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Proceedings of the

Sixth AASPP Workshop on Asian Nuclear Reaction Database Development

Hokkaido University, Sapporo, Japan

15 – 17 September 2015

Edited by

Aiganym Sarsembayeva, Bo Zhou
Hokkaido University, Sapporo, Japan

and

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Nuclear Data Section, International Atomic Energy Agency, Vienna, Austria

January 2016

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Abstract

The 6th Workshop on Asian Nuclear Reaction Database Development was held from 15-17 September 2015 at Hokkaido University, Sapporo, Japan. This 6th workshop followed the workshops in Sapporo (Japan, 2010), Beijing (China, 2011), Pohang (Korea, 2012), Almaty (Kazakhstan, 2013) and Mumbai (India, 2014). The workshop was coordinated by the Asian Centre Heads of the International Network of Nuclear Reaction Data Centres and supported by International Atomic Energy Agency. The topics of the workshop were sharing information on activities of the nuclear data centres, EXFOR compilation, data evaluation, computational simulations and other related topics. The participants were attended from Austria, China, India, Japan, Kazakhstan, Korea, Mongolia, United States and Vietnam. In the workshop, 20 presentations were presented and summarized in these proceedings.

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Sep.15 (Tuesday)

09:00-10:00	**Registration**
10:00-10:15	Opening & Welcome Address, Group Photo Prof. Koichiro Ishimori Dean of Faculty of Science, Hokkaido University
Section 1	**Asian Nuclear Data Center Activity** Chairman: V. Semkova/Z. Ge
10:15-10:40	Recently Progress of Nuclear Data Evaluations and Measurements in China Zhigang Ge (China Nuclear Data Center (CIAE))
10:40-11:05	Filtered neutron beam applications at DALAT research reactor Tran Tuan Anh (Nuclear Research Institute)
11:05-11:30	Recent Activities of Nuclear Data Physics Centre of India Pritam Das Krishnani (BARC)
11:30-11:55	International Collaboration of Hokkaido University Nuclear Reaction Data Centre Masayuki Aikawa (Hokkaido University)
11:55-13:20	**Lunch Time**
13:20-13:45	Overview of Compilation to the EXFOR Library in Mongolia Myagmarjav Odsuren (National University of Mongolia)
13:45-14:10	CANRDB: Current activities, issues and prospects Nurgali Takibayev (Al-Farabi Kazakh National University)
14:10-14:35	Nuclear Data Services provided by IAEA-NDS Valentina Semkova (International Atomic Energy Agency)
14:35-15:00	Measurement of Charged particle-, Neutron-, and Photon-induced Reactions in Korea Guinyun Kim (Kyungpook National University)
15:00-15:15	**Break Time**
Section 2	**Nuclear Data Compilation** Chairman: M. Odsuren
15:15-15:40	Recent EXFOR Compilation in CNDC Guochang Chen (China Nuclear Data Center (CIAE))
15:40-16:05	Upgrade of Japanese editor for EXFOR compilation Sarsembayeva Aiganym (Hokkaido University)
16:05-16:30	Recent charged-particle induced reaction data measurements performed in Kazakhstan Nurzat Kenzhebayev (Al-Farabi Kazakh National University)
16:30-16:55	EXFOR Activity in Korea Young-Ouk Lee (Korea Atomic Energy Research Institute)

Sep.16 (Wednesday)

9:00-14:00	**Meeting Activity**
Section 3	**Nuclear Data Evaluation** Chairman: P.D. Krishnani/H. Masui
14:00-14:25	The Application of EMPIRE for Nuclear Data Evaluation of n+238U Guochang Chen (China Nuclear Data Center (CIAE))
14:25-14:50	The evaluations of 208Pb, 207Pb, 206Pb and 204Pb in CENDL-3.1 Xi Tao (China Nuclear Data Center (CIAE))
14:50-15:15	Evaluation of deuteron-induced excitation functions for 186W(d,p)187W and 186W(d,2n)186Re Jimin Wang (China Nuclear Data Center (CIAE))
15:15-15:35	**Break Time**
15:35-16:00	Monte Carlo simulation for thick-target yields deduced from inverse kinematics Shotaro Imai (Hokkaido University)
16:00-16:25	Evaluation of the photoabsorption cross section of few-nucleon systems with time-dependent method Rie Sekine (Hokkaido University)
16:25-16:50	The container picture with two-alpha correlation for the ground state of 12C Bo Zhou (Hokkaido University)
16:50-17:15	The scattering cross sections for 6,7Li+n reactions Ichinkhorloo Dagvadorj (Hokkaido University)
17:15-17:40	Computational cross sections of Bc absorption by hadrons M. A. K. Lodhi (Texas Tech University)
18:00-20:30	**Banquet**

Sep.17 (Thursday)

Section 4	**Nuclear Data Measurement and Application** Chairman: F. Ergashev/S. Ebata
9:25-9:50	(n,alpha) Reaction Cross Sections and Angular Distributions for Several MeV Neutrons Myagmarjav Odsuren (National University of Mongolia)
9:50-10:15	Nuclear data activities at Bangalore University Rudraswamy Basavanna (Bangalore University)
10:15-10:25	**Break Time**
10:25-10:50	Investigation of the nuclear reaction 12C(p,g)13N at the proton energies below 1 MeV Feruzjon Ergashev (Institute of Nuclear Physics AS RUz)

10:50-11:15	Neutron resonances at crystalline structures in the thermal range Nurgali Takibayev (Al-Farabi Kazakh National University)
11:15-13:00	**Lunch Time**
Section 5	**Discussion and Conclusion** Chairman: M. Aikawa
13:00-15:00	Discussions
15:00-15:15	Concluding Remark

Recent news in nuclear data development and services on EXFOR and IBANDL databases provided by IAEA-NDS

V. Semkova, P.Dimitriou, N. Otuka, S.P. Simakov, V. Zerkin

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Accurate nuclear data are needed in many fields of science and technology. The main tasks of the IAEA Nuclear Data Section include collection, compilation, evaluation and dissemination of nuclear data. The EXFOR library [1] provides comprehensive collection of experimental nuclear reaction data for neutron-, charged-particle-induced and photonuclear data in the energy range up to 1 GeV. In addition, libraries, related to specific applications such as: ion beam analysis; nuclear safeguards; neutron activation analysis etc., are available to users as well.

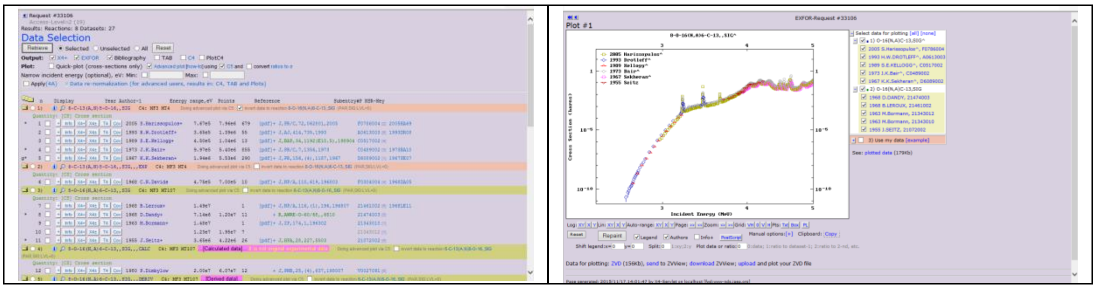
The development of the EXFOR system (including library, database, software and Web interface [2]) is a major task for the IAEA Nuclear Data Services Unit. The system is regularly updated and upgraded both in terms of content and functionality.

The scope of the EXFOR database has been recently extended by addition of the beta-delayed neutron emission data from individual precursors. The status of the EXFOR completeness for particular type of data is periodically checked using bibliographic information from various sources. Updates of the rules for the compilation of neutron Kerma factors and a list of missing articles were proposed in [3], based on the comprehensive review of publications reporting such type of data. The EXFOR completeness checking for the articles published in the conference proceedings of the “Symposia on Reactor Dosimetry” (ISRD) since 1975 was recently performed. The data missing in EXFOR were included in a Memo 4C-3/400 and distributed within the NRDC Network.

