 6.0$	$0 < E_n < 60$	$r_{SO} = 1.01$	$a_{SO} = 0.50$
ALPHA PARTICLES (r _c = 1.4 fm)			
Well Depth (MeV)	Range (MeV)	Geometr	<u>ry (fm)</u>
$V_{R} = 193.0 - 0.15 E_{\alpha}$	$0 < E_{\alpha} < 100$	$r_{R} = 1.37$	$a_{R} = 0.56$
$W_{\rm D}=0.00$	$0 < E_{\alpha} < 100$		
$W_V = 21.0 + 0.25 E_{\alpha}$	$0 < E_{\alpha} < 100$	$r_{V} = 1.37$	$a_{V} = 0.56$

B. Neutron, Proton, and Alpha Potentials for Analysis of n + 54,56Fe Reactions

Starting from an analysis of reactions on 54,56 Fe and nearby nuclei,¹⁹ an optical model parameterization was developed for use in calculating neutron and proton reactions to 100 MeV.²⁰ These parameters have been used recently to calculate $n + {}^{56}$ Fe cross sections to 40 MeV for a planned update of ENDF/B-VI and to compare with experimental measurements of alpha particle spectra from the Weapons Neutron Research (WNR) facility.²¹ Calculated cross sections agree reasonably with the available experimental data, including 56 Fe(p,n) and (p,2n) measurements as well as (n,x γ) data and neutron elastic angular distributions. The neutron, proton, and alpha particle optical model parameters are included in Table 3.

C. Neutron, Proton, and Alpha Potentials for Analysis of n + ⁵⁹Co Reactions

Similar to the above calculations on Fe, reaction theory analyses that were made earlier for n + 59 Co reactions²² have been modified slightly for a planned extension of the ENDF/B-VI library to 40 MeV and for calculations of alpha particle spectra to compare with recent measurements from WNR.²³ Again, these parameters result in good agreement with the available total, elastic, nonelastic, inelastic, and (n,2n) cross section measurements and reasonable agreement with (n,p) and (n, α) data. The parameters are listed in Table 4. It should be noted that reaction theory calculations using these parameters have only been performed to ~ 50 MeV but reasonable total and reaction cross sections are calculated out to 100 MeV. Also note that the earlier set of alpha parameters given in Ref. 22 also give good results, especially at lower neutron energies.

Table 3. Spherical optical model potentials for 54,56 Fe + n calculations over the incident neutron energy range 1 keV $\leq E_n \leq 100$ MeV. Above 62 MeV for neutrons and 28 MeV for protons, the Madland global potential¹¹ is used (Table 1).

NEUTRONS TO 62 MeV			
Well Depth (MeV)	Range (MeV)	Geon	netry (fm)
$V_{\rm R} = 49.747 - 0.297 E_{\rm n} - 0.0003 E_{\rm n}$	2 0 < E _n <62	$r_{\rm R} = 1.28$	$a_{\rm R} = 0.56$
$W_D = 6.00 + 0.42 E_n$	$0 < E_n < 6$	$r_{\rm D} = 1.34$	$a_{\rm D} = 0.47$
$= 8.52 - 0.224 (E_n - 6)$	$6 \le E_n \le 62$		
$W_V = 0.00$	$0 < E_n < 8.9$	$r_{V} = 1.28$	$a_V = 0.56$
$= -1.60 + 0.18 E_{\rm n}$	$8.9 \le E_n \le 62$		
$V_{SO} = 6.20$	$0 < E_n < 62$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
<u>PROTONS TO 28 MeV</u> ($r_c = 1.25 \text{ fm}$)			
Well Depth (MeV)	Range (MeV)	Geometr	<u>ry (fm)</u>
$V_{R} = 58.384 - 0.55 E_{p}$	$0 < E_{p} < 28$	$r_{R} = 1.25$	$a_{R} = 0.65$
$W_D = 13.5 - 0.15 E_p$	$0 < E_{p} < 28$	$r_{\rm D} = 1.25$	$a_{\rm D} = 0.47$
$W_V = 0$	$0 < E_{p} < 28$		
$V_{SO} = 7.5$	$0 < E_{p} < 28$	$r_{SO} = 1.25$	$a_{SO} = 0.47$
ALPHA PARTICLES ($r_c = 1.4 \text{ fm}$)			
Well Depth (MeV)	Range (MeV)	Geometr	v (fm)
$V_{\rm R} = 193 - 0.15 E_{\alpha}$	$0 < E_{\alpha} < 100$	$r_{\rm R} = 1.37$	$a_{\rm R} = 0.56$
$W_{\rm D} = 0.00$ (0	$ < E_{\alpha} < 100 $		
$W_V = 21.0 + 0.25 E_{\alpha}$	$0 < E_{\alpha} < 100$	r _V = 1.37	$a_{V} = 0.56$

D. Neutron, Proton, and Alpha Potentials for Analysis of $n + \frac{64,66,68}{2n}$ Reactions

A set of optical model parameters for Zn isotopes was developed in support of 14.8-MeV activation measurements of the 64 Zn(n,p) 64 Cu and 64 Zn(n,2n) 63 Zn cross sections, covering the incident neutron energy range up to 20 MeV.²⁴ The parameters were obtained by fitting elastic angular distribution and total cross section measurements, and were validated in calculations of activation cross sections for neutron reactions on 64,66,68 Zn and for (p,n) reactions on 63 Cu and 65 Cu. The optical model parameters that resulted are given in Table 5.

E. Neutron and Proton Potentials for Analysis of Neutron Reactions on Sr, Y, and Zr Isotopes

Results of a detailed analysis of neutron and proton reactions on Sr, Y, and Zr isotopes at incident energies from 50 keV to 20 MeV were reported in 1980.²⁵ The optical model parameters obtained in that study were thoroughly tested against experimental data over that energy range.

Since that time, the optical model analyses and reaction theory calculations have been extended to higher energies. Calculations of neutron-induced reactions on 89 Y have been compared with higher energy (n,x γ) measurements from WNR.²⁶ Similarly, in the case of 90 Zr proton-induced reactions were calculated to 160 MeV for the recent NEA-sponsored intermediate energy data calculations.²⁷ The optical model potentials for protons and neutrons used in these studies are given in Table 6.

Table 4. Spherical optical model potentials for ${}^{59}Co + n$ calculations over the incident neutron energy range 1 keV $\leq E_n \leq 100$ MeV. Above 62 MeV for neutrons and 23 MeV for protons, the Madland global potential¹¹ is used.

NEUTRONS

	Well Depth (MeV)	Range (MeV)	<u>Geometr</u>	<u>y (fm)</u>
VR	$= 47.604 - 0.3636 E_{n} - 0.0003$	$3 E_n^2 = 0 < E_n < 62$	$r_{R} = 1.2865$	$a_{R} = 0.561$
WD	$= 8.047 + 0.0805 E_{n}$	$0 < E_n < 6$	$r_D = 1.3448$	$a_{\rm D} = 0.473$
	$= 8.530 - 0.2509 (E_n - 6)$	$6 \le E_n \le 62$		
W_V	= 0.00	$0 < E_0 < 0.5$	$r_V = 1.3448$	$a_V = 0.473$
	$= -0.0721 + 0.1475 E_{n}$	$0.5 \le E_n \le 62$		
V _{SO}	= 6.20	$0 < E_n < 62$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
PROT	<u>ONS TO 23 MeV</u> ($r_c = 1.25$ fm)		
	Well Depth (MeV)	Range (MeV)	Geometry (<u>fm)</u>
$\mathbf{V}_{\mathbf{I}}$	$R = 57.175 - 0.55 E_p$	$0 < E_p < 23$	$r_{\rm R} = 1.25$ a	R = 0.65
W	$V_{\rm D} = 13.5 - 0.15 {\rm E_p}$	$0 < E_p < 23$	$r_{\rm D} = 1.25$ a	_D = 0.47
W	$v_{\mathbf{V}} = 0$	$0 < E_p < 23$		
Vs	0 = 7.5	$0 < E_p < 23$	$r_{SO} = 1.25$ as	_O = 0.47
ALPH	<u>A PARTICLES</u> ($r_c = 1.4 \text{ fm}$)			
	Well Depth (MeV)	Range (MeV)	Geometry (1	<u>fm)</u>
V	$= 217.0 - 0.15 E_{\alpha}$	$0 < E_{\alpha} < 100$	$r_{\rm R} = 1.416$ a	R = 0.493
W	$V_{\rm D} = 0.00$	$0 < E_{\alpha} < 100$		
W	$V_{\rm V} = 24.0$	$0 < E_{\alpha} < 100$	$r_{V} = 1.416$ a	v = 0.493

Table 5. Optical Model Parameters for Neutron Reactions with Zn Isotopes.

Well Depth (MeV)	Range (MeV)	Geomet	ry (fm)
$V_R = 49.11 - 16 \eta - 0.376 E_n$	$0 \leq E_n \leq 20$	$r_{\rm R} = 1.295$	$a_{R} = 0.58$
W _D = 8.545 - 8η	$0 \leq E_n \leq 20$	$r_{\rm D} = 1.295$	$a_{\rm D} = 0.48$
$W_V = -0.094 + 0.197E_n$	$0 \leq E_n \leq 20$	$r_{V} = 1.295$	$a_{V} = 0.58$
$V_{SO} = 6.2$	$0 \leq E_n \leq 20$	$r_{SO} = 1.12$	$a_{SO} = 0.48$

Table 6. Spherical optical model potentials for proton and neutron reactions on Sr, Y, and Zr isotopes in the vicinity of A = 90. At energies above the maxima indicated, the global potential of Madland¹¹ was used for protons and neutrons.

$n + {}^{89}Y$

Well Depth (MeV)	Range (MeV)	Geometr	<u>y (fm)</u>
$V_{R} = 49.5 - 0.28 E_{n}$	$0 < E_n < 21$	$r_{\rm R} = 1.24$	$a_{\rm R} = 0.62$
$W_D = 4.63 + 0.3 E_n$	$0 < E_n < 10$	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.58$
$= 7.63 - 0.13 E_{n}$	$10 \le E_n < 21$		
$W_V = 0$ = -1.42 + 0.13 E _n	$0 < E_n \le 10.9$ $10.9 < E_n < 21$	$r_{V} = 1.24$	$a_{V} = 0.62$
$V_{SO} = 6.2$	$0 < E_n < 21$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

$n + {}^{90}Zr$

We	ell Depth (MeV)	Range (MeV)	Geometr	<u>y (fm)</u>
VR	$= 49.0 - 0.28 E_{n}$	$0 < E_n < 20$	$r_{\rm R} = 1.24$	$a_{R} = 0.62$
WD	$= 3.4 + 0.3 E_{n}$	$0 < E_n < 10$	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.58$
	$= 6.4 - 0.13 E_{n}$	$10 \le E_n < 20$		
Wv	= 0	$0 < E_n \le 10.9$	$r_{V} = 1.24$	$a_{V} = 0.62$
	$= -1.42 + 0.13 E_{n}$	$10.9 < E_n < 21$		
V _{SO}	= 6.2	$0 < E_n < 20$	$r_{SO} = 1.12$	$a_{SO} = 0.47$

p + Sr

<u>We</u>	ll Depth (MeV)	Range (MeV)	Geometr	<u>y (fm)</u>
$V_{\mathbf{R}} = 56.$	$4 + 24\eta + \Delta V_c - 0.32 E_p$	$0 < E_p < 21$	$r_{\rm R} = 1.20$	$a_{R} = 0.68$
$W_{\rm D} = 3.0$	$+ 0.60 E_{p}$	$0 < E_p < 17.5$	$r_{\rm D} = 1.225$	$a_{\rm D} = 0.40$
= 13.	.5 - 0.15 É _p	$17.5 \le E_p < 21$		
$W_V = 0$	-	$0 < E_p < 21$		
$V_{SO} = 6.4$	k i i i i i i i i i i i i i i i i i i i	$0 < E_{p} < 21$	$r_{SO} = 1.03$	$a_{SO} = 0.63$

<u>p + Y</u>

Well Depth (MeV)	Range (MeV)	Geomet	r <u>y (fm)</u>
$V_{\rm R} = 56.4 + 24\eta + \Delta V_{\rm c} - 0.32 E_{\rm p}$	$0 < E_p < 21$	$r_{\rm R} = 1.20$	$a_{\rm R} = 0.73$
$W_{\rm D} = 4.0 + 0.5 E_{\rm p}$	$0 < E_p < 17.5$	$r_{\rm D} = 1.30$	$a_{\rm D} = 0.40$
$= 12.75 - 0.15 E_{p}$	$17.5 \le E_p < 21$		
$W_V = 0$	$0 < E_p < 21$		
$V_{SO} = 6.4$	$0 < E_p < 21$	$r_{SO} = 1.03$	$a_{SO} = 0.63$

IV. REGIONAL AND LOCAL COUPLED-CHANNELS OPTICAL MODEL POTENTIALS

A. Incident Neutron and Proton Potentials for Nuclides in the Region $63 \le Z \le 82$

A number of coupled-channels optical model analyses have been performed at Los Alamos for use in reaction theory calculations, including several rare earth and transition elements. In all cases modified SPRT⁶ approaches were used to determine the neutron parameters, requiring reasonable agreement with low-energy resonance data and neutron total cross sections, as well as with elastic and inelastic scattering measurements if available. Inclusion of proton data in most cases was accomplished using a simple Lane model.

An analysis was performed of neutron-induced reactions with ¹⁶⁵Ho and ¹⁶⁹Tm to establish reasonable optical parameters for reaction theory calculations on Tm isotopes.²⁸ The parameters are based mainly on fits to ¹⁶⁹Tm low-energy resonance and total cross section data, and to a neutron elastic scattering angular distribution measurement for ¹⁶⁵Ho at 11 MeV. The parameters are listed in Table 7.

In preparation for a major update of the ENDF/B-V cross sections, a coupled-channels optical model analysis was performed on the W isotopes.²⁸ That analysis included high-resolution neutron elastic and inelastic scattering data below 4 MeV, neutron total cross sections, 16-MeV (p,p') differential cross sections, and low-energy resonance data. A set of neutron parameters specific to each major isotope was obtained in the analysis, and the potentials produce good agreement with the available data to 20 MeV. Since that time, a general form of the potential was extended to higher energies and was used to calculate data libraries to 100 MeV for incident neutrons and protons.²⁰ The generalized potential is included in Table 8.

Table 7.	Coupled-Channels Optical Model and Deformation Parameters for Proton and Neutron
	Reactions with ¹⁶⁵ Ho and ¹⁶⁹ Tm.

	Well Depth (MeV)	Range(MeV)	Geometry (fm)		
V _R	$=49.8 \pm 16\eta + \Delta V_c - 0.25H$	$E \qquad 0 \le E \le 100$	$r_{\rm R} = 1.26$	$a_{R} = 0.63$	
WD	$= 5.020 \pm 8\eta + 0.51E$	$0 \le E \le 6.5$	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.48$	
	$= 8.335 \pm 8\eta - 0.092$ (E-6.5	6.5 \leq E \leq 100			
$\mathbf{W}_{\mathbf{V}}$	= 0	$0 \le E \le 8.3$	$r_{V} = 1.26$	$a_{V} = 0.63$	
	= -1.0 + 0.12E	$8.3 \le E \le 100$			
Vso	= 6.0	$0 \le E \le 100$	$r_{SO} = 1.26$	$a_{SO} = 0.63$	
	$\beta_2 (^{165}\text{Ho}) = 0.30$	$\beta_4 (^{165}\text{Ho}) = -0.02$	(3 States Coup	pled)	
	$\beta_2 (^{169}\text{Tm}) = 0.29$	$\beta_4 (^{169}\text{Tm}) = -0.01$	(5 States Coup	oled)	

Table 8.Deformed optical potential for proton and neutron reactions on W isotopes over the
energy range 10 keV to 100 MeV.