We consider that guidelines and recommendations developed in collaboration with experts will improve the quality of the EXFOR compilations and provide essential information for the experimental conditions and derived quantities. The proper interpretation and the analysis of the neutron induced data in the resonance region measured by the time-of-flight technique require detailed description on experimental set-up [4]. The characterisation of TOF spectrometers’ response functions was discussed with experimentalist from RPI Gaerttner LINAC Center, Oak Ridge Electron Linear Accelerator (ORELA), Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) at the Japan Proton Accelerator Research Complex (J-PARC), EC-JRC-IRMM TOF - Facilities GELINA during the Consultants’ Meeting “EXFOR Data in Resonance Region and Spectrometer Response Function”. Work on collection of response functions for different measurement setups is ongoing.

New functionality has been recently added to the IAEA-NDS EXFOR retrieval system. The conversion of $^{13}C(\alpha,n)^{16}O$ reaction cross section into $^{16}O(n,\alpha)^{13}C$ employing principle of detailed balance was demonstrated for the needs of the CIELO project and was recommended for implementation in the EXFOR retrieval system [5]. Such tool was implemented as additional option for reversible nuclear reactions [6]. As an example, the Table 1 shows the cross section plot of $^{16}O(n,\alpha)^{13}C$ and $^{13}C(\alpha,n)^{16}O$ inverse reaction (indicated with flag “^”).

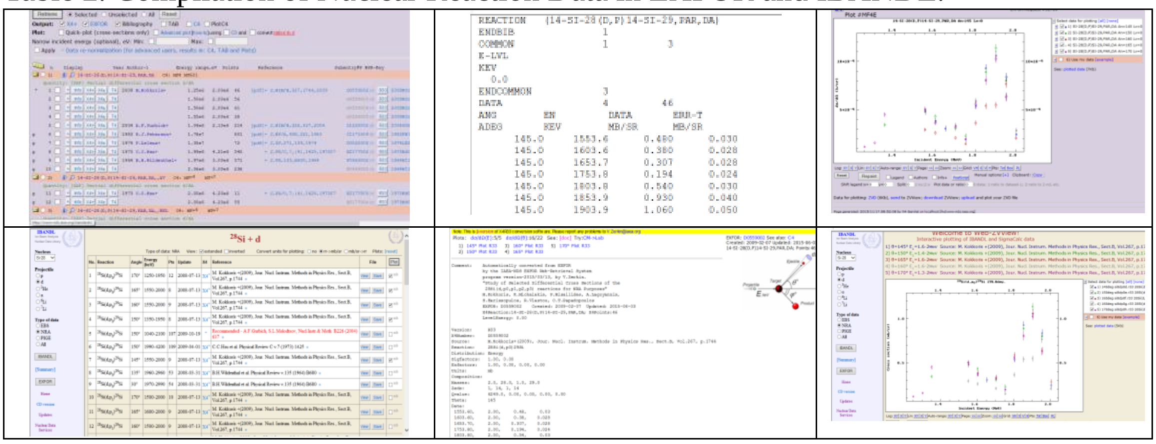
Table 1. Inverse reaction cross section conversion and retrieval.



IAEA-NDS provides also some application oriented databases. Various techniques have been developed for material characterization applying MeV Ion Beam Analysis (IBA) on small accelerators [7]. Some of the most commonly applied methods for bulk composition analysis and depth profiling (near the surface) are ion backscattering (elastic EBS or Rutherford RBS), nuclear reaction analysis (NRA) and particle-induced gamma ray emission (PIGE). These techniques involve measurements of energy spectra of specific reaction products at certain angles. For quantitative analysis all IBA techniques rely strongly on differential cross-section data. A specialized Ion Beam Analysis Nuclear Data Library (IBANDL) [8] was created by members of the IBA community under the auspices of an IAEA CRP [9] to address the nuclear data needs related to IBA. The database and Web interface [10] are currently maintained by IAEA-NDS and regularly updated and upgraded both in terms of content and functionality. The differential cross section data $d\sigma/d\Omega$ (E) at fixed angles (as well as total cross sections and yields) for selected reactions are compiled in R33 format.

Charged-particle induced differential cross sections are compulsory for compilation in EXFOR database and have been extensively compiled. An EXFOR to R33 conversion implemented in EXFOR Web retrieval system allows differential cross section data from EXFOR to be translated into R33 files. In addition to the format conversion a transformation from centre of mass to laboratory system is performed if needed [11]. R33 output files from EXFOR system are used as input for compilation to the IBANDL database.

Table 2. Compilation of Nuclear Reaction Data in EXFOR and IBANDL.



Correspondingly links to EXFOR datasets are provided by IBANDL Web interface. Recently Web IBANDL has been upgraded with the possibility of performing conversion to inverse kinematics. The new functionality provides users with a tool that allows them to compare data measured in different kinematics and use an extended database of measured cross sections in their applications as shown in Figure 1. More information on conversion and retrieval procedures is provided in Ref. 5.

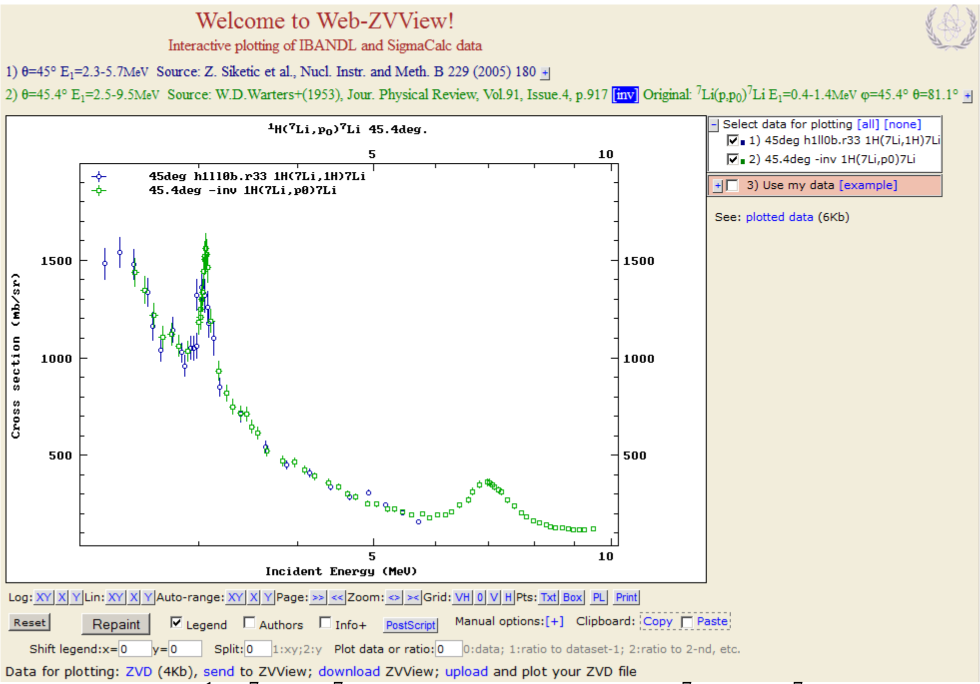


Figure 1. Comparison of $^{1}H(^{7}Li,p_0)^{7}Li$ and inverse kinematics $^{7}Li(p,p_0)^{7}Li$ cross sections

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Recent EXFOR Compilation in CNDC

Chen Guochang, Wang Jimin, Tao Xi, Zhuang Youxiang, Ge Zhigang

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1. Introduction

The EXFOR library has become the most comprehensive compilation of microscopic experimental nuclear reaction data. It contains cross sections and other nuclear reaction quantities induced by neutron, charged-particle and photon beams, etc. Currently compilation is mandatory for all low and intermediate energy neutron and light charged-particle induced reaction data. Heavy-ion and photon induced reaction data are also additionally compiled on a voluntary basis.

Currently fourteen data centers are participating in the International Network of Nuclear Reaction Data Centres (NRDC) and are collaborating mainly for compilation and exchange of experimental data by using the common Exchange Format (EXFOR Format) under the auspices of the IAEA Nuclear Data Section (NDS).