Well Depth (MeV)	Range(MeV)	Geome	try (fm)
$V_{\rm R} = 49.73 \pm 16\eta + \Delta V_{\rm c} - 0.25E$	$0 \le E \le 100$	$r_{\rm R} = 1.26$	$a_{R} = 0.61$
$W_D = 4.95 \pm 8\eta + 0.76E$	$0 \le E \le 4.5$	$r_{\rm D} = 1.24$	$a_{\rm D} = 0.45$
$= 8.37 \pm 8\eta - 0.10(E - 4.5)$	$4.5 \le E \le 100$		
$W_V = 0$	$0 \le E \le 5.8$	$r_{V} = 1.26$	$a_{V} = 0.61$
= -0.70 + 0.12 E	$5.8 \le E \le 100$		
$V_{SO} = 7.5$	$0 \le E \le 100$	$r_{SO} = 1.26$	$a_{SO} = 0.61$
(3 States	Coupled)	$r_{c} = 1.20$	
$\beta_2(^{182}W) = 0.223$ $\beta_2(^{182}W) = 0.223$	$4(^{182}W) = -0.054$		
$\beta_2(^{183}W) = 0.220$ β	$4(^{183}W) = -0.055$		
$\beta_2(^{184}W) = 0.209$ β	$_4(^{184}W) = -0.056$		
$\beta_2(^{186}W) = 0.195$ β	$4(^{186}W) = -0.057$		

Because of a need to provide radiative capture cross section calculations for Eu and Re isotopes, very similar coupled-channels potentials were developed for the two systems covering the neutron energy range up to 20 MeV. The results were utilized in (n,γ) cross section calculations for $151,153Eu^{29}$ and $185,187Re.^{30}$ The parameterizations are included in Tables 9 and 10. Similarly, a requirement to perform $(n,x\gamma)$ calculations on 197Au led to an investigation of coupled-channels potentials for that system. In that case the potential of Delaroche³¹ was found to be highly suitable and was used to perform extensive calculations to 20 MeV.³² The potential, which was later used to calculate data for the ENDF/B-VI evaluation, is given in Table 11.

An optical model potential coupling in vibrational states was developed for n + 208 Pb reactions, primarily for use in analyzing high-resolution (n,x γ) measurements³³ and in performing calculations for the NEA intermediate energy data calculations.²⁷ Beginning with the coupledchannels neutron potential by Shamu and Young³⁴ (obtained for experimental neutron data in the range 8.5 to 10 MeV), the potential was modified and extended to both lower and higher neutron energies by matching the available experimental neutron total, elastic scattering, and nonelastic scattering data. The collective model assumed for ²⁰⁸Pb was a first-order vibrational model with complex coupling. Excited states included in these calculations were all the ²⁰⁸Pb states below 10 MeV excitation energy known from various alpha-particle, proton and/or electron inelastic scattering experiments to be highly collective, as follows: discrete states at 2.615(3⁻), 4.085(2⁺), 4.323(4⁺), 4.424(6⁺), and 4.610(8⁺) MeV; and a low-energy octupole resonance (LEOR) state, centered at 5.38 MeV (3⁻). The β_L used for the discrete states were adopted proton values,³⁵ except at $E_x = 2.615$ MeV where $\beta_3 = 0.115$, and $E_x = 5.38$ where $\beta_3 = 0.10$ was used. The potential that resulted, which is presented in Table 12, gives a reasonable representation of the available neutron total, elastic, and nonelastic scattering data to approximately 200 MeV.

Table 9. Coupled-Channels Optical Model and Deformation Parameters for ^{151,153}Eu Isotopes

	Well Depth (MeV)	<u></u>	ange(Me	: <u>V)</u>	Geom	etry (fm)	
V _R	$= 49.8 \pm 16 \eta + \Delta V_c - 0.32$	25E _n 0	$\leq E_n \leq$	20	$r_{\rm R} = 1.28$	$a_{\rm R} = 0.63$	
WD	$= 4.02 \pm 8\eta + 0.51 E_{n}$	0	$\leq E_n \leq$	10	$r_{\rm D} = 1.28$	$a_{\rm D} = 0.48$	
	$= 9.12 \pm 8\eta - 0.09(E_n - 10)$) 10	$\leq E_n \leq$	20			
$\mathbf{W}_{\mathbf{V}}$	= 0	0	$\leq E_n \leq$	8	$r_{V} = 1.28$	$a_{V} = 0.63$	
	$= -2.0 + 0.1E_{n}$	8	$\leq E_n \leq$	20			
V _{SO}	= 6.0				$\mathbf{r}_{\mathrm{SO}} = 1.28$	$a_{SO} = 0.63$	
	$\beta_2 (^{151}Eu) = 0.16 \qquad \beta_2 (^{151}Eu) = 0.16$	53Eu) = 0.3	30 β4	(151,15	$^{3}Eu) = 0$	(3 States Coup	led)

Table 10.Coupled-Channels Optical Model and Deformation Parameters for Neutron
Reactions with ^{185,187}Re

	Well Depth (MeV)	Range(MeV)	Geomet	ry (fm)
VR	$=49.8 \pm 16\eta + \Delta V_{\rm c} - 0.30$	$E_n \qquad 0 \le E_n \le 20$	$r_{R} = 1.26$	$a_{R} = 0.61$
WD	= $4.02 \pm 8\eta + 0.75E_n$ =10.77 $\pm 8\eta - 0.05(E_n - 9)$	$\begin{array}{l} 0 \leq E_n \leq 9 \\ 9 \leq E_n \leq 20 \end{array}$	$r_{\rm D} = 1.26$	a _D = 0.47
Wv	= 0 = -1.8 + 0.2E _n	$\begin{array}{l} 0 \leq E_n \leq 9 \\ 9 \leq E_n \leq 20 \end{array}$	$r_{V} = 1.26$	$a_{V} = 0.61$
V_{SO}	= 7.5	$0 \leq E_n \leq 20$	$r_{SO} = 1.26$	$a_{SO} = 0.61$
	$\beta_2 (^{185}\text{Re}) = 0.22$ $\beta_2 (^{187}\text{Re}) = 0.21$	$\beta_4 (^{185}\text{Re}) = -0.085$ $\beta_4 (^{187}\text{Re}) = -0.085$	(3 States Cou (3 States Cou	pled) pled)

Table 11. Deformed optical potential for proton and neutron reactions on ¹⁹⁷Au over the energy range 10 keV to 57 MeV.

	Well Depth (MeV)	Range(MeV	') <u>Geom</u>	netry (fm)
V _R	$=49.9 \pm 18\eta + \Delta V_c - 0.25H$	$E 0 \leq E \leq 57$	$r_{\rm R} = 1.26$	$a_{R} = 0.64$
W_D	$= 4.20 \pm 9\eta + 0.50E$	$0 \le E \le 10$) $r_{\rm D} = 1.26$	$a_{\rm D} = 0.47$
	$= 9.20 \pm 9\eta - 0.18(E - 10)$	$10 \le E \le 57$		
Wv	= 0	$0 \le E \le 10$	$r_{V} = 1.26$	$a_{V} = 0.63$
	= -8.54 + 2.7 √E	$10 \le E \le 57$		
Vso	= 6.2	$0 \le E \le 57$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
			$r_{c} = 1.10$	
	$\beta_2 = 0.30$ β	4 = -0.02 (3)	States Coupled)	

Table 12. Coupled-channels optical model potential for $^{208}Pb + n$ calculations over the neutron energy range 1 keV $\leq E_n \leq 200$ MeV

Well Depth (MeV)	Range(MeV) Geom		etry (fm)	
$V_{R} = 53.425 - 16\eta - 0.279 E_{n}$ = 114.477 - 16η - 19 ln E _n	$0 < E_n < 60$ $60 \le E_n \le 200$	$r_{\rm R} = 1.183$	a _R = 0.6966	
$W_{D} = 2.692 - 8\eta + 0.2502 E_{n}$ = 7.414 - 8η - 0.08705 E _n = 0	$0 < E_n < 14$ $14 \le E_n \le 65.7$ $65.7 \le E_n \le 200$	r _D = 1.273	a _D = 0.699	
$W_V = 0$ = -2.60 + 0.18 E _n	$0 < E_n < 14.4$ $14.4 \le E_n \le 40$	$r_V = 1.273$	a _V = 0.699	
= $2.20 + 0.06 E_n$ = 8.20 V _{SO} = 6.18	$40 \le E_n \le 100$ $100 \le E_n \le 200$ $0 < E_n < 200$	r _{SO} = 1.16	a _{SO} = 0.677	

B. Actinide Potentials for Incident Neutrons and Protons

Coupled-channels optical potentials have been developed for several actinides in order to provide theoretical analyses³⁶⁻³⁸ for ENDF/B evaluations. The analyses use as a starting point the potentials determined by Lagrange,³⁹ with modifications to enhance agreement with data, especially above 10 MeV. As described above, low-energy resonance data, neutron total and differential elastic and inelastic data were used to optimize the potentials. In this manner potentials have been determined for neutron reactions on ^{235,237,238}U, ²³⁷Np, ^{239,242}Pu, and ²⁴¹Am, and the parameters are listed in Table 13.

In conjunction with our work in extending data libraries to higher energies, a generalized neutron/proton potential was developed for ^{238}U that was used in reaction theory calculations to 100 MeV.²⁰ This parameterization is included in Table 14.

V. CONCLUSIONS

In this paper a variety of optical model potentials used in reaction theory analyses at Los Alamos National Laboratory have been assembled and presented. While many other potentials have been used that are not included here, the present list is a reasonable sampling of our efforts and includes the systems for which more concentrated efforts have been made. In all cases presented, however, we expect that refinements and improvements can be made. Our hope is that the present parameterizations will be adequate with minimal revision for some applications and will provide an initial basis for future detailed analyses.

The parameterizations included here become progressively less certain as the incident energy increases. In our view substantial additional work is needed at higher energies and into the medium energy region in order to put optical model characterizations on a sound basis. In addition to the Madland potential described here,¹¹ Kozack and Madland have combined Dirac

phenomenology with a relativistic generalization of the Lane model to fit both neutron total cross sections and proton elastic scattering data for ²⁰⁸Pb between 95 and 300 MeV.⁴⁰ It is our view that a systematic study utilizing both a Schrödinger and Dirac approach is needed to develop a reliable global nucleon-nucleus optical model potential that extends into the medium energy region.

n + ²³ Well Depth (MeV)	³⁵ U Parameters (E _n Bange(MeV)	= 0 - 30 MeV)	etry (fm)
	Range(Ivie V)		
$V_{\rm R} = 46.4 - 0.3E_{\rm n}$	$0 \leq E_n \leq 30$	$r_{\rm R} = 1.26$	$a_{\rm R} = 0.63$
$W_D = 3.3 + 0.4E_n$	$0 \leq E_n \leq 8$	$r_{D} = 1.24$	$a_{\rm D} = 0.50$
$= 6.5 - 0.046(E_n - 8)$	$8 \leq E_n \leq 30$		
$W_V = 0$	$0 \leq E_n \leq 7$	$r_{V} = 1.26$	$a_{V} = 0.63$
$= -0.7 + 0.1E_{n}$	$7 \leq E_n \leq 30$		
$V_{SO} = 6.2$	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
$\beta_2 = 0.215$	$\beta_4 = 0.075$ (3 States	Coupled)	

	P2 01-10		corpier,			
	n + 237U Parameters (E _n = 0 - 30 MeV)					
Well Depth (MeV) Range(MeV) Geometry (fm)						
VR	$= 46.25 - 0.275E_{n}$	$0 \leq E_n \leq 30$	$r_{\rm R} = 1.26$	$a_{R} = 0.63$		
W_D	$= 3.206 + 0.4E_{n}$	$0 \leq E_n \leq 8$	$r_{D} = 1.26$	$a_{\rm D} = 0.52$		
	$= 6.406 - 0.046(E_n - $	$8) \qquad 8 \le E_n \le 30$				
W_{V}	= 0	$0 \leq E_n \leq 8$	$r_{V} = 1.26$	$a_{V} = 0.63$		
	$= -1.4 + 0.175 E_{n}$	$8 \leq E_n \leq 30$				
V _{SO}	= 6.2	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$		
	$\beta_2 = 0.195$	$\beta_4 = 0.060$ (6 States)	Coupled)			

	n + 238U Parameters (E _n = 0 - 30 MeV)				
W	ell Depth (MeV)	Range(M	leV)	Geome	try (fm)
V _R	$= 46.2 - 0.275 E_n$	$0 \leq E_n \leq$	30	$r_{\rm R} = 1.26$	$a_{R} = 0.63$
WD	$= 3.18 + 0.4E_{n}$	$0 \leq E_n \leq$	8	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.52$
	$= 6.38 - 0.046(E_n - 8)$	$8 \le E_n \le$	30		
Wv	= 0	$0 \leq E_n \leq$	8	$r_V = 1.26$	$a_{V} = 0.63$
	$= -1.4 + 0.175 E_{n}$	$8 \leq E_n \leq$	30		
V _{SO}	= 6.2	$0 \leq E_n \leq$	30	$r_{\rm SO} = 1.12$	$a_{SO} = 0.47$
	$\beta_2 = 0.198$	$\beta_4 = 0.057$	(3 States Cou	pled)	

 Table 13.
 Optical Model and Deformation Parameters Used in the Coupled-Channel Calculations for Actinides

	n + ²³	³⁷ Np Parameters	$(\mathbf{E_n} = 0 - 30 \; \mathrm{MeV}$	7)
W	ell Depth (MeV)	Range(MeV)	Geome	etry (fm)
VR	$= 46.2 - 0.3E_{n}$	$0 \leq E_n \leq 30$	$r_{\rm R} = 1.26$	$a_{R} = 0.63$
WD	$= 3.6 + 0.4E_{\rm n}$	$0 \leq E_n \leq 8$	$r_{\rm D} = 1.24$	$a_{\rm D} = 0.52$
	$= 6.8 - 0.046(E_n - 8)$	$8 \le E_n \le 30$		
Wv	= 0	$0 \leq E_n \leq 7$	$r_{\rm V} = 1.26$	$a_{V} = 0.63$
	$= -0.7 + 0.1E_{n}$	$7 \le E_n \le 30$		
V _{SO}	= 6.2	$0 \leq E_n \leq 30$	$r_{SO} = 1.12$	$a_{SO} = 0.47$
	$\beta_2 = 0.214$	$\beta_4 = 0.074$ (3 Sta	ates Coupled)	

n + ²³⁹ Pu	Parameters	$(E_n = 0 - 30 \text{ MeV})$

Well Depth (MeV)		Range(M	MeV) Geometry (fm		etry (fm)
V _R	$= 46.2 - 0.3E_{n}$	$0 \leq E_n \leq$	30	$r_{R} = 1.26$	$a_{\rm R} = 0.63$
WD	$= 3.3 + 0.45 E_{n}$	$0 \leq E_n \leq$	8	$r_{\rm D} = 1.24$	$a_{\rm D} = 0.50$
	$= 6.9 - 0.046(E_n - 8)$	$8 \le E_n \le$	30		
Wv	= 0	$0 \leq E_n \leq$	7	$r_{V} = 1.26$	$a_{V} = 0.63$
	$= -0.7 + 0.1E_{n}$	$7 \le E_n \le$	30		
V _{SO}	= 6.2	$0 \le E_n \le$	30	$r_{SO} = 1.12$	$a_{SO} = 0.47$
	$\beta_2 = 0.205$	$\beta_4 = 0.075$	(7 States C	oupled)	

 $n + {}^{242}Pu$ Parameters (E_n = 0 - 20 MeV)

	Well Depth (MeV)	Range(MeV)	Geometry (fm)		
V _R	$= 53.016 - 0.344E_n - 24.5r$	$0 \le E_n \le 20$	$r_{\rm R} = 1.203$	$a_R = 0.30 + 1.492\eta$	
WD	$= 8.905 - 0.255E_{n} - 13.6r$	$0 \leq E_n \leq 20$	$r_{\rm D} = 1.306$ $a_{\rm D} = 0.25 + 1000$	(0.733E-2)E _n + 1.42m	
Wv	= 0 = -0.566 + 0.21E _p	$\begin{array}{l} 0 \leq \mathbf{E_n} \leq 2.7 \\ 2.7 \leq \mathbf{E_n} \leq 20 \end{array}$	$r_V = 1.306$ $a_V = 0.25 +$	$(0.733E-2)E_{n} + 1.42m$	
V _{SO}	= 6.2 $\beta_2 = 0.260$ $\beta_4 =$	$0 \le E_n \le 20$ 0.036 (5 States)	$r_{SO} = 1.01$ Coupled)	$a_{SO} = 0.75$	

$n + {}^{241}Am$	Parameters	(E _n =	= 0	-	30	MeV)

W	Vell Depth (MeV)	Range(N	MeV)	Geom	etry (fm)
VR	$= 46.23 - 0.3E_{n}$	0 ≤ E _n ≤	30	$r_{\rm R} = 1.25$	$a_{\rm R} = 0.60$
WD	$= 3.314 + 0.45E_{n}$	0 ≤ E _n ≤	8	$r_{\rm D} = 1.24$	$a_{\rm D} = 0.55$
	$= 6.914 - 0.046(E_n - 8)$	$1 > 8 \le E_n \le$	30		
Wv	= 0	$0 \le E_n \le$	8	$r_{V} = 1.24$	$a_{V} = 055$
	$= -1.6 + 0.2E_{n}$	$8 \le E_n \le$	30		
V _{SO}	= 6.2	0 ≤ E _n ≤	30	$r_{SO} = 1.01$	$a_{SO} = 0.75$
	$\beta_2 = 0.210$	$\beta_4 = 0.0756$	(5 State	es Coupled)	

Table 14.Coupled-Channels Optical Model and Deformation Parameters for Neutron and ProtonReactions with ²³⁸U to 100 MeV

	n +	²³⁸ U Parameter	rs $(E_{n,p} = 0 - 1)$	00 MeV)	
$n + {}^{238}U Param$ Well Depth (MeV) $V_{R} = 49.8 \pm 16\eta + \Delta V_{c} - 0.29E + 0.000$ $W_{D} = 3.18 \pm 8\eta + 0.4E$ $= 6.38 - 0.046(E - 8)$ $W_{V} = 0$ $= -0.7 + 0.10 E$ $V_{SO} = 6.2$ $B_{2} = 0.198$ $B_{4} = 0.057$)	Range(MeV)	Geomet	ry (fm)	
$V_{R} = 49.8$	$\pm 16\eta + \Delta V_c - 0$	$0.29E + 0.0005E^2$	$0 \leq E \leq 30$	$r_{\rm R} = 1.26$	$a_{R} = 0.63$
$W_D = 3.18$	± 8η + 0.4E		$0 \leq E \leq 8$	$r_{\rm D} = 1.26$	$a_{\rm D} = 0.52$
= 6.38	- 0.046(E - 8)		$8 \le E \le 30$		
$W_V = 0$			$0 \leq E \leq 8$	$r_{V} = 1.26$	$a_{V} = 0.63$
= -0.7	+ 0.10 E		$8 \le E \le 30$		
$V_{SO} = 6.2$			$0 \leq E \leq 30$	$r_{SO} = 1.12$	$a_{\rm SO} = 0.47$
	$\beta_2 = 0.198$	$\beta_4 = 0.057$	(3 States Coupled)		

REFERENCES

- 1. P. G. Young, "Global and Local Optical Model Parameterizations," Proc. Specialists' Meeting on Use of the Optical Model for the Calculation of Neutron Cross Sections below 20 MeV, sponsored by the NEANDC, Nov. 13-15, 1985, Chateau de la Muette, Paris, France, OECD/NEA report NEANDC-222'U' (1986) p. 127.
- 2. O. Bersillon, "SCAT2 Un Programme de Modele Optique Spherique," Commissariat a l'Energie Atomique report CEA-N-2227 (1978), and Proc. ICTP Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety, 10 February - 13 March, 1992, Trieste, Italy.
- 3. P. Schwandt, Indiana University, private communication to D. Madland, May 1984.
- 4. J. Raynal, "Optical Model and Coupled-Channel Calculations in Nuclear Physics," International Atomic Energy Agency report IAEA SMR-9/8 (1970) p. 281.
- 5. H. Rebel et al., Karlsruhe report KFK-1333 (1971).
- 6. J. P. Delaroche et al., "The Optical Model with Particular Considerations of the Coupled-Channel Optical Model," IAEA-190 (1976) p. 251.
- 7. C. M. Perey and F. G. Perey, Atomic Data and Nuclear Data Tables 17, 1 (1976).
- N. Yamamuro, "Nuclear Cross Section Calculations with a Simplified-Input Version of ELIESE-GNASH Joint Program," Proc. Int. Conf. on Nucl. Data for Sci. and Tech., May 30-June 3, 1988, Mito, Japan (LA-UR 88-1618) (Ed. S. Igarasi, Saikon Publ. Co., Ltd., 1988) p. 489.
- R. L. Walter and P. P. Guss, "A Global Optical Model for Neutron Scattering for A>53 and 10 MeV<E<80 MeV," Proc. Int. Conf. Nuclear Data for Basic and Applied Science, Santa Fe, N.M., May 13-17, 1985 [Gordon and Breach Science Pub., Inc. (1986)] p. 1079.

- 10. P. Schwandt et al., Phys. Rev. C. 26, 55 (1982).
- D. G. Madland, "Recent Results in the Development of a Global Medium-Energy Nucleon-Nucleus Optical-Model Potential," Proc. Specialists' Mtg. Preequilibrium Nuclear Reactions, Semmering, Austria, 10-12 February 1988 [Ed: B. Strohmaier, NEANDC-245 'U' (1988)] p. 103.
- 12. D. G. Madland, personal communication, December, 1986.
- 13. S. Watanabe, Nucl. Phys. 8, 484 (1958).
- 14. Ch. Lagrange, O. Bersillon, and D. G. Madland, Nucl. Sci. Eng. 83, 396 (1983).
- D. G. Madland and P. G. Young, "Neutron-Nucleus Optical Potential for the Actinide Region," Proc. Int. Conf. on Neutron Physics and Nuclear Data for Reactors and Other Applied Purposes, Harwell, England, Sept. 25-29, 1978 [published by the OECD (1978)], p. 349.
- H. Hitzenberger, A. Pavlik, H. Vonach, R. C. Haight, R. O. Nelson, and P. G. Young, "Study of ²⁷Al (n,xγ) Reaction up to E_n = 400 MeV," Proc. Int. Conf. on *Nuclear Data for Sci. and Tech.*, 9-13 May 1994, Gatlinburg, Tenn. (LA-UR 93-3808).
- 17. J. S. Petler, M. S. Islam, R. W. Finlay, and F. S. Dietrich, Phys. Rev. C 32, 673 (1985).
- 18. F. G. Perey, Phys. Rev. 131, 745 (1963).
- E. D. Arthur and P. G. Young, "Evaluated Neutron-Induced Cross Sections for ^{54,56}Fe to 40 MeV," Los Alamos National Laboratory report LA-8636-MS (ENDF-304) (1980).
- P. G. Young, E. D. Arthur, M. Bozoian, T. R. England, G. M. Hale, R. J. LaBauve, R. C. Little, R. E. MacFarlane, D. G. Madland, R. T. Perry, and W. B. Wilson, "Transport Data Libraries for Incident Proton and Neutron Energies to 100-MeV," Los Alamos National Laboratory report LA-11753-MS (July 1990).
- S. M. Sterbenz, F. B. Bateman, T. M. Lee, R. C. Haight, Rc C. Goeckner, C. E. Brient, S. M. Grimes, H. Vonach, P. Maier-Komor, P. G. Young, and M. B. Chadwick, "The ⁵⁶Fe(n,xα) Reaction from Threshold to 30 MeV," Proc. Int. Conf. on *Nuclear Data for Sci. and Tech.*, 9-13 May 1994, Gatlinburg, Tenn. (LA-UR-93-3626).
- E. D. Arthur, P. G. Young, and W. K. Matthes, "Calculation of ⁵⁹Co Neutron Cross Sections Between 3 and 50 MeV, "Proc. Symp. on Neutron Cross Sections from 10 to 50 MeV, BNL (May 1980), p. 751.
- T. M. Lee, F. B. Bateman, P. G. Young, et al., "The ⁵⁹Co(n,α) Reaction from Threshold to 30 MeV," Proc. Int. Conf. on Nuclear Data for Sci. and Tech., 9-13 May 1994, Gatlinburg, Tenn. (LA-UR-93-3627).
- 24. P. G. Young and D. A. Rutherford, "Calculation of Neutron Cross Sections of 64, 66, 68Zn for Fusion Applications," Proc. IAEA Advisory Group Mtg. on Nuclear Theory for Fast Neutron Data Evaluation, 12-16 Oct., 1987, Beijing China (LA-UR 87-3189), International Atomic Energy Agency report IAEA-TECDOC-483 (1988) p. 167.

- 25. E. D. Arthur, Nucl. Sci. Eng. 76, 137 (1980).
- H. A. O'Brien, R. O. Nelson, C. M. Laymon, S. A. Wender, and P. G. Young, "Studies of Higher-Order (n,xγ) Reactions in ⁸⁹Y Targets," Proc. 7th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Asilomar, California, 14-19 October 1990, LA-UR-90-3498 (October, 1990).
- P. G. Young and M. B. Chadwick, "Calculation of Proton and Neutron Emission Spectra from Proton Reactions with ⁹⁰Zr and ²⁰⁸Pb to 160 MeV with the GNASH Code", Proc. OECD Nuclear Energy Agency Specialists Meeting on *Intermediate Energy Nuclear Data*, May 30 - June 1, 1994, Issy-les-Moulineaux, France, to be published (LA-UR-94-1830).
- E. D. Arthur and C. A. Philis, "New Calculations of Neutron-Induced Cross Sections on Tungsten Isotopes," in Applied Nuclear Data Research and Development, July 1 - Sept. 30, 1980, Los Alamos Scientific Laboratory report LA-8630-PR (1980) p. 2.
- 29. R. L. Macklin and P. G. Young, Nucl. Sci. Eng. 95, 189 (1987).
- 30. R. L. Macklin and P. G. Young, Nucl. Sci. Eng. 97, 239 (1987).
- J. P. Delaroche, "Potentiel Optique Nucleon-¹⁹⁷Au Entre 10 keV et 57 MeV," Proc. Int. Conf. on Neutron Physics and Nuclear Data for Reactors and Other Applied Purposes, Harwell, England, Sept. 25-29, 1978 [published by the OECD (1978)], p. 366.
- P. G. Young and E. D. Arthur, "Analysis of n + ¹⁹⁷Au Cross Sections for E_n = 0.01-209 MeV," Proc. 5th Int. Symp. on Capture Gamma Ray Spectroscopy and Related Topics, Oak Ridge Nat. Lab., Knoxville, Tenn., Sept. 9-14, 1984, AIP Proceedings No. 125, p. 530 (LA-UR-84-2767).
- H. Vonach, A. Pavlik, M. B. Chadwick, R. C. Haight, R. O. Nelson, S. A. Wender, and P. G. Young, "207,208Pb(n,xny) Reactions for Neutron Energies up to 200 MeV," accepted for publication in *Phys. Rev. C* (1994).
- 34. R. E. Shamu and P. G. Young, J. Phys. G: Nucl. Part. Phys. 19, L169 (1993).
- 35. M. J. Martin, Nucl. Data Sheets 47, 797 (1986).
- D. G. Madland and P. G. Young, "Evaluation of n + ²⁴²Pu Reactions from 10 keV to 20 MeV," Los Alamos National Laboratory report LA-7533-MS (1978).
- P. G. Young and E. D. Arthur, "Calculation of ²³⁵U(n,n') Cross Sections for ENDF/B-VI, Proc. Int. Conf. on Nucl. Data for Sci. and Tech., May 30-June 3, 1988, Mito, Japan (LA-UR-99-1740) (Ed. S. Igarasi, Saikon Publ. Co., Ltd., 1988), p. 603.
- P. G. Young and E. D. Arthur, "Theoretical Analyses of (n,xn) Reactions on ²³⁵U, ²³⁸U, ²³⁷Np, and ²³⁹Pu for ENDF/B-VI," Proc. Int. Conf. on Nuclear Data for Science and Technology, Jülich, Germany, 13-17 May 1991 (LA-UR-91-1424), [Ed. S. M. Qaim, Springer-Verlag, Germany (1992)], p. 894.
- 39. G. Haouat, J. Lachkar, Ch. Lagrange et al., Nucl. Sci. Eng. 81, 491 (1982).
- 40. R. Kozack and D. G. Madland, Phys. Rev. C. 39, 1461 (1990).

OPTICAL MODEL AND LEVEL DENSITY PARAMETERS FOR NUCLEAR DATA EVALUATION

S.B.Garg and Ashok Kumar Bhabha Atomic Research Centre Trombay,Bombay-400 085 (India)

1. Introduction : It is now well known that all the desired nuclear reaction cross-sections required in reactor and accelerator industries and other allied sciences can not be measured in a reasonably short span of time due to various limitations imposed by the complexity of measuring techniques and appropriateness of neutron sources. Nuclear models are , therefore , destined to play a vital role in predicting a large variety of data for meaningful technological and applications. Accuracy and acceptability scientific nf nuclear data generated with various nuclear models are , however , dependent on some basic input parameters which form the core of this Co-ordinated Research Programme and include the following:

(\mathbf{i})	Optical	Model	Potential	Parameters
----------------	---------	-------	-----------	------------

- (ii) Nuclear Level Densities
- (iii) Pairing and Shell Energy Corrections
- (iv) Atomic Masses and Deformations
- (v) Average Neutron Resonance Data
- (vi) Gamma-Ray Strength Functions and
- (vii) Discrete Energy Level Schemes

Undoubtedly, compilation of these parameters for a large number of elements spread over the entire chart of nuclides is a gigantic task. We, at BARC, have selected optical potential, level density and pairing and shell energy correction parameters for inclusion in the First Phase of the Reference Input Parameter Library Project.

A brief discussion of these parameters together with an outline of work plan is made in the following paragraphs.

2. Optical Model Potential Parameters: These parameters are required to infer reaction, shape-elastic, and total cross-sections of a given nuclide at a given incident energy and are, generally, dependent on the mass of the target nucleus and the energy of the incident particle. So, it is rather improbable to find a single potential which could be applied to all the nuclides over a wide range of incident energies. Attempt is, therefore, made to extract a 'regional potential' which could be valid for a certain mass range and in a certain energy region.

The computed reaction cross-section is split up into various components depending on the available open reaction channels In other words, estimation of binary, tertiary and multiparticle reaction cross-sections is desired by including neutron, proton, alpha-particle and gamma-rays in the outgoing channels. This would necessitate inclusion of the optical potential parameters for neutron, proton, and alpha-particle in the Input Library

Analysis of cross-section data with the optical model is done by making use of its spherical , non-local and coupledchannel (deformed) forms. But , non-local form is generally not adopted in many applications So , parameters corresponding to spherical and deformed forms of optical model are required to be compiled. In fact, Coupled channel calculations are more involved and time consuming and so attempt is made to find an equivalent spherical potential which can reproduce reaction and total cross-sections within the acceptable limits of accuracy

is planned to compile the spherical optical model It. potential parameters for nuclides of interest in reactor technology in SCAT-2 format /1/. The potential is composed of real central , surface imaginary , volume imaginary and spinorbit terms. Each term is represented by a guadratic in energy in the laboratory frame of reference. The real and volume imaginary potential terms are of Woods-Saxon form , the surface imaginary term is usually of Woods-Saxon derivative or of Gaussian form and the spin-orbit term is represented by Thomas form Wherever possible , parameters for deformed optical model potential would also be compiled. The energy range covered in this compilation is expected to be up to 30 MeV.

Spherical optical model potential parameters for several nuclides in the mass range 40 to 250 have been compiled in the SCAT-2 format. These parameters have been taken from the literature and some of them are tailor made for some specific nuclides like Pb , Bi , W-182 ,W-183 , W-184 , W-186 , Fe-54 , Fe-56 , Fe-57 , Fe-58 , Ni-58 , Ni-60 , Ni-61 , Ni-62 ,Ni-64 , Cr-50 , Cr-52 , Cr-54. It may be noted that potential parameters for incident neutron , proton and alpha particle have been included in the compilation.

3. Level Density Parameters : The computed cross-sections show sensitivity to the level density parameters employed in the calculations. Usually, parameters based on the following recipes are adopted :

(a) Fermi Gas Model based on the formalism of Gilbert and Cameron /2/ with pairing and energy shell corrections of Cook et al /3/

- (b) Back-shifted Fermi Gas Model based on the formulation of Dilg et al /4/
- (c) Super-Fluid Model of Ignatyuk et al /5/, and
- (d) Model Based on Thermodynamic Considerations of Kataria , Ramamurthy and Kapoor /6/.

From the application point of view (c) and (d) appear to be equivalent as shown by Ramamurthy et al /15/, but these concepts need to be further tested .