2. EXFOR Compilation in CNDC

Since China joined IAEA at 1984 and China Nuclear Data Center (CNDC) joined NRDC in 1987, we are takes part in scanning Chinese journals and compiling EXFOR entries and collaborating with NRDC. CNDC is one specialized center at NRDC as shown in **Fig. 1**. Which the experiments are carried out by Chinese researcher, the experiments are measured in China and measurements are published in Chinese journals, compilation of bibliographic references (CINDA) to microscopic neutron reaction data and related data published in Chinese, CNDC need to scan and collect measured results and compile these data and information as EXFOR format including neutron and charge particle induced reactions. CNDC are respond more than 9 Chinese journals now such as **Fig. 2** and IAEA assigns EXFOR compilation task.

Country	Center	Joined
Russia	Nucl. Struc. & Nucl. Reac. Data Centre	1974
Japan	Japan Nuclear Reaction Data Center	1975
Russia	Centre for Exp. Photonuclear Data	1982
China	*China Nuclear Data Center*	*1987*
Japan	Nuclear Data Center	1991
Korea	Nuclear Data Evaluation Laboratory	2000
India	Nuclear Data Section	2008

Fig. 1: The specialized center at NRDC

In 1985, IAEA and CNDC hold a working meeting about compilation in EXFOR. Fifteen charged particle EXFOR entries were transmitted to IAEA for NRDC communication at this meeting as shown in **Fig. 3** and started to compile neutron entries at 1989.

1. Chinese Physics C(ENG/2007;HEN)
2. Atom. Energy Sci. & Tech.(CHN/1959)
3. J. of Nucl. & Radiochemistry(CHN/1979)
4. Nuclear Physics Review(CHN/1984)
5. Nuclear Techniques(CHN/1978;+ENG/1989)
6. Com. of Nucl. Data Prog.(ENG/1989)
7. Nuclear Science and Techniques(ENG/1989)
8. Chinese Physics Letters(ENG/1984)
9. Chinese Physics B (ENG)
10. Acta Physica Sinica(ENG/1933)
11. Conference, Workshop etc.

Fig. 2: List of the responsibility of CNDC

01 Li Zhichang+ Yuanzineng Kexue Jishu 3(1977)229
02 Liang Qichang+ Yuanzineng Kexue Jishu 1(1977)10
03 Mao Zhenlin+ Conf. on Low Energy Nucl. Phys.3(1972)
04 Yuan Rongfang+ Chin. J. Nucl. Phys. 3(1981)155
05 Jiang Chenglie+ Conf. on Low Energy Nucl. Phys.3(1972)
06 Sun Hancheng+ Yuanzineng Kexue Jishu 3(1984)329
07 Yan Chen+ Chin. J. Nucl. Phys. 2(1980)137
08 Sun Hancheng+ Yuanzineng Kexue Jishu 2(1981)185
09 Ma Weiyi+ Chin. J. Nucl. Phys. 2(1980)239
10 Shen Wenqen+ High Energ.Phys.Nucl.Phys.1(1977)70
11 Tao Zhenlan+ Canadian Nucl Technol.45(1987)
12 X.Long+ NST-001 (1985)
13 Long Xianguan+ NST-003 (1989)
14 Tao Zhenlan+ Chin. J. Nucl. Phys. 3(1981)242
15 Tao Zhenlan+ Yuanzineng Kexue Jishu 5(1983)506

Fig. 3: CNDC provided the first 15 charged particle EXFOR entries

	No.	Ref.	Title	Vol.	Issue	Page	Lab	Publish date	Author	Status	Action	Delay date(m)	Compiler	Entry	Sub.	Memo
修改 详情	1	J,RCA	Cross section measurements for gallium in the neutron energy range of 13.5 to 14.8 MeV	100	4	231	3CPRHXU	201202	J. Luo	Allocated	Compiling	6	Youxiang ZHUANG	32704	n	Assigned this entry a …
修改 详情	2	J,IPC	Cross-sections for formation of 99mTc through nat-Ru(n, x)99mTc reaction induced by neutrons at 13.5 and 14.8 MeV	81	5	495	3CPRHXU	201201	Junhua Luo	Allocated	Compiling	7	Youxiang ZHUANG	32702	n	Assign this entry is …
修改 详情	3	J,IPC	Cross-sections for (n,2n), and (n,a) reactions on 55Mn isotope around neutron energy of 14 MeV	81	10	1563	3CPRLNZ	201204	Yanbin Zhang	Allocated	Compiling	4	Jimin WANG	32701	n	Assign this entry is …
修改 详情	4	J,JRN	Cross section measurements for 141Pr(n, g)142Pr reaction at neutron energies from 13.5 to 14.8 MeV	293	1	261	3CPRHXU	201204	Junhua Luo	Allocated	Compiling	4	Guochang CHEN	32703	n	It is assigned at Aug …
修改 详情	5	J,HPH	239Pu(nth, f)短寿命裂变产物产额测量	34	2	88	3CPRAEP	201203	刘世龙	Allocated	Compiling	5	Guochang CHEN	32700	n	It is assigned at Au …
修改 详情	6	J,EPJ/A	New determination of the astrophysical 13C(p, y)14N S(E) factors and reaction rates via the 13C(7Li, 6He)14N reaction	48	2	13	3CPRAEP	201202	Y.J.Li	Allocated	Compiling	6	Xi TAO	S0054	cp	Assigned this entry …
修改 详情	7	J,HEN	Cross section measurements for (n,p) reaction on stannum isotopes at neutron energies from 13.5 to 14.6 MeV	35	5	445-448	3CPRLZT	201105	PU Zhongsheng(蒲忠胜)	Allocated	Compiling	15	Youxiang ZHUANG	32699	n	Finish compile at Ju …
修改 详情	8	ASI	13 兆电子伏氘核所引起的一些反应的激发函数	22	2	250	3CPRNRS	196602	程晓五	Allocated	Finalized	558	Guochang CHEN	S0060	cp	Finalized this entry …
修改 详情	9	JP/CS	Fusion-fission and quasifission competition in the 32S+184W reaction	282	1	12013	3CPRAEP	201103	H.Q.Zhang	Allocated	Compiling	17	Youxiang ZHUANG		cp	This is calculation r …
修改 详情	10	J,EPJ/A	Level structures in the 114In nucleus	47	11	141	3CPRAEP	201111	C.B.Li			9			cp	This paper couldn't b …

Fig. 4: EXFOR compilation managed Website

Present we have a small group to attend EXFOR compilation work. Everyone respond to scan 2 journals, collect the scanning results of all responsible journals, and assign neutron and charged particle tasks. After that, upload the information such as the assigned entry No., paper in pdf, author, publication date, delayed date, the compiler and the processing of compilation to our EXFOR compilation managed Website as shown in **Fig. 4**.

Since 2009, CNDC compiled 88 EXFOR entries as shown in **Fig. 5** which is included 50 neutron and 38 charged particle entries. Up to now, we still have more than 40 articles should be compiled in 2015. We can find recently the charged particle induced reaction measurement is become more and more. And we also remain a lot of charge particle papers in earlier issues of "High Energy Physics and Nuclear Physics" and "Chinese Nuclear Physics" to be compile in the future.