For the sake of completeness and for proper appreciation of the parameters involved in these level density recipes it is worthwhile to review these concepts :

3.1 **Fermi Gas Model :** Formulation of Gilbert and Cameron is adopted It divides the energy range into two regions with the higher energy range represented by

$$f_1(U,J) = [\sqrt{\pi} e \times p(2\sqrt{a}U)]/(12 (a)^{1/4} U^{5/4})$$
$$* [2J+1]e \times p(-(J+1/2)^2/2 \sigma^2)/2 \sigma^3 \sqrt{2\pi}$$

and applicable for all energies higher than $E_{\mathbf{x}}$ defined by

$$E_y = U_y + P(N) + P(Z)$$

and the lower energy region represented by

 $f_2(0) = 1/T \exp [(0 - 0_0)/T]$

Where T is the nuclear temperature and U_{0} is a normalization factor P(N) and P(Z) are the pairing energy corrections for neutrons and protons respectively and are taken from Cook et al. The level density parameter a is calculated with the shell energy corrections S(N) and S(Z), again taken from Cook et al , as follows :

a/A = 0.00917 [S(N) + S(Z)] + C C = 0 142 for spherical nuclides and = 0.120 for deformed nuclides

 $\sigma(U)$ is the spin cut off factor and is given by

 $\sigma^2 = C_C A^{2/3}$ (JaU); C_C being 0.0888 or 0.146

The parameters T , U_0 and $U_{\rm X}$ are determined by matching the number of cumulative discrete levels in the energy interval 0

to $U_{\rm C}$ e.g. $N_{\rm exp}$ and by matching the regional level density expressions at the excitation energy $U_{\rm X}$ i.e. by requiring

$$N_{e\times p} = 1/T \int_{0}^{U_{c}} \exp[(U - U_{0})/T] dU$$

= $\exp[(U_{c} - U_{0})/T] - \exp(-U_{0}/T)$
 $f_{1}(U_{x}) = f_{2}(U_{x})$; and
 $[df_{1}/dU]_{U=U_{x}} = [df_{2}/dU]_{U=U_{x}}$

Thus by knowing the pairing and shell energy corrections and the cumulative discrete energy levels in the low energy region i.e. up to 5 MeV or so the level density can be calculated for a given excitation energy This technique is being utilized in the currently used nuclear model codes.

Pairing and shell energy corrections of Cook et al have been compiled and stored in a computer file.

3.2 **Back-shifted Fermi Gas Model :** Here the formulation of Dilg et al is adopted for all excitation energies. The relevant expressions are given below :

 $f(U) = \exp \left[2J(a(U-\delta)) \right] / \left[12 J_2 \sigma (a)^{1/4} (U-\delta+t)^{5/4} \right]$ $f(U,J) = (2J+1) \exp \left[2 J(a(U-\delta)) - J(J+1)/2 \sigma^2 \right] / \left[24J_2 \sigma^3 + (a)^{1/4} (U-\delta+t)^{5/4} \right]$

Where the thermodynamic temperature (t) is given by

$$U-\delta = a t^2 - t$$
; and
 $\sigma^2 = I_{rr} t / h^2 \approx 0.015 (A)^{5/3} t$
 $I_{rr} = 2/5 A M_n R^2$; $R = 1.25 (A)^{1/3}$

 I_{rr} is the moment of inertia of a rigid spherical rotator ;

M_n being the mass of nucleon

In the above equations the unknown parameters are 'a' -the level density parameter and ' δ ' - the energy shift parameter which can be estimated by fitting cumulative discrete energy levels, N_{exp}, in the excitation energy interval 0 to U₀ and the known s-wave resonance spacing, $\langle D \rangle_0$, at the neutron binding energy Thus, the following two equations are obtained:

$$N_{exp} = \int_{0}^{U_{o}} f(U) dU = F(a, \delta, A, U_{0})$$

$$1/\langle D \rangle_{0} = f(S_{n}, I+1/2) + f(S_{n}, I-1/2) \text{ for } I # 0$$

$$= f(S_{n}, 1/2) \qquad \text{ for } I = 0$$

$$= F_{1}(a, \delta, S_{n}, I)$$

These two equations can be solved numerically to yield the values of 'a' and ' δ '. These values have been listed by Dilg et al for a large number of nuclides. Recently Ivascu et al /7/ have also looked at the nuclides in the mass range 40 to 65.

fat and δ values of Dilg et al and Ivascu et al have been compiled and stored in a computer file.

3.3 **Super Fluid Model Considerations :** Based on the super fluid model considerations of the nucleus, Ignatyuk et al have given an expression for the level density parameter 'a' which includes the effect of shell closures. In this formulation 'a' becomes energy dependent and is given by

$$a(U) = a(*) [1 + E_{eb}/U \{ 1 - exp(-\tau U) \}]$$

Where a(*) is the asymptotic level density parameter to which a(0) converges at high excitation energies and τ is a damping parameter given by

$$\tau = 0.40 (A)^{-1/3}$$
 and

 $E_{\rm Sh}$ is the shell energy correction given by the difference of the experimental mass , $M_{\rm exp}$, and the theoretical liquid drop model based mass of the nucleus , $M_{\rm ld}$, and is calculated as

$$E_{sh} = M_{exp} - M_{ld}$$

 E_{sh} is usually calculated with the theoretical mass formulisms but the model of Myers and Swiatecki /8/ is usually adopted in the computations.

These considerations can be easily incorporated in to the existing recipes of calculating the level density as shown recently by Mengoni and Nakazıma /9/. A brief discussion of this procedure is made in the following :

We recall the level density expression as given by Gilbert and Cameron and discussed earlier in this manuscript i.e. $f(U,J) = [J\pi \exp \{2 J(aU)\} (2J+1) \exp \{-(J+1/2)^2/2 \sigma^2 \}]$ $/ [24 \sigma^3 (a)^{1/4} (U)^{5/4} J2\pi]$ Where $\sigma^2 = 0.015 (A)^{5/3} T$ and the nuclear

temperature T is evaluated with the relation

$$1/T = (1/f) * df /dV$$

= $1/J(U/a) - 5/4U$

Now at the neutron binding energy , a(U) is calculated in terms of a(*) and a(*) is inferred by fitting the experimental s-wave resonance level spacing , $\langle D\rangle_{0}$, as follows

$$1/\langle D \rangle_{0} = f (U, J = 1/2)$$
 for $I = 0$
= $f (U, J = I+1/2) + f (U, J=I-1/2)$ for $I # 0$

3 4 Model Based on Thermodynamical Considerations: Kataria et al have built in excitation energy dependence of the shell effects on level densities. The level density f (Ex,I) is written as:

 $f(E_{X},I) = C[(2I+1)/2\sqrt{2\pi} \sigma^{3}(E_{X})] \exp[S(E_{X})]$

*exp [-I(I+1)/2 σ² (Ex)]

Where C = $\sqrt{\pi}$ / (12 $a^{1/4}$ Ex $^{5/4}$) ,S(Ex) is the entropy of the nucleus.

It was shown in Ref./6/ that both the entropy and excitation energy have a smooth temperature dependent part and a fluctuating shell dependent term as given below:

 $S = 2aT + \delta_{s} /T [\pi^2 w^2 T^2 \cosh(\pi wT) / \sinh^2(\pi wT) - \pi wT / \sinh(\pi wT)]$

 $E_{X} = aT^{2} + \delta_{s} [\pi^{2}w^{2}T^{2}\cosh(\pi wT)/\sinh^{2}(\pi wT) - 1]$

Where δ_S is the ground state shell energy correction and $w = 2\pi/\Omega$, Ω being the characteristic major shell spacing

(Ω=k/A^{1/3}), k is of the order of 35 MeV. 'a' is the level density parameter which has smooth dependence on mass (a=A/K),K lying between 7 and 10 The ground state shell and pairing energy corrections are used as inputs in the calculation of temperature and level density of the nucleus This formula takes into account nuclear shell effects and shows that at high excitation energies, these effects are washed out. The noteable feature of this formula is that the liquid drop part of the level density parameter 'a is dependent shell explicitly retained and temperature corrections are incorporated in the level density as function of excitation energy.

4. Application : We have carried out an analysis of (n,2n) cross-sections of W-182, W-183, W-184, and W-186 by making use of the basic input parameters compiled by us. We have utilized neutron optical potential parameters of Delaroche et al /10/, atomic masses of Wapstra et al /11/, pairing and shell energy corrections of Cook et al , discrete energy levels from Nuclear Data Sheets and level density models of Gilbert-Cameron and Ignatyuk et al. Neutron, proton, alphaparticle and gamma-ray decay competition is included in the reaction channels. Multistep Hauser-Feshbach statistical theory including pre-equilibrium decay model and the geometry dependent hybrid model are employed in the analysis using the model codes GNASH /12/ and ALICE-91 /13/.

The calculated and measured (n,2n) cross-sections of natural tungsten and W-182 are compared in Figs 1 and 2. The measured data are taken from Ref. /14/. The calculated data for W-183,W-184 and W-186 are not explicitly given in this paper but their trend is similar to that of W-182. It is noted that both Gilbert-Cameron and Ignatyuk et al level density models in multistep Hauser-Feshbach scheme reproduce the measured data quite well where as the predictions of geometry dependent hybrid model are higher. The calculated data also certify that the other basic input parameters as mentioned above are acceptable. In Fig.2 the predicted values of (n,3n) cross-section data are also given.

References :

1. D.Bersillon ; Report CEA-N-2227 (1981)

- 2. A.Gilbert and A.G.W.Cameron ; Can.J.Phys. 43,1446 (1965)
- 3. J.L.Cook , H.Ferguson and A.R.Musgrove ; Aust.J Phys. 20,477 (1967)

4 W Dilg , W Schantl , H. Vonach and M. Uhl ; Nucl. Phys. A217,269 (1971) 5 A.V. Ignatyuk G N Smirenkin and A.S.Tishin , 2 Sov J. Nucl. Phys. 21,255 (1975) б. S K.Kataria , V.S Ramamurthy and S.S.Kapoor ; Phys.Rev. C18,988 (1978) 7 M.Ivascu , V.Avrigeanu and M.Avrigeanu ; Rev.Roum.Phys. 32,697 (1987) 8 W.D Myers and W.J Swiatecki ; Nucl Phys. 81,1 (1966) J.Nucl Sci Technol. 9 A. Mengoni and Y. Nakajima ; 31,151 (1994)10 J.F Delaroche et al ; Proceedings of the Intern. Nuc 1 Data Conf , Knoxville (U.S.A), 336 (1979) 11. A.H.Wapstra et al ; At.Nucl.Data Tables 39,281 (1988) 12 E.D.Arthur ; The GNASH Pre-equilibrium Statistical Model Code , Los Alamos National Laboratory Manuscript LA-UR-88-382 (1988) P G Young and E.D.Arthur 5 Los Alamos National Laboratory Report LA-6947 (1977) M Blann : Private Communication (1992) 13 J Frehaut et al ; Report BNL-NCS-51245 Vol.1,399(1980) 15. V.S.Ramamurthy et al; Review of Recent Phenomenological Approaches to the Description of Nuclear Level Densities;Report BNL-NCS-51694, page 187 (1983)



Fig. 1 (n.2n) x-sections of natural tungsten with MSHF and GDH models



Fig.2 (n.2n) and (n.3n) X-Sections of W-182 with MSHF and GDH models and IST and GC level densities

ANALYSIS OF THE NEUTRON RESONANCE DENSITIES, LOW-LYING LEVELS AND LEVEL DENSITY PARAMETERS

A V Ignatyuk Institute of Physics and Power Engineering, 249020 Obninsk, Kaluga Region, Russia

Abstract: For a practical application of the statistical models it is very important to achieve the level density description that reproduces both the average distances between neutron resonances and the observed cumulative numbers of low-lying levels. Main contradictions between existing evaluations of the neutron resonance densities and the low-lying level densities are considered. Problems of a consistent systematics of the level density parameters are discussed briefly.

1 Introduction

The statistical properties of excited nuclear levels have been a matter of concern and study for over fifty years. One of the basic statistical properties of such levels is their density. For the description of the level densities the Fermi-gas and constant temperature models are used very frequently with parameters obtained from fitting some experimental data [1,2]. But the physical assumptions upon which both these models are based are not sophisticated enough to allow them to account properly for variations of level densities over the wide energy interval from the ground state to the energies much higher than the neutron separation energy. This is not surprising considering that the models discussed were first put forward over fifty years ago, when nuclear physics was in its infancy.

Some of the most important concepts, upon which current understanding of the structure of low-lying nuclear levels is based, include the shell effects, pairing correlations and collective phenomena. All these concepts have been incorporated into the Generalized Superfluid Model (GSM) developed by many authors over the last 20 years [3] To simplify the analysis of experimental data the phenomenological versions of this model were developed too [4,5].

For any practical applications of the statistical models it is very important to obtain the parameters of the level density description from the reliable experimental data. The cumulative numbers of low-lying levels and the average distances between neutron resonances are usually used as such data. In this report the main problems of the corresponding parameter systematics are discussed briefly

2 Average spacing of neutron resonances

The average parameters of neutron resonances were analyzed by many authors [1-14] The main problems of such an analysis are connected with the reliable separation of s- and p- resonances and the estimation of missing resonances.

If the identification of s- and p- resonances is accurate enough then the neutron strength functions can be obtained rather simply from the analysis of the cumulative sums of the reduced neutron widths by the staircase method. The resonances with large widths give the dominant contribution to these sums and the missing weak resonances distort the neutron strength functions just a little.

To evaluate the average resonance spacing the problem of both missing and spurious resonances becomes important. If there is no loss of resonances the average spacing can be defined as $\langle D \rangle = \Delta E/N$, where ΔE is the energy interval and N is the number of resonances adopted. The statistical error of this estimation can be defined [6] as:

$$\frac{\Delta D}{D} = \frac{.45\sqrt{\log N + 2.18}}{N} \approx \frac{1}{N}$$
(1)

It is obvious from these relations that the loss of some resonances results in an error which exceeds essentially the statistical one

More reliable methods of the resonance spacing evaluation based on the fitting of the Porter-Thomas distribution of neutron widths were developed too [8,9] These methods allow us to correct the analyzed data with regard to missing and spurious resonances and give consistent estimation of both average resonance spacings and neutron strength functions. Unfortunately these methods require a rather large number of resonances considered more than 40-50 as a rule

All the methods mentioned have been used to evaluate the average resonance parameters submitted as candidates for the Reference Input Parameter Library [10-14] For the nuclei where the number of observed resonances exceed 60-80 the evaluated parameters agree rather well. For such nuclei some variances exist only concerning the errors of the recommended parameters. The highest of the errors seems the most reasonable estimation for the recommended errors.

However for more than a half of the considered nuclei the number of the identified sresonances does not exceed 40-50 Discrepancies between the average resonance spacings for such nuclei are big enough and differences of the recommended spacings by a factor 2 are common. Some typical examples of contradictions available are given in Table 1. It follows from these examples that essential differences of derived average spacings can exist even for the nuclei with the number of resonances higher than 100. The analysis of used data shows that the main reasons for discrepancies are connected with the identification of s- and p-resonances. We must do a large job in the framework of the CRP activity to eliminate the spurious identifications of resonances and to obtain more accurate estimations of the recommended average parameters for many nuclei considered in the submitted evaluations [12-14]

Compound	BNL [10]	Obninsk [11]	Bologna [13]	Beijing [14]	N [13]
nucieus					- <u> </u>
Cr-55	(26+2)k	(60+9)k	(31 9+6.4)k	<u>(37+4)k</u>	15
Cu-64	320+30	1040+110	1450+320	504+20	120
Sr-89	(25+5)k	(40+10)k	(55+5)k	(27+6)k	17
Zr-91	(6 4+1 1)k	(8 6+1 6)k	(10.5+2 5)k	(7 8+ 7)k	35
Nb-94	44+4	90+20	105+10	45+2	70
Pd-109	45+3	200+80	130+30	175	32
Ag-110	14+2	18.7+1.3	30+2	26 9+1 5	80
Sn-121	1400+70	1640+200	3400+300	1360+250	30
Te-124	130+15	147+12	260+50	130+15	90

Table 1 Average spacings for the s-resonances evaluated by different groups. The spacing is given in eV or keV and N is the number of resonances taken into account

3 Cumulative numbers of low-lying levels

Data on the cumulative numbers of the observed low-lying levels were compiled practically for all nuclei with the estimated average neutron resonance spacings [1,12,14] The main uncertainties of such data are connected with the evaluation of the boundary excitation energy below which all the levels are taken into account. The loss of levels considerably reduces the value of corresponding data for applications connected with the analysis of the nuclear level densities.

A few typical examples of the cumulative number estimations are presented in Table 2 Essential differences between both the boundary energies and level numbers can be seen in the evaluations of different groups

For the last years some new experimental data on low-lying levels of these nuclei have been obtained and it allows us to test the former recommendations on the basis of revised data. The observed cumulative numbers of levels are shown in Fig. 1 together with the values evaluated by different groups. We can conclude from this comparison that the numbers of levels are underestimated for many nuclei in the old evaluations [1]. On the other hand the evaluations of Obninsk's and Beijing's groups [12,14] don't contradict each other as a rule. They give approximately the same level densities of low-lying levels (the derivative of the cumulative level numbers).

Nucleus	Dilg e.a [1]		Obninsk	Obninsk [12]		Beijing [14]		lysis
	U ,MeV	N	U ,MeV	N	U ,MeV	N	U ,MeV	N
In-116	.75	23	37	9	.46	12	98	40
Sn-116	-	-	3.10	29	2 59	11	3.50	50
Sn-117	1.60	10	1 63	14	1.25	8	1 60	16
Sn-120	3.07	23	2 84	24	3 30	34	3 30	40
Sn-121	2.10	12	1 10	10	1.88	26	1 20	13
Sb-122	40	15	.19	10	.32	16	50	28
Sb-124	30	11	.15	9	.48	24	.50	25
Te-124	3.00	44	2.38	29	3.00	77	2 80	64
Te-125	80	11	.64	10	.84	13	.90	15
Ho-166	.52	28	.40	20	.43	23	.43	25
Er-167	1.00	36	.82	31	82	31	.82	31
Er-168	1.70	34	1.66	34	2 60	166	1.65	33

Table 2. Boundary excitation energies U and cumulative numbers N of low-lying levels evaluated by different groups.

For some nuclei cumulative numbers of levels estimated by Beijing's group are big enough and well agree with the last experimental data. Nevertheless the analysis of the corresponding level densities shows a loss of some levels for the recommended excitation energies (see, for example, data for Te-124 and Er-168 in Table 1 or for Sn-121 in Fig 1). Some reductions of excitation energies or correction of level numbers are required for such nuclei. On the other hand the level numbers of Obninsk's group are estimated in many cases for too low excitation energies. So the revision of the submitted data [12,14] should be recommended to obtain the reliable numbers of low-lying levels for the RIPL

4 Level density description

In order to obtain a consistent description of the shell, superfluid and collective effects the total level density of excited nuclei should be approximated as

$$\rho(U) = \rho_{ab}(U) \cdot K_{vib}(U) \cdot K_{rot}(U), \qquad (2)$$

where $\rho_{qp}(U)$ is the level density of quasi-particle excitations, K_{vib} and K_{rot} take into account of the collective enhancement of the level density due to vibrational and rotational excitations. The expressions needed to calculate $\rho_{qp}(U)$, K_{vib} and K_{rot} are given in Refs 3-5, 15

In the phenomenological approach we use the superfluid model equations to calculate the density of quasi-particles excitations and the collective enhancement coefficients and employ as the level density parameter the following expression

$$a(U,Z,A) = \widetilde{a}(A) \cdot \left(1 + \delta \mathcal{E}(Z,A) \cdot \frac{f(U-E_{cond})}{U-E_{cond}}\right) \quad \text{for } U > U_{cr}$$
(3)
$$a(U,Z,A) = a(U_{cr},Z,A) \quad \text{for } U < U_{cr}$$

Here \tilde{a} is the asymptotic value of the level density parameter at high excitation energy, the dimensionless function $f(U) = 1 - \exp(-\gamma U)$ determines the energy behavior of this parameter and $\delta \mathcal{E}(Z,A)$ is the shell correction in the nuclear binding energies. The energy dependence of the level density parameter is very important for a consistent description of the shell effects in the excited nuclei

The change of the level density parameter energy dependence (3) below and above the critical excitation energy U is related to the nucleus phase transition from the superfluid low-energy state to the normal state in the high energy region. The critical energy U_{cr} and the condensation

energy E_{cond} are directly connected with the pairing correlation function Δ that is the second basic parameter of the phenomenological description. If we use the same values of the correlation functions and the collective enhancements of the level densities calculated in the phenomenological approach and the more reliable microscopic models based on the realistic single-particle level schemes will be very similar [16]

Using the phenomenological model described above we can extract the values of the level density enhancement coefficients from the experimental data on the densities of neutron resonances In such analysis the asymptotic values of the level density parameters were defined as $\tilde{a} = (0.073A + 0.115A^{2/3})$ MeV⁻¹, the shell corrections were taken from Ref.17 and the correlation functions were approximated as $\Delta = 12 \cdot A^{-1/2}$ MeV. The coefficients obtained are shown in the upper part of Fig.2. In the lower part the values of similar coefficients calculated in the adiabatic approximation are given A correlation of both coefficients is very strong but the adiabatic estimations usually give higher values of coefficients than the ones extracted from the observed density of neutron resonances. The difference of these two definitions of the level density enhancement factors demonstrates that the damping of the enhancement coefficients for high excited nuclei must be taken into account

For the last ten years some microscopic models have been developed to consider the collective effects in highly excited nuclei [3,18-20]. The results of all these models demonstrate the important role of nonadiabatic effects in heated nuclei and the corresponding damping of the level density enhancement factors with the increase of excitation energies. Various phenomenological descriptions of this damping were also proposed [3-5,18,19] For typical rotational and vibrational nuclei the temperature dependencies of the enhancement coefficients obtained in various approaches are shown in Fig 3 Large uncertainties in evaluations of the collective enhancement damping are seen and unfortunately up to now we have no experimental data that could be used to verify the predictions of different models

5 Local and general systematics of the level density parameters

For many practical applications of the statistical models the necessity arises to achieve an agreement between the calculated level densities and some experimental data. To account for possible defects of global parameterization of the pairing correlation functions and collective enhancement damping an additional parameter defined as the shift of the excitation energy δ_{shift} was introduced in the phenomenological GSM. Within the framework of such approach the set of parameters \tilde{a} and δ_{shift} was obtained which describes simultaneously the cumulative numbers of low-lying levels and observed neutron resonance densities for all nuclei where the corresponding experimental data exist [5]. These parameters are shown in Fig.4. The individual parameters fluctuate a little and these fluctuations reflect to some degree the simplifications included in the phenomenological GSM. To remove these fluctuations we need a better understanding of the collective enhancement damping for spherical, deformed and intermediate nuclei.

For any practical applications the individual parameters are preferable of course. Some examples of the experimental data description for such parameters are shown on Fig. 5. Uncertainties of parameters are not very important for a prediction of the level densities in an intermediate energy region if experimental data for the neutron resonances and low-lying levels were chosen correctly

On the other hand for many tasks we need the level density parameters for nuclei where experimental data are missing. For such goals the global parameters may be used effectively. Some local parameter systematics based on extrapolations of the isotopic or isotonic changes of the individual parameters may also be proposed. In many cases experimental data on the cumulative number of low-lying levels might be very useful because such data allow us to fit one of the individual parameters keeping the global systematics for others.

The systematics of the level density parameters discussed above is based on the neutron resonance densities and cumulative numbers of low-lying levels estimated by Obninsk's group Any changes of input data will reflect in some way on the systematics of parameters. So the final recommendations for the level density parameters should be done on the basis of the densities of both neutron resonances and low-lying levels included in the RIPL.

6 Concluding remarks

Today it seems almost obvious that in the systematic analysis of the level densities of excited nuclei we should use models which are more consistent than the Fermi-gas model, but inevitably more complex. The success of the Generalized Superfluid Model is attributed to the inclusion of the main well-known characteristics of nuclear structure pairing correlations, shell effects and collective excitations. The complexities of the model are justified by the mutual consistency of the parameters obtained from the various experimental data and by the close interconnection of the theoretical concepts which are used to describe the structure of low-lying nuclear levels and the statistical properties of highly excited nuclei

The updated systematics of the level density parameters should be done on the basis of the consistent sets of the neutron resonance and low-lying level densities selected in the framework of the CRP activity

References

- Ericson T Adv. Phys 9, 425 (1960),
 Gilbert A ,Cameron A Can. J. Phys., 43, 1446 (1965),
 Dilg W , Schantl W , Vonach H , Uhl M Nucl Phys., A217, 269 (1973)
- 2 Lynn J.E The Theory of Neutron Resonance Reactions. Clarendon Press (Oxford), 1968
- 3 Ignatyuk A V Statistical Properties of Excited Atomic Nuclei, Energo- atomizdat (Moscow), 1983, translated in IAEA Report INDC-233(L), 1985
- 4 Ignatyuk A V, Istekov K K., Smirenkin G.N. Sov J. Nucl Phys., 29, 450 (1979)
- 5 Grudzevich O T., Ignatyuk A V, Plyaskin V I, Zelenetsky A V In Proc Conf.on Nuclear Data for Science and Technology (Mito, 1988), JAERY, p 187
- 6 Dyson F, Mehta M L. J Math. Phys., 4, 489 (1965)
- 7 Camarda H et al In⁻ Statistical Properties of Nuclei. Ed J D.Gard, Plenum Press (NY), 1972, p.205
- Fort E., Derrien H, Lafond D In Proc.Meet on Neutron Cross Sections of Fission Product Nuclei /Bologna, 1979/ NEANDC(E)-209, p 121, Froehner F H Ibid , p 145, Delfini G , Gruppelaar H Ibid , p 169
- 9 Froehner F.H. In. Proc Conf. on Nuclar Data for Science and Technology /Antwerp, 1982/. Ed. K.H.Boeckhoff, Reidel Publ Comp., 1982, p.623
- 10 Mughabghab S.F., Divadeenam M., Holden N.E. Neutron Cross Sections Academic Press (NY-London), v.1, part A, 1981, Mughabghab S.F., v 1, part B, 1984
- 11 Belanova N.S., Ignatyuk F.V., Pashchenko A.B., Plyaskin V.I. Radiative Cupture of Neutrons -Handbook Energoatomizdat (Moscow), 1986
- 12 Ignatyuk A.V Contribution to IAEA Consultants' Meeting at Sirolo, September 1993.
- 13. Reffo G Report to this Meeting, 1994
- 14 Huang Zhongfu, He Ping, Su Zhongdi, Zhou Chunmei. Report to this Meeting, 1994
- 15 Ignatyuk A.V., Weil J.L., Raman S., Kahane S. Phys. Rev., C47, 1504 (1993)
- 16 Rastopchin E.M., Svinn M.N., Smirenkin G,N. Sov J. Nucl. Phys., 52, 1258 (1990)
- 17 Myers W D. Droplet Model of Atomic Nuclei IFI/Plenum Press, 1977
- 18. Hansen G., Jensen A. Nucl. Phys., A406, 236 (1983)
- 19 Maino G, Mengoni A., Ventura A.: Phys. Rev, C42, 988 (1990)
- 20. Lauritzen B., Bertsch G. Phys. Rev., **C39**, 2412 (1989); Lauritzen B., Bertsch G., Bortignon P., Broglia R. Phys. Lett., **B256**, 329 (1989)



Fig 1 Cumulative numbers of the low-lying levels for some even-even, odd and odd-odd nuclei in comparison with the recommended values by Vienna (^a), Obninsk (O) and Beijing groups (◊)










Fig 4 Comparison of the individual and global level density parameters of the phenomeno-logical GSM.



Fig 5 Comparison of the experimental data on the level density of some even-even, odd and odd-odd nuclei with the phenomenological description

Partial level densities for modeling continuum angular distributions in nuclear reactions

A physical basis for the Kalbach Systematics

M.B. Chadwick¹ and P. Obložinský²

¹University of California, Nuclear Data Group, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA ²Nuclear Data Section, International Atomic Energy Agency, 1400 Vienna, Austria

We present an overview of the general features of continuum angular distributions in nuclear reactions and the theories that have been developed to model them in nuclear data evaluation work. We show how momentum conservation is fundamental to the description of angular distributions in preequilibrium nuclear reactions. The properties of "state densities with linear momentum" and their relation to energyand spin-dependent state densities are discussed. By using these state densities to describe the phase space during the preequilibrium cascade, angular distributions can be derived in a transparent way. Fermi-motion and Pauli-blocking effects are included, and correlations between the emission particle's energy and angle are obtained for all orders of scattering. Our model provides a physical basis for many features of the widely-used phenomenological systematics of Kalbach, and provides a framework for understanding the systematical properties of continuum angular distributions. We apply our results to the analysis of angular distributions in a number of nucleon-induced reactions. We also show an application where these densities can be applied - photonuclear reactions in the quasideuteron regime - which cannot be analyzed using Kalbach's systematics.

I. INTRODUCTION

Evaluated nuclear data files usually require a description of the angular distribution of particles emitted in a nuclear reaction since angular effects are important when determining the transport of radiation through matter. The angular distribution of emitted particles is a subject which has attracted a great deal of interest from a physics perspective, since the angular effects give information about the underlying reaction mechanisms involved in the evolution of a quantum system towards equilibrium. In this paper we review some recent developments in the modeling of angular distributions which are of use in nuclear data evaluation work.

Particles ejected during the early stages of a nuclear reaction are typically of high energy and have forward-peaked angular distributions, since they are emitted prior to nuclear equilibration and partially preserve the incident projectile's direction of motion [1-7]. These preequilibrium particles account for the continuum region of double differential emission spectra. Theoretical attempts to understand such spectra span from semiclassical approaches, notably exciton and hybrid models, up to recent quantum mechanical multistep theories [8]. The quantum mechanical approaches -have been used with a certain amount of success for analyzing nucleon reactions up to 200 MeV. However, they still face open questions regarding the formulation of multistep processes [9], multiple particle emission, and the emission of complex particles. Semiclassical models have provided a clear insight into the physics of preequilibrium processes and have successfully explained many angle-integrated spectra, though they were initially not formulated to account for angular effects. Therefore a widely-adopted approach [1-4] is to use these angle-integrated spectra, and obtain angular distributions from the Kikuchi-Kawai [10] nucleon-nucleon scattering kernel in a Fermi-gas. While this has been able to explain certain features of the forward-peaking, it has not been able to account for many of the systematic properties of continuum angular distributions [11]. Furthermore, most works assume a fast leading-particle that carries all the directional information during the cascade. This is in contradiction to the equiprobability assumption used in the exciton model which puts all the excited particles and holes on an equal footing, and does not follow the individual particle's motion [2].

In the absence of a sufficient theoretical understanding of the general properties of continuum angular distributions, Kalbach developed phenomenological systematics to describe them [11]. She analyzed a large body of experimental measurements (over 900 data sets) in nucleon and alpha-induced reactions at energies up to several hundreds of MeV, and found simple angular variations and a surprising similarity between angular distributions in reactions involving varying types of projectile and ejectile. While these systematics are very useful for describing and predicting differential cross sections, their physical basis has remained obscure. The fact that observed continuum preequilibrium cross sections tend to vary smoothly with angle and energy, and lend themselves to simple parameterizations [11], suggests that they should be describable using a relatively simple model of the reaction process. In this paper we show how momentum considerations are fundamental to the description of continuum angular distributions, and using a semiclassical preequilibrium model we derive Kalbach's parameterization of the forward-peaking shape.

An important step in reconciling the role of linear momentum in the preequilibrium cascade with the statistical assumptions of the exciton model was made by Madler and Reif in 1980 [5]. They abandoned the leading particle assumption and treated the cascade in a fully statistical manner. As in the usual exciton model, it was assumed that exciton states compatible with energy conservation can be excited in a transition (so one implicitly assumes that there is mixing between particle-hole states within a given exciton class). But in addition, accessible states were restricted to those that satisfy momentum conservation. To do this the concept of the linearmomentum dependence of state densities was introduced. Our recent work on exciton model angular distributions also uses this picture of the preequilibrium cascade [6,7, 12]. However, the partition function technique used by Madler and Reif to derive the state densities is impractical for numerical computations. In contrast, our approach uses new and computationally tractable methods for determining the state densities with linear momentum.

In section II we describe the general features of preequilibrium angular distributions. Section III discusses state densities with linear momentum, and in Sec. IV we apply these densities in an exciton model to obtain preequilibrium angular distributions and derive Kalbach's parameterization. We also apply the model to analyze experimental nucleon and photonuclear measurements. Our conclusions and an outline of future areas for work are given in Sec. V.