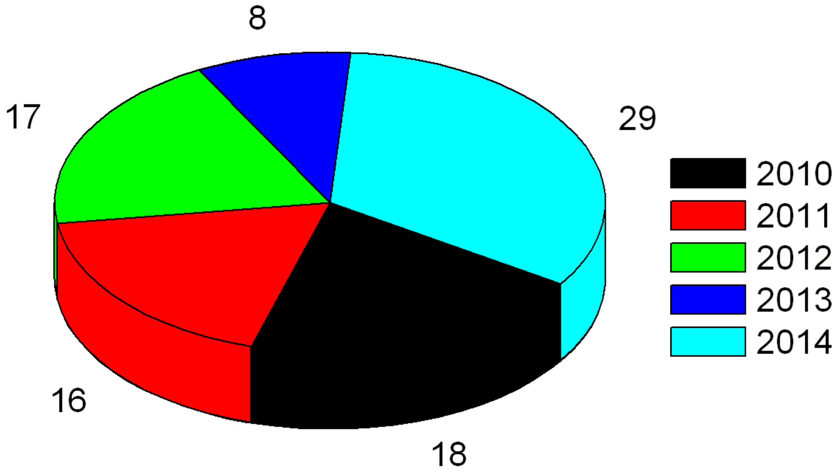

Fig. 5: Compiled EXFOR entries of each year

3. Nuclear Data Service

CNDC provides the nuclear data service in China for different institute, school or other requirements. CNDC joined the developing of Chinese basic database and established a "The Database of Nuclear Physics" website as shown in **Fig. 6** including experimental data (EXFOR), evaluation data, decay data, nuclear structure, astrophysical data and nuclear data for medical applications for online retrieve and plotting, and the website is "www.nuclear.csdb.cn". CNDC also established the mirror site of IAEA-NDS at Aug. 31 2013, which is "www-nds.ciae.ac.cn". And the database of this mirror site is update with IAEA-NDS website at the same time. Up to now, the contents of mirror site includes EXFOR database and evaluation database as shown in **Fig. 7**. And the contents will be enriched in the future.

Fig. 6: Webpage of "The Database of Nuclear Physics"

Fig. 7: Webpage of IAEA-NDS mirror site

4. Conclusion

The needs for experimental reaction data are always growing. CNDC response to scan, collect and compile the experimental information which are carried out by Chinese researcher, the experiments are measured in China and measurements are published in Chinese journals, and related data published in Chinese. Present CNDC have a small group to attend EXFOR compilation work and construct an EXFOR compilation managed Website for EXFOR compilation organization. CNDC will continue to scan, collect and compile EXFOR data and collaborate with NRDC.

The Evaluations of ^{208,207,206,204}Pb in CENDL-3.1

Tao Xi, Wang Jimin, Chen Guochang, Zhang Huanyu
[1] *China Nuclear Data Center, China Institute of Atomic Energy, Beijing 102413, China*

There are 4 stable isotopes for the element lead. New evaluations of ^{208}Pb, ^{207}Pb, ^{206}Pb and ^{204}Pb are obtained in CENDL-3.1.

A set of neutron optical model potential parameters has been chosen for theoretical calculation. The code of DWUCK is used for calculating the direct reaction, and the codes of UNF and TALYS1.0 are used for theoretical calculation. The cross sections, angular distributions and double differential cross sections are obtained. The most evaluation of cross sections in CENDL-3.0 is good, and the focus is on revising the elastic scattering angular distributions and double differential cross sections.

Based on the evaluation of ^{208}Pb in CENDL-3.0, the resonance parameters, the cross sections of (n,tot), (n,g), (n,el), (n,inl), and the inelastic scattering of discrete states, are revised. The total cross section is similar to the evaluation of ENDF/B-VII.0[1] and JENDL-4.0[2](**Fig. 1**). There is little difference between 5 to 15MeV, which comes from the elastic scattering cross section. The (n,γ) cross section of CENDL-3.1 is same with ENDF/B-VII.0. The result of JENDL-4.0 is quite different with other databases at 10keV, the background of resonance energy range may be mistaken(**Fig. 2**).

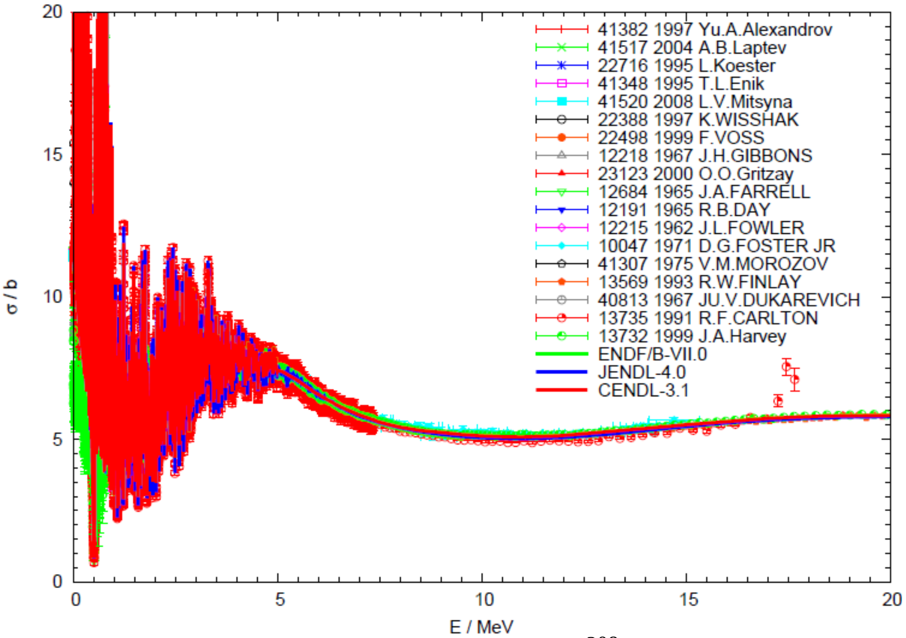

Fig. 1: The total cross section of n+^{208}Pb reaction.

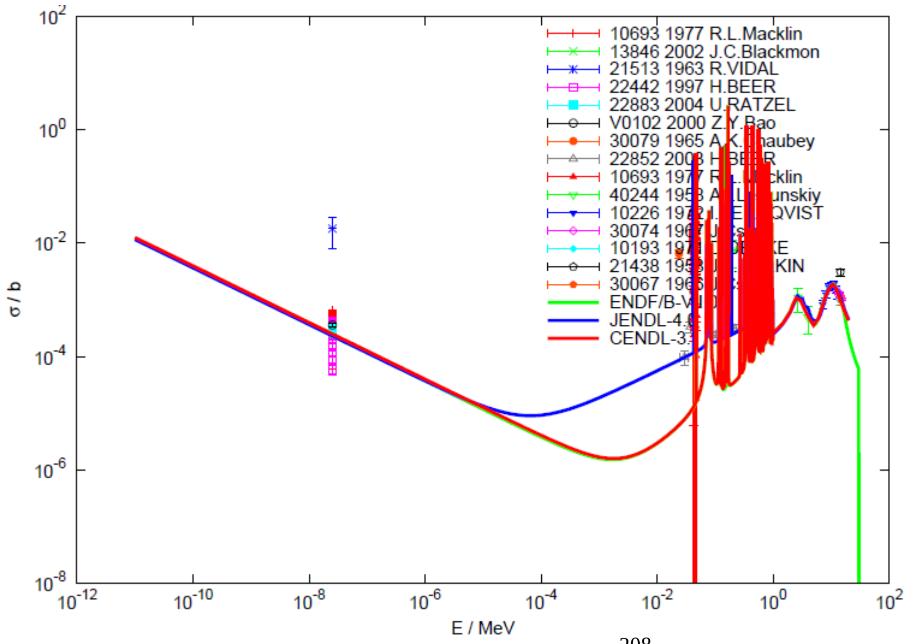

Fig. 2: The (n,γ) cross section of n+^{208}Pb reaction.