II. GENERAL FEATURES OF PREEQUILIBRIUM ANGULAR DISTRIBUTIONS

Kalbach's work [11] on the systematical properties of angular distributions highlighted a number of features of the measured angular distribution data that must be modeled correctly in applications:

- 1. The shape of a preequilibrium angular distribution has the general form of $\exp(a \cos \theta)$, where a is a parameter that governs the magnitude of the forwardpeaking. Thus, when data is plotted on a logarithmic scale against angle, it exhibits a cosine shape. This functional form for the angular distributions applies (approximately) to all types of reactions, independent of the projectile/ejectile type.
- 2. The a parameter is independent of target mass.
- 3. The *a* parameter is approximately independent of projectile/ejectile mass.
- 4. The *a* parameter, to a good approximation for energies up to 130 MeV, is a function of emission energy, but not incident energy.

Later in Sec. III we show how our model of preequilibrium reactions accounts for many of the above features. Before discussing this model we describe state densities with linear momentum, which play an important role in our derivation.

III. STATE DENSITIES WITH LINEAR MOMENTUM

We have developed two methods for determining state densities with linear momentum. The most useful technique for practical calculations is a statistical approach which leads to a Gaussian solution, described below. Another method, based on a convolution of single-particle and hole densities in momentum space, is fully described in Ref. [6]. The two solutions become numerically equivalent when the number of excitons becomes large [6] (though in practice they are similar even when there are only a few excitons).

The state density with linear momentum can be expressed [7] as the product of a state density in energy space, $\rho(p, h, E)$, and a linear momentum distribution function $M(p, h, E, \mathbf{K})$,

$$\rho(p,h,E,\mathbf{K}) = \rho(p,h,E) \ M(p,h,E,\mathbf{K}), \tag{1}$$

in analogy to the usual partitioning of the angular-momentum state density. It has units of $MeV^{-1}(MeV/c)^{-3}$, is independent of the direction of \mathbf{K} , and yields the energy-dependent state density when integrated over all momenta, $\int \rho(p, h, E, \mathbf{K}) 4\pi K^2 dK = \rho(p, h, E)$. The individual momenta of the particles and holes are oriented in random directions, and the state density with linear momentum counts all configurations which sum to the required total energy and total momentum. The Central Limit Theorem implies that the ensemble of the various particle and hole momenta sum to yield a distribution of total momenta which follows a Gaussian,

$$M(p,h,E,\mathbf{K}) = \frac{1}{(2\pi)^{3/2}\sigma^3} \exp(-K^2/2\sigma^2),$$
(2)

where σ is the momentum cut-off (representing the width of the distribution). The momentum cut-off can be obtained by considering the average-squared value of the exciton momentum projections on the direction of K in a Fermi-gas nucleus, giving

$$\sigma^2 = n \left(\frac{2m\epsilon_{\rm av}}{3}\right),\tag{3}$$

where *m* is the nucleon mass, n = p + h, and ϵ_{av} is the average exciton energy relative to the bottom of the nuclear well. Thus, as *n* increases with more excited particles and holes, the width of the total momentum distribution increases. If the excitation energy is less than the Fermi energy (ϵ_F) and $p \approx h$, then $\epsilon_{av} \approx \epsilon_F$, but in general in an equidistant single-particle model it is given by

$$\epsilon_{av} = \frac{2p(p+1)}{ng} \frac{\rho(p+1,h,\tilde{E})}{\rho(p,h,\tilde{E})} - \frac{\tilde{E}}{n} + \epsilon_F, \qquad (4)$$

with the notation that \tilde{E} denotes the excitation energy relative to the Fermi-level, $\tilde{E} = E - (p - h)\epsilon_F$, and the state densities in Eq. (4) are taken from the equidistant model with finite well-depth restrictions [13].

We highlight in Fig. 1. certain features and uses of these densities. For further details, see the discussions in Refs. [6, 7, 12].

IV. PREEQUILIBRIUM ANGULAR DISTRIBUTIONS

A. Derivation of Kalbach-systematics parameterization

In the exciton model the emission rate from the n^{th} preequilibrium stage containing p particles and h holes, leaving p_r particles and h_r holes in the residual nucleus, is obtained by applying detailed balance. By explicitly conserving linear momentum we obtain an angle-dependent rate for emission with energy ϵ and direction Ω given by

$$\frac{d^2\lambda_n(\epsilon,\Omega)}{d\epsilon d\Omega} = \frac{2\mu\epsilon\sigma_{\rm inv}}{\pi^2\hbar^3} \frac{\rho(p_r,h_r,E-\epsilon_\Omega,\mathbf{K}-\mathbf{k}_\Omega)}{4\pi\ \rho(p,h,E,\mathbf{K})},\tag{5}$$

where for clarity we have omitted model-dependent factors which may be applied to account for the type of ejectile particle [8]. μ is the ejectile reduced mass, and the reaction cross section for the inverse process is σ_{inv} . The composite system total energy and momentum before particle emission are E and \mathbf{K} , respectively, and the residual nucleus energy and momentum after emission are $E - \epsilon_{\Omega}$ and $\mathbf{K} - \mathbf{k}_{\Omega}$, respectively, all these quantities being measured relative to the bottom of the nuclear well. The energy and momentum of the emitted particle relative to the bottom of the nuclear well are $\epsilon_{\Omega} = \epsilon + B_{em} + \epsilon_F$ and k_{Ω} , where $|k_{\Omega}| = \sqrt{(2\mu\epsilon_{\Omega})}$, B_{em} being the emission particle separation energy. Momentum, like energy, is not transferred to the whole residual nucleus; rather, it is carried solely by the excited particles and holes. The forward-peaked angular variation for a given emission energy follows directly from the variation of $\rho(p_{\tau}, h_{\tau}, E - \epsilon_{\Omega}, \mathbf{K} - \mathbf{k}_{\Omega})$ with angle Ω in Eq. (5). This in turn follows from the inclusion of Fermi-motion and Pauli-blocking in the state-densities, and ignores deviations from center-of-mass isotropy in nucleon-nucleon scattering. During the preequilibrium cascade our model assumes that particle-hole states can be populated providing that both energy and momentum are conserved, and the memory of the initial projectile direction is not maintained solely by a fast leading-particle, but rather it is carried by both the excited particles and the holes.

Following the preequilibrium emission of a particle with momentum k_{Ω} , the squared absolute value of the residual nucleus momentum is

$$|\mathbf{K} - \mathbf{k}_{\Omega}|^2 = K^2 + k_{\Omega}^2 - 2Kk_{\Omega}\cos\theta,$$

where θ is the angle of emission in relation to the projectile direction. This residualnucleus momentum appears in the state density in the numerator of Eq. (5) and accounts for the angular-dependence of the emission rate. Since the cross section for emission is proportional to the emission rate, we obtain from Eqs. (1-5)

$$\frac{d^2\sigma_n(\epsilon,\Omega)}{d\epsilon d\Omega} = \frac{d\sigma_n(\epsilon)}{d\epsilon} \frac{1}{4\pi} \frac{2a_n}{e^{a_n} - e^{-a_n}} \exp(a_n \cos\theta), \tag{6}$$

where $d\sigma_n(\epsilon)/d\epsilon$ is the nth-stage angle-integrated exciton model cross section, the pre-exponential factor arises from the normalization conditions, and

$$a_n = \frac{3Kk_\Omega}{2n_r m\epsilon_{\rm av}},\tag{7}$$

where $n_r = p_r + h_r$. The total preequilibrium emission is a sum of the above contributions for all preequilibrium stages. Conservation of linear momentum, and hence angle-energy correlation, is maintained for all orders of scattering. As would be expected, the forward-peaking increases with incident and emission energy, and decrease with increasing n as the incident momentum is shared among more particles and holes. Eq. (6) has exactly the same functional form that Kalbach used to describe the preequilibrium angular distributions. While the Kalbach-systematics formula is of the same functional form as our result, her expression applies to the full preequilibrium spectrum whereas ours applies to each preequilibrium stage component. The variable "a" that she parameterized by comparisons with many measurements can be understood as an averaged value of our a_n over all preequilibrium stages.

Our model also provides a framework for understanding previously-unexplained features of the systematic behavior of angular distributions, as enumerated in Sec. II:

- 1. The angular variation as an exponential in $\cos \theta$ results from the Gaussian accessible phase space, and the vector addition of momenta using the cosine formula. Our model therefore explains the general shape of measured continuum angular distributions [11] and its applicability to various projectile and ejectile types.
- 2. The independence of the angular distribution on target mass mass naturally out of our equations, since the momentum cut-off (unlike the spin cut-off) is independent of A.
- 3. The independence of a on projectile and ejectile mass is harder to show exactly, though possible explanations can be easily seen. In the case of composite projectiles, the increased number of excitons in the initial state due to cluster fragmentation approximately cancels the extra incident momentum. As for ejected clusters, models such as the pickup cluster model of Iwamoto and Harada include extra nucleons participating in the pick-up mechanism which again increases n. We hope that future developments of our model may account for this effect more quantitatively.

4. The (approximate) independence of Kalbach's a parameter on incident energy below 130 MeV arises because of the approximate canceling of the incident energy dependence in our expression for a_n with the increasing number of preequilibrium stages (each with successively flatter angular distributions) that contribute.

There are similarities between our model and exciton models which use the Kikuchi-Kawai angular kernel (see Fig. 1). If instead of using our Gaussian (statistical) solution, the state densities with linear momentum are determined in a Fermi-gas by convoluting single-particle densities while conserving energy and momentum, the Kikuchi-Kawai result follows for 1-step scattering [7]. But our result for multistep scattering differs from a convolution of Kikuchi-Kawai kernels since we do not make a leading-particle assumption. We showed in Ref. [7] that the Gaussian solution approximates the exact Fermi-gas result very well even when the number of excitons is small. We are further encouraged to use the Gaussian solution since Reffo and Herman [14] found that a Gaussian angular momentum distribution described shell-model with BCS pairing calculations well, even when there are just two excitons.

B. Comparison with Measurements

We compare angular distributions predicted by our linear-momentum conserving exciton model with a sample of experimental measurements for nucleon reactions, where the reaction mechanism is well established. Even though our model includes the quantum phenomena of Fermi-motion and Pauli-blocking, it does not account for other quantum effects such as refraction and diffraction from the nuclear potential, and finite-size effects. At low incident energies these have been shown to be important for obtaining sufficient backward-angle emission [2-4, 15], and result in a flatter angular distribution. A simple applications-oriented way to account for these effects is to modify a_n in Eq. (7) so that it is decreased by an energy-dependent parameter ζ . Writing a_n in terms of channel energies we then obtain for nucleon reactions

$$a_n = \frac{3\sqrt{(\epsilon_{\rm in} + B_{\rm in} + \epsilon_F)(\epsilon + B_{\rm em} + \epsilon_F)}}{\zeta \ (n-1)\epsilon_{\rm av}},\tag{8}$$

and we take the Fermi-energy as 35 MeV. By analyzing a few experimental data sets we have found that the simple parameterization $\zeta = max(1, 9.3/\sqrt{\epsilon})$, with ϵ in MeV, works fairly well up to 80 MeV. This factor tends to 1 for the higher emission energies where the quantum effects become small, and increases to 2 at 20 MeV. Above 80 MeV, contributions from multiple preequilibrium processes can be significant, and while our model can be generalized to describe such processes, a more involved treatment is needed. It can also be straightforwardly extended to include a distinguishing of neutron and proton excitations in a two-component formalism.

We calculate exciton model cross sections using the GNASH [16] code and analyze three different preequilibrium reactions which span a range of energies and nucleon projectile and ejectile types. In Fig. 2 we show calculated angular distributions compared with experimental data of Galonsky *et al.* [17], for the 45-MeV induced 90 Zr(p, n) reaction. Contributions from various preequilibrium stages are indicated for a 20 MeV emission energy. The forward-peaking is seen to decrease for higher-stage preequilibrium emission. Our model is compared with the 80-MeV induced 90 Zr(p, p') reaction measured by Cowley *et al.* [18] in Fig. 3 and the 26-MeV induced 93 Nb(n, n') reaction measured by Marcinkowski *et al.* [19] in Fig. 4, and is seen to account for the experimental data well.

C. Photonuclear Reactions

There is a great deal of interest at Livermore, and at other laboratories, to develop photonuclear cross section libraries. Such libraries will be of importance to a range of new applications including modeling the impact of secondary (contamination) neutrons produced in photon cancer radiation therapy accelerators; and detecting the presence of nuclear materials. Ref. [20] describes recent progress at Livermore and Los Alamos in the modeling of these processes.

Our model describes the photonuclear absorption as a giant resonance excitation at low energies, and a quasideuteron mechanism at higher energies. In the case of the quasideuteron regime, the initial interaction produces particle-hole excitations and initiates a preequilibrium cascade. We follow Blann's prescription of treating the initial configuration as a 2p-1h state, to account for correlations in the two hole's degrees of freedom. We use an exciton model to describe the preequilibrium emission of fast nucleons.

There are virtually no experimental measurements of the angular distributions of emitted nucleons, for reactions induced by monoenergetic photons with incident energies in the range 40 - 140 MeV. Also, Kalbach did not include photonuclear processes in her systematics work. Our model for angular distributions can be easily applied in this case, using the above formulae. In comparison to nucleon-induced reactions, photonuclear preequilibrium emission would be expected to be less forwardpeaked due to the small momentum that a photon carries. In Fig. 5. we show the calculated energy spectra of neutrons in the reaction $^{208}Pb(\gamma, xn)$, for 140 MeV photons, for a variety of emission angles. In Fig. 6 we show the calculated emission spectra at just one angle, 67 degrees, for a 70 MeV incident photon energy. Our results agree well with experimental "difference" bremsstrahlung data for incident photons in the range 55-85 MeV.

V. SUMMARY AND FUTURE DIRECTIONS

Our model accounts for many features of observed continuum angular distribution: the angular shape as an exponential in $\cos \theta$ that is seen for all projectile/ejectile types up to several hundreds of MeV; the target-mass independence, and we give a theoretical prediction for the *a*-parameter which governs the degree of forward-peaking. The model is straightforward to apply computationally since the usual exciton model can be used for the angle-integrated cross section, and describes measurements well when modifications which approximate quantum finite-size and refraction effects are included.

The Kalbach systematics will remain an invaluable tool for predicting angular distributions in evaluation work since they work well, are computationally straightforward to apply, and they are fairly comprehensive in describing most projectile/ejectile types of interest in applications. On the other hand, we believe that our theoretical model may be useful for nuclear model calculations and evaluations since: (a) it is grounded in theory and explains many features of the phenomenological systematics; (b) it can be applied to reactions not considered by Kalbach, for instance photonuclear reactions in the quasideuteron regime; and (c) the model provides a different angular distribution for each preequilibrium step of the reaction and includes the physically-expected behavior of a decrease in forward-peaking as the system moves towards equilibrium.

We gave a preliminary parameterization of the ζ parameter which approximates the quantum finite-size and refraction effects. As a next step we intend to analyze a larger body of data to better determine this parameter and improve the predictive power of our model.

VI. ACKNOWLEDGMENTS

We gratefully acknowledge useful discussions with J. Akkermans, M. Blann, C. Kalbach-Walker, and A. Kerman. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, and under the International Atomic Energy Agency contract No. 8002/CF.

Properties of State Densities with Linear Momentum



Fig. 1. Features of state densities with linear momentum. For a detailed discussion see Chadwick and Oblozinsky *Phys Rev* C46, 2028 (1992); for link with Bethe-Peierls photonuclear phase space see *Phys Rev* C44, 814 (1991); for link with Kikuchi-Kawai result, see *Phys Rev* C44, R1740



Figure 2: Calculated angular distribution of 20 MeV neutrons in the 45 MeV 90 Zr(p, n) reaction compared with experimental data of Galonsky. Contributions from different preequilibrium stages are shown, 2p1h being the initial stage.



Figure 3: Calculated angular distributions in the 80 MeV 90 Zr(p, p') reaction compared with experimental data of Cowley.



Figure 4: Calculated angular distributions in the 26 MeV $^{93}Nb(n, n')$ reaction compared with experimental data of Marcinkowski.