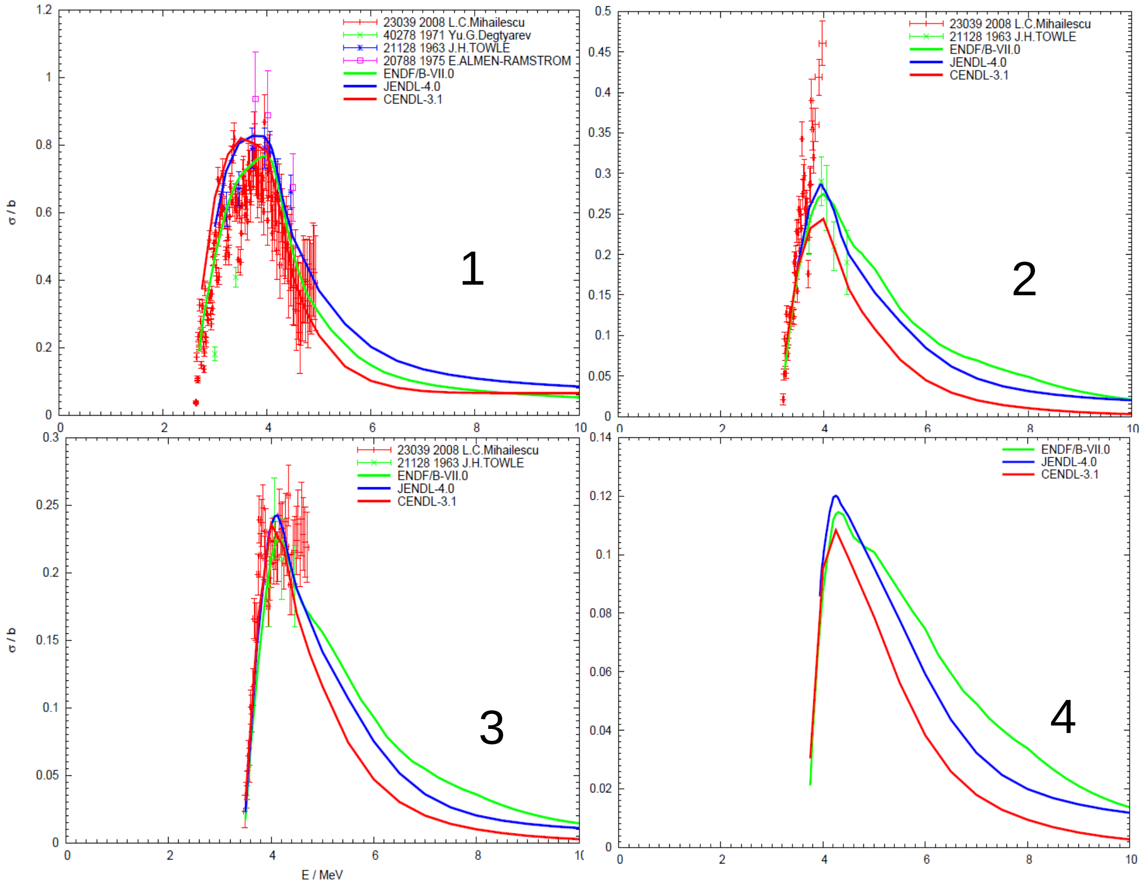

Fig. 3: The inelastic scattering of excited states.

Fig. 3 is the inelastic scattering cross sections of excited states. The evaluations of 3 databases all are in agreement with the experimental data, and contributions of direct reaction are different.

Elastic and inelastic scattering angular distributions, double differential neutron emission spectra and photon production multiplicities and transition, are taken from the results of the theoretical calculation. **Fig. 4** shows the elastic scattering angular distributions at 14.6MeV[3], the amplitudes of 3 databases are same with experimental data and little different in large angle.

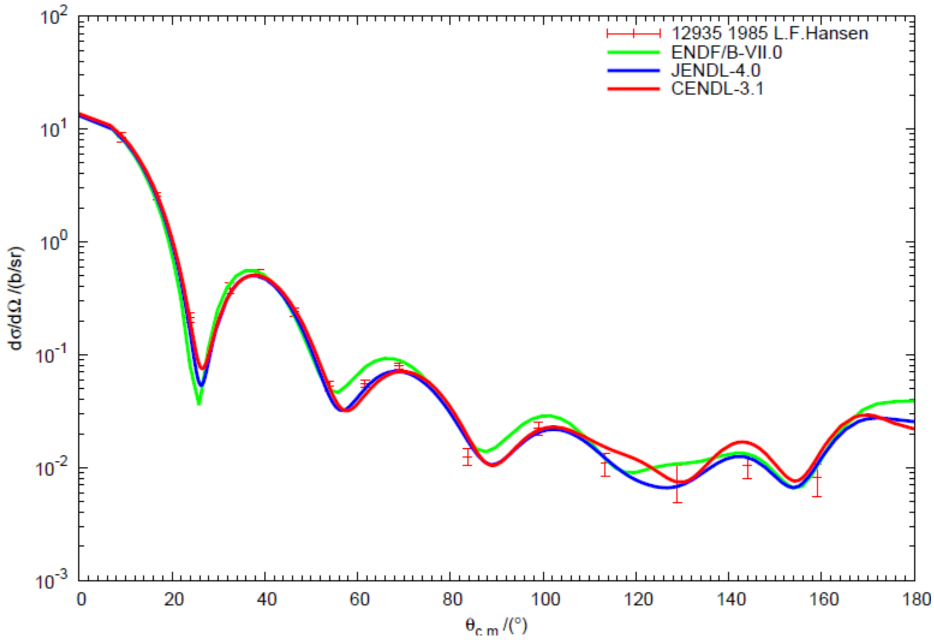

Fig. 4: The elastic scattering angular distributions at 14.6MeV.

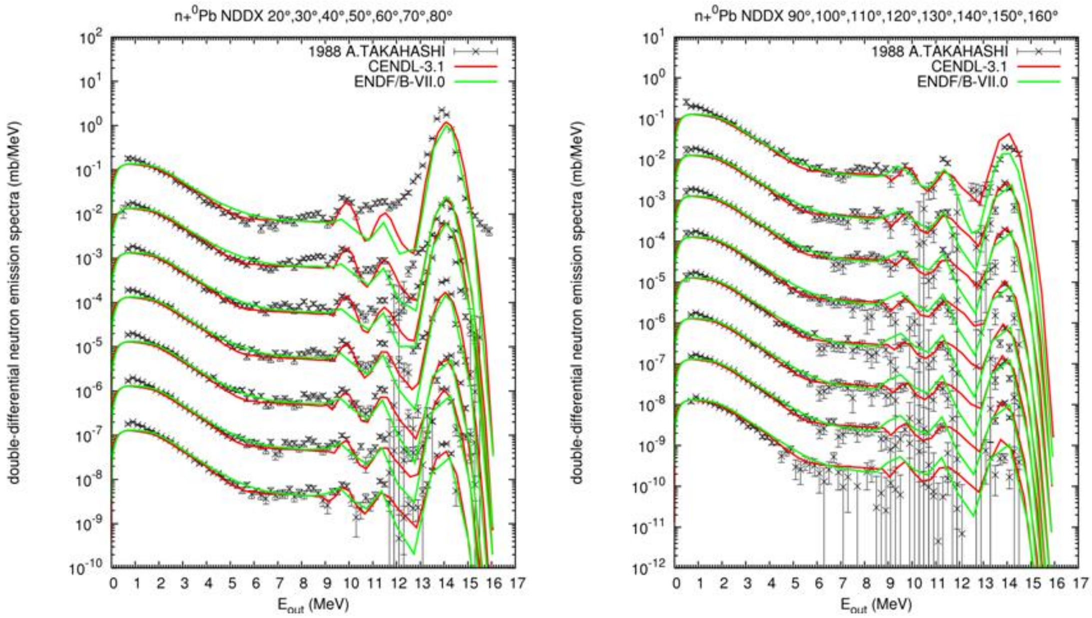

Fig. 5: The double differential neutron emission spectra of ^{nat}Pb.

The evaluations of ^{207}Pb, ^{206}Pb and ^{204}Pb are similar to ^{208}Pb. Base on the evaluation results of $^{208,207,206,204}Pb$, a code nature_ddx is used to calculate the nature lead double differential neutron emission spectra. The evaluations of CENDL-3.1 are in good agreement with the experimental data[4]. The result of CENDL-3.1 is better than ENDF/B-VII.0 in small angle(**Fig. 5**).