Figure 5: GNASH Model calculations of the photoneutron emission spectra at various angles in the 208 Pb (γ, xn) reaction, for an incident photon energy of 140 MeV.



Figure 6: GNASH Model calculation of the 67degrees photoneutron spectrum at $E_{\gamma}=70$ MeV in the ²⁰⁸Pb(γ, xn) reaction, compared to measurements of difference neutrons from a bremsstrahlung beam of photons with energies between 55 and 85 MeV.

REFERENCES

- Sun Ziyang, Wang Shunuan, Zhang Jingshang, Zhou Yizhong, Z. Phys. A305, 61 (1982).
- [2] C. Costa, H. Gruppelaar, and J.M. Akkermans, Phys. Rev. C28, 587 (1983).
- [3] A. Iwamoto and K. Harada, Nucl. Phys. A419, 472 (1984).
- [4] M. Blann, W. Scobel, and E. Plechaty, Phys. Rev. C 30, 1493 (1984).
- [5] P. Madler and R. Reif, Nucl. Phys. A 337, 445 (1980).
- [6] M.B. Chadwick and P. Obložinský, Phys. Rev. C 44, R1740 (1991)
- [7] M.B. Chadwick and P. Obložinský, Phys. Rev. C 46, 2028 (1992)
- [8] E. Gadioli and P.E. Hodgson, Pre-equilibrium Nuclear Reactions (Clarendon Press, Oxford, 1992).
- [9] H. Feshbach, Phys. Rev. C 48, R2553 (1993).
- [10] K. Kikuchi and M. Kawai, Nuclear Matter and Nuclear Reactions (North-Holland, Amsterdam, 1968), p. 44; M.L. Goldberger, Phys. Rev. 74, 1269 (1948).
- [11] C. Kalbach, Phys. Rev. C 37, 2350 (1988).
- [12] M.B. Chadwick and P. Obłožinský, Phys. Rev. C (1994, in print).
- [13] F.C. Williams, Nucl. Phys. A166, 231 (1971); E. Betak and J. Dobes, Z. Phys. A 279, 319 (1976).
- [14] G. Reffo and M. Herman, Nuovo Cimento Lett. 34, 261 (1982).
- [15] K. Sato, Phys. Rev. C32, 647 (1985).
- [16] P.G. Young, E.D. Arthur, and M.B. Chadwick, Los Alamos National Laboratory Report No. LA-12343-MS (1992).
- [17] A. Galonsky, R.R. Doering, D.M. Patterson, and H.W. Bertini, Phys. Rev. C14, 748 (1976).
- [18] A.A. Cowley, A. van Kent, J.J. Lawrie, S.V. Fortsch, D.M. Whittal, J.V. Pilcher, F.D. Smit, W.A. Richter, R Lindsay, I.J. van Heerden, R. Bonetti, and P.E. Hodgson, Phys. Rev. C43, 678 (1991).
- [19] A. Marcinkowski, R.W. Finlay, G. Randers-Pehrson, C.E. Brient, R. Kurup, S. Mellema, A. Meigooni, and R. Taylor, Nucl. Sci. Eng. 83, 13 (1983).
- [20] M.B. Chadwick and P.G. Young, "Photonuclear reactions in the GNASH code: Benchmarking model calculations for reactions on lead up to 140 MeV", Lawrence livermore National Laboratory document (in preparation, 1994).

Gamma-ray Strength Function Models and Their Parameterisation

M. Uhl

Institut für Radiumforschung und Kernphysik, University of Vienna, Austria

J Kopecky

Netherlands Energy Foundation ECN, Petten, The Netherlands

<u>Abstract</u>: An upgraded compilation of experimental E1- and M1 strength functions resulting from the analysis of discrete resonance data is presented The dependence of these strength functions on the mass number can be described by simple expressions

We further study the impact of models for gamma-ray strength functions f_{XL} on the calculation of capture cross sections and related quantities For M1 and E2 radiation we employ strength functions derived from a standard Lorentzian with a global set of parameters For the dominant E1 strength, however, individual Lorentzian parameters derived from photoabsorption data are used as far as possible Besides the standard Lorentzian we apply for f_{E1} also a generalised Lorentzian, which is characterised by an energy dependent width and a finite limit as the energy tends to zero. In the mass region A=100-200 a standard Lorentzian for f_{E1} works only for strongly deformed nuclei. For these nuclei the generalised Lorentzian, which reasonably reproduces the data for many spherical and transitional nuclei in this mass region, fails In order to obtain an E1 strength function model for the whole mass region we propose an "enhanced generalised Lorentzian" with two parameters depending rather smoothly on the mass number

1 Introduction

The gamma-ray strength function for multipole type XL is defined as the average reduced partial radiation width $\varepsilon_{v}^{-(2L+1)}\langle\Gamma_{\chi L}(\varepsilon_{v})\rangle$ per unit energy interval

$$f_{\underline{v}\underline{\iota}}\left(\varepsilon_{\gamma}\right) = \varepsilon_{\gamma}^{-(2L+1)} \langle \Gamma_{\underline{v}\underline{\iota}}\left(\varepsilon_{\gamma}\right) \rangle / D$$

of resonances with average spacing D; ε_{1} is the transition energy The corresponding gamma-ray transmission coefficient $T_{12}(\varepsilon_{1})$ is given by the relation

$$T_{\lambda L}(\varepsilon_{r}) = 2 \pi \varepsilon_{r}^{2L+1} f_{\lambda L}(\varepsilon_{r})$$

Therefore gamma-ray strength functions enter as important ingredients into compound nucleus model calculations of capture cross sections, gamma-ray production spectra, isomeric state populations and into the assessment of the competition between gamma-ray and particle emission. The relevant multipolarities in this context are E1, M1 and E2

In this contribution we test strength function models by comparison to various experimental data related to neutron capture Cross sections and spectra depend on the gamma-ray strength at all transition energies but do not differentiate between multipolarities, so they are mainly sensitive to the dominant E1 strength Analysis of resonance transitions allows to determine the multipolarity but the resulting strength functions comprise only a narrow energy region

2 Strength function models

The simplest model for gamma-ray strength functions is the *single particle model* prescribing an energy independent strength [1] We used this model for M2-, E3- and M3 radiation with a strength of 1 Weisskopf unit per MeV

Gamma-ray strength functions may be related to the photoabsorption cross section. If the latter is dominated by a giant resonance (GR) of Lorentzian shape Brink's hypothesis [2] leads to a strength function derived from a *standard Lorentzian* (SLO)

$$f_{\rm YL}^{SLO}(\varepsilon_{\gamma}) = \frac{26 \times 10^{-8} \left[mb^{-1} MeV^{-2} \right]}{2L+1} \sigma_0 \Gamma_0 \frac{\varepsilon_{\gamma}^{3-2L} \Gamma_0}{(\varepsilon_{\gamma}^2 - E_0^2)^2 + \varepsilon_{\gamma}^2 \Gamma_0^2},\tag{1}$$

where the Lorentzian parameters (σ_0, E_0, Γ_0) respectively stand for peak cross section, energy and width of the GR We used this model for E1, M1 and E2 radiation For E1 the Lorentzian parameters were taken from

the analysis of the photoabsorption cross section [3] of the compound or a neighbouring nucleus. Global parameters were employed for M1 and E2 radiation. i) an M1 spin-flip resonance as proposed by Bohr and Mottelson [4] with $E_0 = 41A^{-1/3}(MeV)$, $\Gamma_0=4(MeV)$ and the peak cross section determined either from experimental data or from the systematics $f_{MI}(7MeV)=1.88A^{1.41} \times 10^{-11} (MeV^{-3})$ [5] u) an (isoscalar) quadrupole GR with $E_0=63A^{-1/3}(MeV)$ [6], $\Gamma_0=(6-0.012A)(MeV)$ [7], and $\sigma_0=1.5\times 10^{-4} Z^2 E_0^2 A^{-1/3} \Gamma_0^{-1} (mb)$ [7].

For the dominant E1 radiation improvements of the SLO based on microscopic theory are available. The theory of Fermi liquids [8] predicts an energy and temperature dependent width of the giant dipole resonance (GDR) $\Gamma(\varepsilon_y, T) = \beta(\varepsilon_y^2 + 4\pi^2T^2)$, where β is a normalisation constant. The first term reflects the spreading of particle hole states into more complex configurations while the second one accounts for collision of quasiparticles. The temperature T refers to the absorbing state and can be calculated within a level density model. Kadmenskij et al. [9] suggested to choose β so as to guarantee compatibility with photoabsorption data

$$\Gamma_{\kappa}(\varepsilon_{r},T) = \frac{\Gamma_{0}}{E_{0}^{2}}(\varepsilon_{r}^{2} + 4\pi^{2}T^{2}).$$
⁽²⁾

The generalised Lorentzian (GLO), as proposed by Kopecky and Chrien [10], consists of two terms a Lorentzian with the energy dependent width according to Eq. (2) and the (non-zero) $\varepsilon_{\gamma} \rightarrow 0$ limit of the model of Kadmenskij et al. [9]

$$f_{E_{1}}^{GLO}(\varepsilon_{\gamma},T) = 8.68 \times 10^{-8} \left[mb^{-1} MeV^{-2} \right] \sigma_{0} \Gamma_{0} \left\{ \frac{\varepsilon_{\gamma} \Gamma_{\kappa}(\varepsilon_{\gamma},T)}{(\varepsilon_{\gamma}^{2} - E_{0}^{2})^{2} + \varepsilon_{\gamma}^{2} \Gamma_{\kappa}^{2}(\varepsilon_{\gamma},T)} + 0.7 \frac{\Gamma_{\kappa}(\varepsilon_{\gamma} = 0,T)}{E_{0}^{3}} \right\}.$$
 (3)

Up to an energy around the neutron binding energy the E1 strength resulting from Eq. (3) and that from the model of Kadmenskij et al [9] are very similar. In Ref 11 we showed for some selected spherical nuclei that the GLO model provides a reasonable simultaneous description of average resonance capture (ARC) data, capture cross sections and gamma-ray production spectra To reproduce also data for strongly deformed nuclei we proposed in Refs 12-14 to use in Eq. (3) instead of $\Gamma_{\kappa}(\varepsilon_{\nu}, T)$ the following *empirical* generalisation of the energy dependent width

$$\Gamma_{En}(\varepsilon, T) = \left[k_0 + (1 - k_0)\frac{\varepsilon_{\gamma} - \varepsilon_0^{\gamma}}{E_0 - \varepsilon_0^{\gamma}}\right]\Gamma_K(\varepsilon_{\gamma}, T), \qquad (4)$$

which is determined by two parameters (k_0, ε_0^r) For $k_0 > 1$ the width is enhanced compared to the result of Eq (2) In that case the resulting E1 strength

$$f_{E1}^{EGLO}(\varepsilon_{r},T) = 8.68 \times 10^{-8} \left[mb^{-1} MeV^{-2} \right] \sigma_{0} \Gamma_{0} \left\{ \frac{\varepsilon_{r} \Gamma_{En}(\varepsilon_{r},T)}{(\varepsilon_{r}^{2} - E_{0}^{2})^{2} + \varepsilon_{r}^{2} \Gamma_{En}^{2}(\varepsilon_{r},T)} + 0.7 \frac{\Gamma_{En}(\varepsilon_{r}=0,T)}{E_{0}^{3}} \right\}$$
(5)

is denoted as derived from an *enhanced generalised Lorentzian* (EGLO) The enhancement k_0 can be used to reproduce the experimental E1 strength around the reference energy ε'_0 Note, that i) for $k_0=1$ the GLO model results and ii) $\Gamma_{E_0}(\varepsilon_x \to E_0, T \to 0) \to \Gamma_0$, i e. compatibility with photoabsorption is maintained.

For nuclei with a split GDR we used in Eqs. (1), (3) and (5) the incoherent sum of two analogue terms, the same parameters (k_0, ε_0) for each term were used in Eqs. (4) and (5). For targets with A=175-205 and for ⁹³Nb we included a SLO pygmy resonance with parameters determined by fitting the high-energy end of the gamma-ray production spectrum

3 E1- and M1 strength functions from resonance transitions

The compilation of E1- and M1 strength functions presented in Ref 5 has been upgraded More nuclei were considered. The corrections for non-statistical contributions are revised The uncertainty of the average resonance spacing is assessed and the absolute calibration of the partial radiation width is discussed. Detailed results will be presented at an "IAEA Specialists' Meeting" in November 1994 [15] Here we only show in Figs 1 and 2 preliminary results for f_{E1} and f_{M1} plotted against the mas number together with simple fit formulas

E1 - Strength functions



Fig. 1 Experimental E1 strength functions and fit formula in terms of the mass number A

4 Model calculations of cross sections and spectra

For the calculation of neutron capture cross sections and the resulting gamma-ray spectra we employed the Hauser-Feshbach theory in the formulation of Moldauer [16] and an appropriate treatment of gamma-ray cascades The calculations were performed with the code MAURINA [17]

In the mass and energy region considered (A>100, $E_n < 3$ MeV) charged particle emission can be neglected Neutron optical potentials were taken from the literature and eventually slightly modified in order to improve the reproduction of total cross sections and (neutron) strength functions. For strongly deformed nuclei the neutron transmission coefficients were generated by coupled channels calculations.

For the **level density**, characterising the excited states beyond the known levels, we used semi-empirical models with parameters relying on recent results for the average spacing of s-wave resonances D_0 and the number of low excited levels N_{lev} . For all nuclei calculations were performed employing the *backshifted Fermi gas model* (BSFG) [18] and the model by *Kataria, Ramamurthy and Kapoor* (KRK) [19] which accounts for shell effects in terms of the ground-state shell correction to the nuclear binding energy. The genuine KRK model is supplemented according to the Gilbert Cameron prescription [20]: a conventional pairing shift and a *constant temperature portion* at lower excitation energy where the spin distribution parameter σ^2 is linearly interpolated between the value σ_{lev}^2 deduced from the levels and $\sigma^2(E_x)$, the value prescribed by the KRK model at the matching energy E_x . For comparisons we used in some cases also a more sophisticated level density model -the generalised superfluid model in its phenomenological version (GSFPH) - which was developed by Ignatyuk and collaborators [21-23]. This model accounts for shell effects, pairing (employing the BCS approach) as well as for collective enhancement with empirical prescriptions for its damping. For each model the respective parameters are chosen so as to reproduce the same values D_0 and N_{lev} ; in case of the GSFPH model this was achieved by an additional shift of the excitation energy as proposed in Ref. 22

When employing a particular level density model we used the pertinent temperature T also in the expressions for the gamma-ray strength functions according to the models GLO and EGLO (see Eqs 2-5) Under these conditions the E1 strength depends on the level density model employed In case of the KRK model we use the genuine temperature prescription also in the constant temperature region

M1 - Strength functions



Fig. 2 Experimental M1 strength function and fit formula in terms of the mass number A

5 Results

As continuation of a previous investigation in the mass region A=140-200 [24] we study here nuclei with 100 < A < 200. For the targets considered at least two pieces of the following experimental information exists average s-wave radiation widths, capture cross section excitation functions and gamma-ray production spectra. We evaluate E1 strength function models by comparing the results of model calculations to these data. We plan to include in future more nuclei with A<140. The results obtained so far can be summarised as



Fig. 3 The capture cross section of 189 Os calculated with different models for the E1 strength The underlying level densities are calculated according to the KRK model (a,b) and the BSFG model (c,d)

follows

i) In general the results of model calculations strongly depend on the level density model employed. For incident energies low enough, so that only the level density of the product nucleus enters, the BSFG model produces larger cross sections and average radiation width. This effect increases with the neutron separation energy and impedes the evaluation of E1 strength function models. This is illustrated in Fig. 3 for the transitional nucleus ¹⁸⁹Os. The capture cross sections are reasonably well reproduced with an E1 strength according to the GLO model and the BSFG model for the level density (Fig. 3c). With the KRK level density, how-



Fig. 4 The gamma-ray production spectrum for 159 Tb(n, γ) calculated with 3 models for the E1 strength The level density models are KRK (a) and BSFG (b)

ever, a description of the data requires the EGLO model with parameters $(k_0 = 1.8, \varepsilon_0^{v} = 4.5 MeV)$ (Fig. 3b)

ii) For strongly deformed nuclei with masses between 150 and 165 we confirmed earlier results for some Gd and Eu isotopes [12]. The GLO model for the E1 strength fails to reproduce the experimental data A reasonably good description is either achieved with the SLO model or the EGLO model with an enhancement $k_a > l$, the actual value depending on the level density model employed. For ^{155,156,157}Gd these results are also directly confirmed by experimental E1 strength functions deduced from average resonance capture data [25]. As an illustration for the model calculations we display in Fig. 4 the gamma-ray production spectrum for 159 Tb(n, γ) at E_n=0.5 The enhancement parameters for the MeV EGLO model (k_0, ε_0^r) required to reproduce the data are indicated on the plots. The failure of the

GLO model does not hold to the same extent for all deformed nuclei. For some isotopes of W and Re a quite reasonable reproduction of cross sections and spectra can be achieved with this model for the E1 strength

in) For transitional and spherical nuclei at the lower and the upper end of the mass region A=100-200 the SLO model in general fails to reproduce the data. The GLO model is reasonably successful but for many nuclei the EGLO model is required. The enhancement, however is considerably lower than for A=150-165. Further we observed that for several targets it is impossible to simultaneously reproduce the capture excitation function and the average total s-wave radiation width This may be either due to valence contributions favoured by the 4s maximum of the neutron strength function [26] and/or inaccuracies in the average spacing D_0 determining the level density parameters.