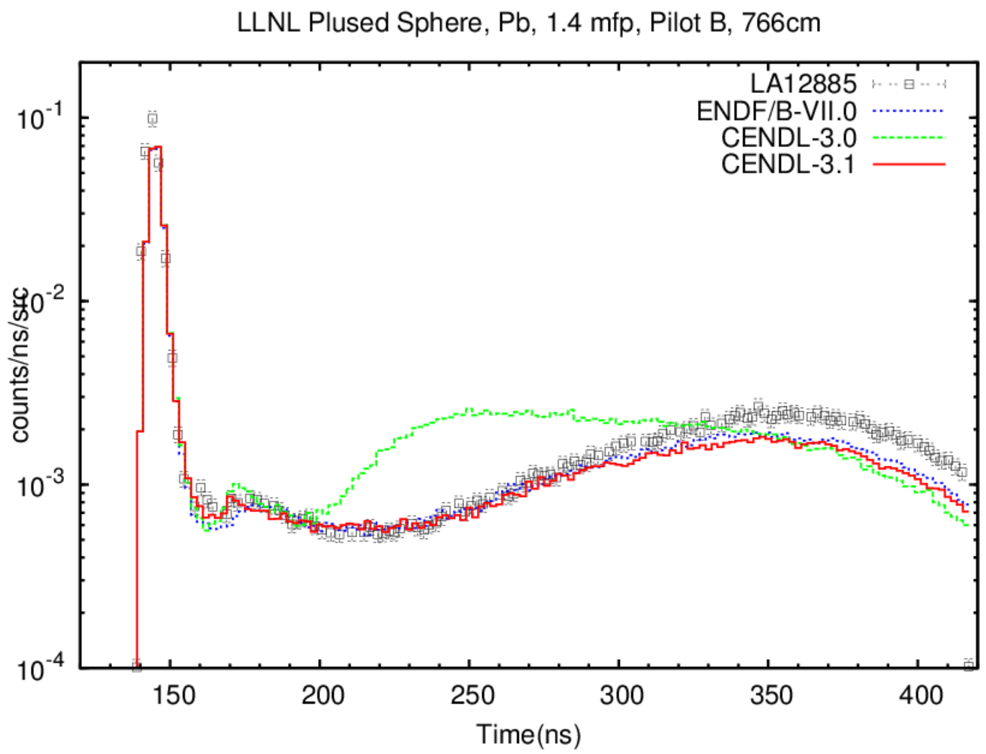

Fig. 6: The result of benchmark testing

The result of benchmark testing is significantly improved, and better than the result of CENDL-3.0.

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Evaluation of deuteron-induced excitation functions for $^{186}W(d,p)^{187}W$ and $^{186}W(d,2n)^{186}Re$

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The charged particle excitation functions are the important part of the nuclear data. This kind of nuclear data are applied to the activation analysis, nuclear medicine investigation, nuclear theory, calculation of integral yield, and so on. The activation method and stacked foil technique are often used in the charged particle excitation functions measurement.

The formula[1] of charged particle excitation functions is as follows:

$$\sigma = \frac{M}{n\varepsilon paN_0} \cdot \frac{c}{t} \cdot \frac{1}{\chi} \cdot \frac{1.6\times 10^{-19} t_i}{Q} \cdot \frac{e^{\lambda t_d}}{1-e^{-\lambda t_i}} \cdot 10^{24} b$$

Where, M is the target molecular weight, n is the target nucleus number in a molecule, ε denotes the detection efficiency of detector at full energy peak, p is the γ-ray branch ratio, α denotes the isotope abundance, N_0 is the Avogadro constant, c/t is the accounting γ-ray number at full energy peak in a unit time, χ denotes the target weight in a unit area, t_i denotes the irradiation time, Q is the total integrated beam current (in Coulomb), t_d denotes the cooling time (start from stop irradiation) and λ is the radioactive decay constant.

From the mentioned-above formula, the cross sections are proportional to the radioactive decay constant, and inversely proportional to the γ-ray branch ratio. Moreover, if the experiment is relative measurement, the cross sections are proportional to the standard cross sections. According to these relations, σ can be corrected by the new p, λ and standard cross sections.

The experimental data of $^{186}W(d,p)^{187}W$ and $^{186}W(d,2n)^{186}Re$ reactions are available in EXFOR library and literature (**Fig. 1** and **Fig. 2**). Analysis and fitting were done with the correction of γ-ray branch ratio, radioactive decay constant and standard cross sections from threshold to 50 MeV. Furthermore, the cross sections were calculated by the nuclear reaction model code TALYS.

For each reaction, the data were normalized to 100% enrichment of 186W, considering the given enrichment of the target in the literature and the isotopic composition of natural tungsten, i.e. ^{180}W (0.12%), ^{182}W (26.50%), ^{183}W (14.31%), ^{184}W (30.64%) and ^{186}W (28.43%). In the measurements of F.Tarkanyi et al.[2], K.Ochiai et al.[3]，S.Manenti et al.[4] and C.Duchemin et al.[5], the samples were thick natural W-metal foils for $^{186}W(d,p)^{187}W$ and $^{186}W(d,2n)^{186}Re$, so the normalization factor is 4.027. In the measurement of F.W.Pement et al.[6], the sample was WO_3 powder, enriched to 97.2% in ^{186}W for $^{186}W(d,2n)^{186}Re$, so the normalization factor is 1.0288.

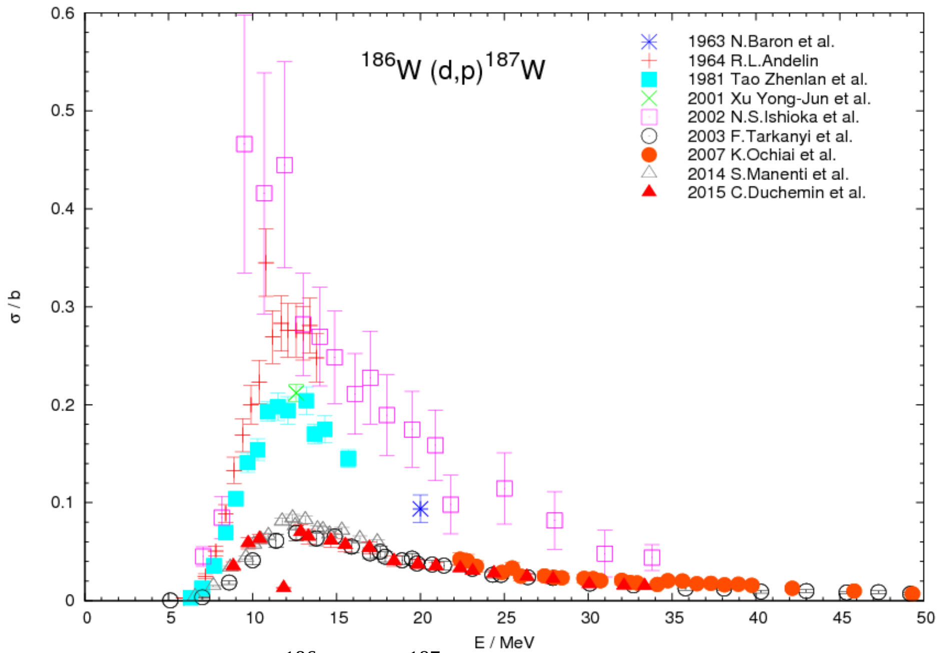

Fig. 1: The experimental data of ^{186}W(d,p)^{187}W retrieved directly from the EXFOR .

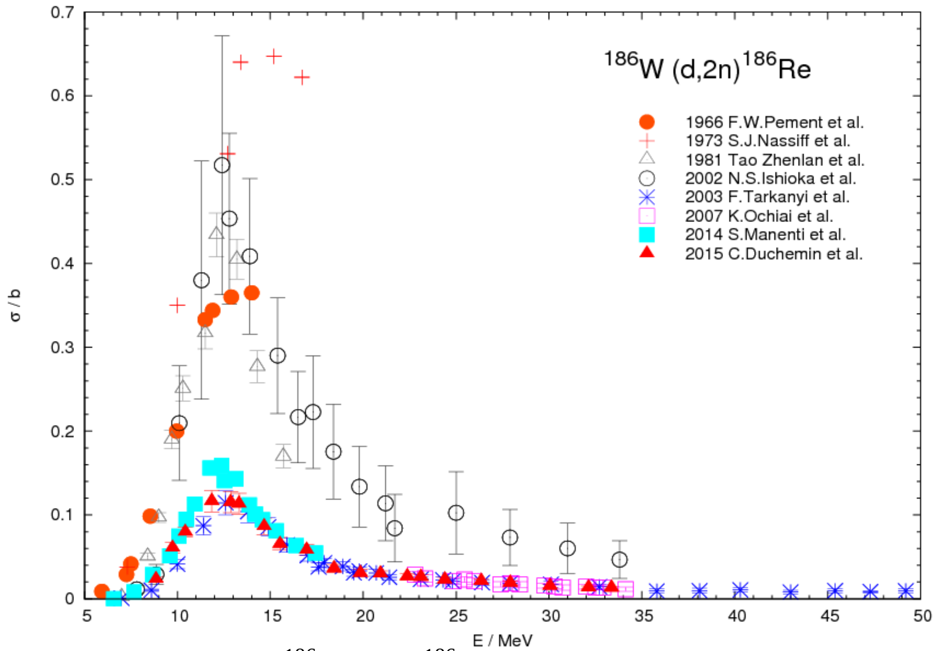

Fig. 2: The experimental data of ^{186}W(d,2n)^{186}Re retrieved directly from the EXFOR .

For ^{186}W(d,p)^{187}W reaction, in the measurement of Tao Zhenlan et al.[1], the γ-ray branching ratio of 479.5 keV are 0.256, and the new value is 0.218[7], thus the corrected factor is 0.256/0.218=1.174. For ^{186}W(d,2n)^{186}Re reaction, in the measurement of Tao Zhenlan et al.[1], the γ-ray branching ratio of 137.16 keV are 0.092, and the new value is 0.0942[7], so the corrected factor is 0.092/0.0942=0.9766. For each reaction, the corrections of radioactive decay constant and standard cross sections are very small, so not mentioned in here.

The cross sections were calculated using TALYS, a nuclear model code, developed by Koning et al. All parameterizations were done within the recommended ranges. The nuclei were considered deformational in shape. The compound nucleus contribution was considered in the frame of Moldaner model. The contributions of direct reactions were taken into account by ECIS. The back-shifted Fermi gas model (BFM) was used for level densities.

After these corrections, the experimental data are reaching unanimity. Considering the results of calculation and fitting, the fitted values below 30 MeV and the calculated values multiply a factor above 30 MeV were recommended for $^{186}W(d,p)^{187}W$ reaction, and the fitted values below 15 MeV and the calculated values multiply a factor above 15 MeV were recommended for $^{186}W(d,2n)^{186}Re$ reaction. The evaluation of excitation functions for $^{186}W(d,p)^{187}W$ and $^{186}W(d,2n)^{186}Re$ reactions were recommended below 50 MeV. (**Fig. 3** and **Fig. 4**).

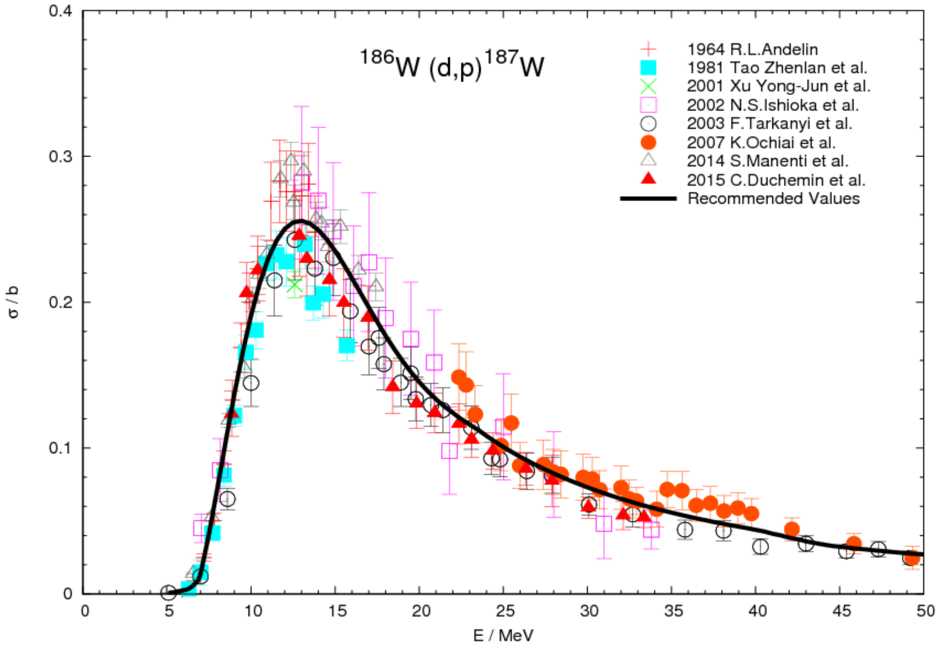

Fig. 3: The corrected experimental data and the recommended values of $^{186}W(d,p)^{187}W$ reaction.

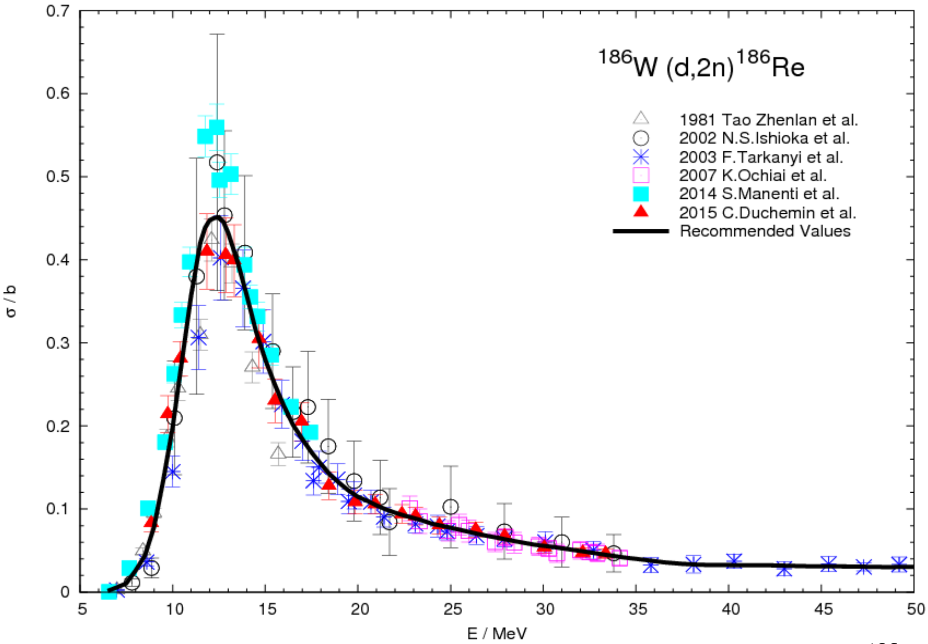

Fig. 4: The corrected experimental data and the recommended values of $^{186}W(d,2n)^{186}Re$ reaction.

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The Application of EMPIRE for Nuclear Data Evaluation of n+^{238}U

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Abstract:
To improve the evaluation method, the EMPIRE code was employed to analyze n+^{238}U reaction up to 30 MeV. According to the special characteristics of neutron induced reaction of actinide nuclei, and choosing proper reaction mechanisms, the model parameters were adjusted and reasonable neutron reaction data were obtained based on the experimental data. Comparing the EMPIRE calculation results with the data of evaluations and measurements, it is found that EMPIRE can obtain reasonable results for n+^{238}U reaction up to 30 MeV.
Key words: EMPIRE, neutron, cross sections, ^{238}U, nuclear data

1. Introduction

According to the requirements of atomic energy development and nuclear fuel waste disposal for nuclear data, especially for more than 20 MeV nuclear data for some important actinide nuclei such as ^{238}U. In recently, only ENDF/B-VII[1] and JEFF-3.1[2] database have some sets of nuclear data above 20 MeV. Recently, we employed the EMPIRE[3] code system and RIPL[4] database to do the model calculation for actinide nuclei below 30 MeV.

2. Model calculation for n+^{238}U

2.1 Optical model parameters

Optical model parameters (OMP) is the most important input parameter for model calculation. RIPL-3 database includes 19 groups neutron OMP for n+^{238}U, which includes spherical nuclei and couple channel OMP. Adopt different OMP to do the model calculation and fit the total cross section, elastic cross section and angular distribution to the experimental data for selecting the best one. Finally, the couple channel neutron OMP of Ch.Lagrange[5] was adopted. The model calculation result of total cross section is compared with the measurement as shown in **Fig. 1**. In the whole energy range, the calculated result is fit well with measurements.