Fig. 5 The enhancements k_0 plotted against the mass number of the compound nucleus They are extracted from calculations employing the KRK (a) and the BSFG model (b) for the level densities

iv) Neither the SLO nor the GLO model can be used for model calculations in the whole mass region. The flexible EGLO model could do the job if its parameters $(k_0, \varepsilon_0^{\prime})$ show a sufficiently smooth behaviour, so that it can be applied for cross section predictions. For a fixed reasonable value of the reference energy, namely $\varepsilon_0^{\prime} = 45 MeV$, we therefore determined for all nuclei considered the enhancement k_0 by simultaneously reproducing at least two pieces of experimental data. This was done by graphical comparisons between experimental data and the results obtained with different k_0 values as illustrated in Figs. 3b and 3c In this context we allowed for k_0 also values moderately smaller than 1. Because of the strong dependence of the results on the level density model we had to do this separately for the KRK and the BSFG model. The derived k_0 values only weakly depend on the reference energy ε_0^{y} ; some test calculations indicated that a change of 1 MeV affects k_0 only by a few percent. The enhancements found in this way are displayed in Fig. 5 as function of the mass number of the compound nucleus. The error bars reflect uncertainties of the experimental data and the spacing D_0 as well as inconsistencies between the enhancements required for different types of data; they were found by rather rough assessments and not by detailed sensitivity studies. The trend of the enhancements can be described as a function of the mass number A by simple *purely empirical* expressions as e g

$$k_{0}(x) = 15 \qquad \text{for } A \le 145$$

= 1.5 + 0 131(A - 145)² exp[-0 154(A - 145)] for A \ge 145 (6a)

for the KRK model and

k

$$for \ A \le 148$$

= 1.0 + 0.090(A - 148)² exp[-0.180(A - 148)] for \ A \ge 148 (6b)

for the BSFG model, receptively. The expressions are actually the same as in Ref 24; the constants may change when we consider more nuclei with A<140 Fig. 6 displays calculated average s-wave radiation width and the experimental value for the nuclei considered for the determination of k_0 and some more. For the calculations we employed the EGLO model with the enhancement k_0 according to Eq. (6a) or (6b)



Fig. 6 The calculated average s-wave radiation width and the corresponding experimental value The calculations employ the EGLO model for the E1 strength with k_0 values according to Eqs (6a) and (6b), depending on the level density models employed, i.e. the KRK model (a) and the BSFG model (b)

6 Discussion

The enhancements k_o derived from the above named experimental data in the frame of the EGLO model show a clear dependence on the mass number A with a peaking between A=150 and 165. Though the individual values scatter considerably we hope that the systematics of k_o given Fig. 5 can be used for cross section predictions. This is illustrated by the reasonable reproduction of the total average radiation width in Fig. 6 by means of the simple empirical relation Eqs. (6) Note, that each k_o systematics is connected with a particular level density model.

The scatter of the individual enhancements is at least in part caused by the uncertainties of the various input data. In addition to the ingredients mentioned before the deduced E1 enhancements also depend on the M1 strength employed. In general M1 radiation contributes only 10 to 20% to the radiative width or the capture cross section and so our often global assessments of its strength is in general of moderate influence on the deduced trend of the enhancements. Special caution, however, deserve strongly deformed nuclei where an isovector collective M1 excitation ("scissors mode") can be observed e. g. in inelastic electron scattering or nuclear resonance fluorescence [27,28]. If Brink's hypothesis [2] holds also for the scissors mode it is conceivable that it apparently contributes to the enhancement of the E1 strength deduced for deformed nuclei from cross sections and related quantities. But we emphasise, that for the targets ^{155,157,158}Gd the E1 enhancement is confirmed by average resonance capture data [25] for which, in contrast to cross sections and spectra the, E1- and M1 contributions can be separated. Moreover, a SLO scissors mode contribution to the M1 strength with parameters based on a theoretical assessment should lead for the target 155 Gd to a low energy peak around an emission energy of 3 MeV [25] in the gamma-ray spectrum which is not confirmed by experimental data. On the other hand, we recently learned that a group in Prague [29] found preliminary evidence for a scissors mode in the analysis of two-step gamma-ray cascades following thermal neutron capture in 162 Dy. As these data are more sensitive than the total gamma-ray spectra the problem of a possible M1 scissors mode contribution to our observed E1-strength enhancements should be kept in mind.

The strong dependence of the extracted E1 enhancement parameter k_0 on the level density model employed is not very satisfying. It probably represents the price for using too simple formulas which both may fail to describe the energy dependence of the level density. We therefore compare for some representative cases the results obtained with KRK - and BSFG level densities to those employing the more advanced GSFPH model The dependence of the cross sections on the level density model stems from two sources: 1) the temperature entering into the E1 strength functions and ii) the level density itself determining the number of final states in the Hauser-Feshbach formula. In Fig. 7 we compare for 106Pd, 158Gd and 197Au the E1 strength functions according to the EGLO model with an enhancement k_0 compromising between the requirements of the KRK - and the BSFG model as well as the level densities summed over those spin values



Fig. 7 The E1 strength functions (a-c) for a given initial energy E-INIT and level densities (d-f) for 106 Pd, 158 Gd and 198 Au, respectively, calculated with three level density models (see text)

populated by s-wave capture under consideration of dipole radiation only. Figs. 7a-c show that due to the different temperatures at a given excitation energy the EGLO strength for the BSFG - is considerably larger than for the KRK - and comparable to that resulting from the GSFPH model; for ¹⁹⁸Au the effect of the pygmy resonance is visible. The summed level densities for ¹⁰⁶Pd and ¹⁵⁸Gd (Figs. 7d and e) show, that in the excitation energy region relevant for the capture cross sections considered her, BSFG results in larger values than KRK (actually its constant temperature region). These results that are typical for many targets are

less pronounced for ¹⁹⁸Au (Fig 7f). For ¹⁰⁶Pd and ¹⁵⁸Gd and to a lesser extent for ¹⁹⁸Au the more sophisticated GSFPH model supports the energy dependence of the level density resulting from the BSFG model. The somewhat deviating behaviour of ¹⁹⁸Au may be related to the large negative shell correction energy due to the nearby major (Z=82, N=126) shell closure.



Fig. 8 The neutron capture cross sections for 105 Pd (a), 156 Gd (b) and 197 Au (c) calculated with three models for the level densities (see text)

Fig 8 displays the neutron capture excitation functions for 105 Pd, 157 Gd and 197 Au calculated with the EGLO model for the E1 strength and the enhancements indicated in Figs 7a-c. The underlying level densities result from the BSFG -, KRK- and GSFPH model. The shape of the excitation functions only weakly depends on the level density model employed. The difference in magnitude of the cross sections represents the combined effect of the temperature dependence of the E1 strength according to the EGLO model and the level density itself as illustrated in Fig. 7. These examples also illustrate why in general the enhancements k_0 required to reproduce the data are considerably larger for the KRK - than for the BSFG model. The results obtained with the GSFPH model are closer to those with BSFG model; for 105 Pd and 157 Gd the difference in the cross sections is quite small.



Fig 9 The gamma-ray production spectrum resulting from neutron capture in 157 Gd (a), 159 Tb (b) and 197 Au (c) calculated with three models for the level density (see text)

A comparison of the gamma-ray spectra for ¹⁵⁷Gd, ¹⁵⁹Tb and ¹⁹⁷Au obtained under the same conditions as the aforementioned excitation functions is displayed in Fig 9 Note, that the experimental data for ¹⁵⁷Gd and ¹⁵⁹Tb by Voignier et al. [30] begin at an emission energy of 1 5 MeV, below that energy the authors extrapolated by a model calculation. The spectra of ¹⁵⁷Gd and ¹⁵⁹Tb (Figs. 9a-b) are quite representative, their shape only weakly depends on the level density model chosen The slope in the central region of emission energies is slightly better reproduced by the KRK model but the effect is marginal The GSFPH - and the BSFG results are very close For ¹⁹⁷Au (Fig. 7c) the best reproduction of the experimental data is achieved with the KRK model, the worst employing the BSFG model. However, because of the large negative shell correction energy and the presence of a pygmy resonance ¹⁹⁷Au is perhaps not very typical. In general neither the shape of excitation functions nor that of gamma-ray spectra critically depend on the underlying level density model.

These preliminary comparisons seem to indicate that the results obtained with the simple BSFG model are closer to those obtained by using the more realistic GSFPH model. However, before concluding that among the two simple models BSFG should be preferred for most nuclei, comparisons as those described before must be performed for a much larger sample of nuclei, this will be done in near future



Fig 10. The spectra of gamma-ray cascades with multiplicity 2 resulting of the capture of 100 keV neutrons in 150 Sm (a), 157 Gd (b) and 197 Au (c) (see text)

Into the calculation of the type of data considered here always enters the product of level densities and gamma-ray strength functions Hence the purely empirical expression Eq. (4) for the enhancement may also afflict conclusions concerning the level density. Therefore the analysis of additional experimental data which depend more critically on the level density model than excitation functions and spectra may prove useful. Preliminary calculations show that the energy distribution of gamma-ray cascades with fixed low multiplicity resulting from neutron capture in the keV region have this property. This is illustrated in Fig. 10 by the spectra of multiplicity-two cascades for the targets ¹⁵⁰Sm, ¹⁵⁷Gd and ¹⁹⁷Au. For each level density model the E1 strength is calculated according to the EGLO model with enhancements chosen to reproduce the capture cross section at an incident energy of 100 keV. The strong dependence of the shape and the intensity (that means the multiplicity distribution) of the spectra is evident. Preliminary experimental data by the Karslruhe group [31] concerning relative spectra with fixed multiplicities support for ¹⁵⁰Sm shapes of the spectra between those obtained with the GSFPH- and the BSFG model. In the case of ¹⁹⁷Au the experimental spectra favour shapes between those resulting from the GSFPH- and the KRK model. As also the multiplicity 2 spectra depend on the E1 strength function model (but hopefully to a lesser extent) one should aim at a simultaneous reproduction of as many different experimental data as possible.

Summarising we may state that the flexible enhanced generalised Lorentzian model (EGLO) for the E1 strength function is useful for the calculation of capture cross sections and related quantities as its parameters exhibit a reasonable smooth behaviour. The required enhancement depends on the level density model employed Therefore a realistic level density model should be used. To this end further comparisons between different level density models are planned. In view of our empirical formulation of the enhancement of the width of the generalised Lorentzian (Eq. 4) a better understanding of the effect and a subsequent theoretical description would be very helpful

Appendix

Here we supply some information on the experimental data used and not quoted in detail. The experimental cross sections and gamma-ray spectra were mostly taken from the EXFOR file and the level data stem from the ENSFD file, both files are available from the OECD Nuclear Energy Agency. We thank Dr Wisshak from the Karlsruhe group for providing us with unpublished preliminary capture cross sections for several Gd isotopes. For the average s-wave resonance spacing we used the compilations of Mughabghab et al. [32] and by Huang Zhongfu [33]. The total average s-wave radiation widths were mostly taken from the compilations of Mughabghab et al [32].

<u>References</u>

- [1] M Blatt and V F Weisskopf, Theoretical Nuclear Physics, p 647, Wiley, New York, (1952)
- [2] D M Brink, Ph D Thesis, Oxford University, (1955)
- [3] S S Dietrich and B L Berman, At Nucl Data Tables 38, 199 (1988)
- [4] A G Bohr and B R Mottelson, *Nuclear Structure*, Vol II, p 636, Benjamin, London, (1975)
- J Kopecky and M Uhl, Proc IAEA Specialists' Meeting on the Measurement, Calculation and Evaluation of Photon Production Cross Sections, Feb 5-7, 1990, Smolenice, (CSFR), p 103, INDC(NDS)-238(1990)
- [6] W V Prestwich, M A Islam, and T J Kennet, Z Phys A315, 103 (1984)
- [7] J Speth and A van der Woude, Rep Progr Phys 44, 719 (1981)
- [8] D Pines and D Nozier, The Theory of Quantum Liquids, Benjamin, New York (1966)
- [9] S G Kadmenskij, V P Markushev, and V I Furman, Sov J Nucl Phys 37, 165 (1983)
- [10] J Kopecky and R E Chrien, Nucl Phys A468, 285 (1987)
- [11] J Kopecky and M Uhl, Phys Rev C41, 1941 (1990)
- [12] J Kopecky and M Uhl, Proc Seventh Intern Symposium on Capture Gamma-ray Spectroscopy and Related Topics, Oct 14-19, 1990, Asilomar, USA, edited by R W Hoff, AIP Conf Proc No 238, p 607, AIP, New York, (1991)
- [13] M Uhl and J Kopecky, Proc Int Conf Nuclear Data for Science and Technology, May 13-17, 1991, Julich, Germany, edited by S M Qaim, p 977, Springer Verlag, Berlin/Heidelberg (1992)
- [14] J Kopecky, M Uhl, and R E Chrien, Phys Rev 47, 312 (1993)
- [15] J Kopecky "Present Status of the Experimental Gamma-Ray Strength Functions" to be presented at the Specialists' Meeting on Measurement, Calculation and Evaluation of Photon Production Data, 9-11 Nov 1994 in Bologna, Italy
- [16] P A Moldauer, Nucl Phys A344, 185 (1980)
- [17] M Uhl (unpublished)
- [18] W Dilg, W Schantl, H Vonach and M Uhl, Nucl Phys A217, 269 (1973)
- [19] SK Kataria, VS Ramamurthy, and SS Kapoor, Phys Rev C18, 549 (1978)
- [20] A Gilbert and A G W Cameron, Can J Phys 43, 1446 (1965)
- [21] A V Ignatyuk, K K Istekov, and G N. Smirenkin, Sov J Nucl Phys 29, 450 (1979)
- [22] O T Grudzevich, A V Ignatyuk, V I Plyaskin, and A V Zelenetsky, Proc Int Conf Nuclear Data for Science and Technology, May 30 - June 3, 1988 Mito, Japan, edited by S Igarasi, p 187, Saikon, Japan (1988)
- [23] A V Ignatyuk, Proc Int Symposium on Nuclear Data Evaluation Methodology, 12-16 Oct 1992, Brookhaven National Laboratory, Upton, New York, p 411, World Scientific, Singapore (1993)
- [24] M Uhl and J Kopecky, Proc Int Conf Nuclear Data for Science and Technology, Gatlinburg, Tennessee, 9-13 May 1994, in press
- [25] J Kopecky, M Uhl, and R E Chrien, Distribution of radiative strength in Gd-156, 157, and 158 nuclei, Rept ECN-RX--92-011 (1992)
- [26] J Kopecky and M Uhl, [23] p 381
- [27] D Zawischa, M Macfarlane, and J Speth, Phys Rev C42, 1461 (1990)
- [28] A Richter, Nucl Phys A522, 139 (1991)
- [29] F Becvar and P Cejnar, private communication, (1994)
- [30] J Voignier, S Joly, and G Grenier, Nucl Sci Eng 93, 43 (1986), 96, 343 (1987)
- [31] K Wisshak, private communication (1992)
- [32] SF Mughabghab, M Divadeenam, and NE Holden, Neutron Cross Sections (Academic, New York), Vol 1, Part A and B
- [33] Huang Zhongfu, Com of Nuclear Data Progress, No 9, 60