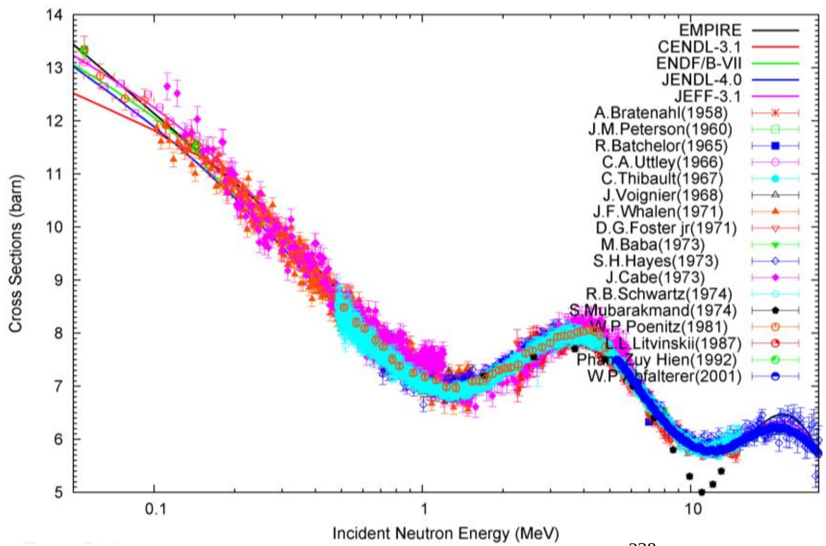


Fig. 1: Comparison of calculation with measurements for ^{238}U(n, tot) reaction

2.2 Reaction cross section calculation results

The exciton model, Multi-step Compound, Multi-step Direct, double-humped fission barriers model were taken into account in model calculation. And the directly inelastic scattering contribution was obtained by couple channel method. Width fluctuations for all incident energies, Myers-Swiatecki shell correction, EMPIRE-specific level density were adopted also. Discrete levels, decay information, mass, etc. were adopted from RIPL-3 directly.

The calculated result of (n, 2n) is compared with the evaluated data and measurements as shown in **Fig. 2**. The calculated result is fit well with the measurements below 15 MeV. However, the result is obvious lower than the measurements and evaluated data above 15 MeV. Modify the input parameters such as level density, pair correction could not effect in this energy region.

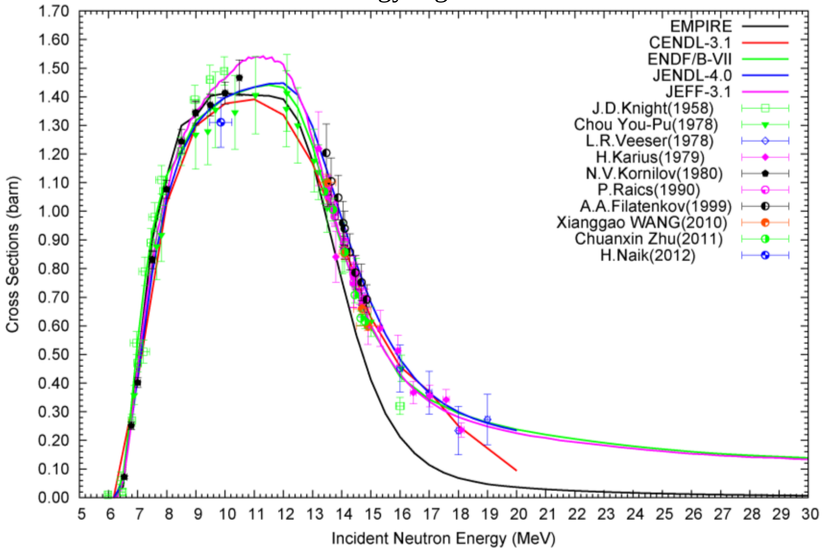


Fig. 2: Comparison of calculation with evaluations and measurements for (n, 2n) reaction

The calculated result of (n, 3n) is compared with the evaluated data and measurements as shown in **Fig. 3**. In general, the calculated result is fit well with the measurements. The calculated result is lower than the evaluated data and fit well with L.R.Veeser's measurement above 20 MeV. And the results above 25 MeV is obvious too low.

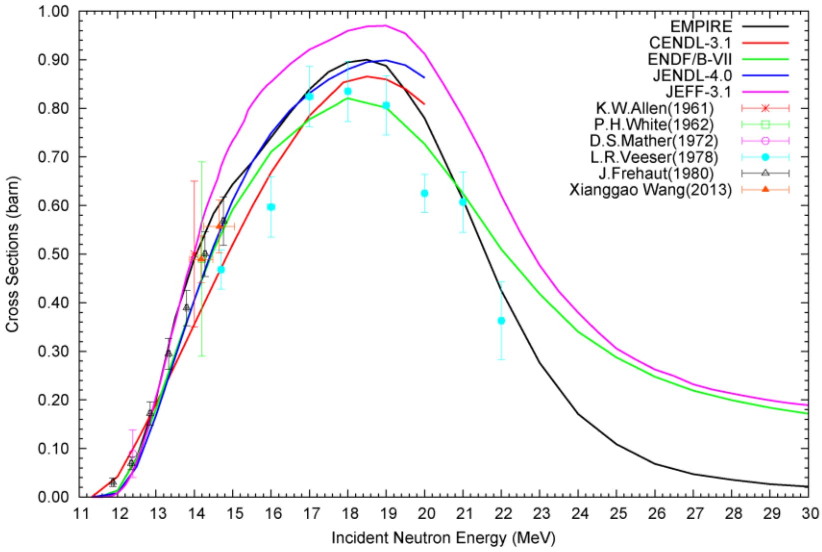


Fig. 3: Comparison of calculation with evaluations and measurements for (n, 3n) reaction

The calculated result of (n, γ) is compared with the evaluated data and measurements as shown in **Fig. 4**. The gamma strength parameters were adopted from RIPL-3 directly. In general, the calculated result is fit well with the measurements. Above 10 MeV, the calculated result is lower than the evaluated data and measurements, and the shape of present work is reasonable..

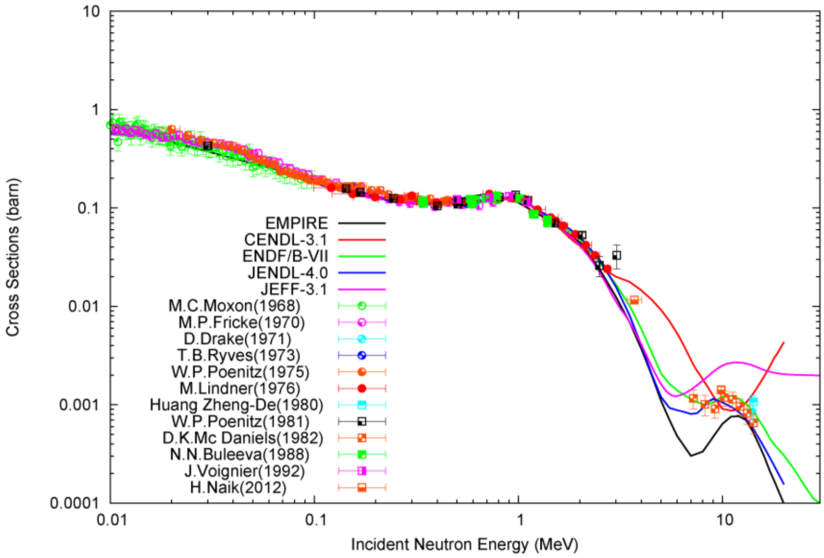


Fig. 4: Comparison of calculation with evaluations and measurements for (n, γ) reaction

The calculated result of (n, f) is compared with the evaluated data and measurements as shown in **Fig. 5**. The evaluated data of JEFF was adopted from the model calculation results directly. In general, the calculated result is fit well with the measurements in the whole energy range. Above 24 MeV, the calculated result is lower than the standard evaluation data.

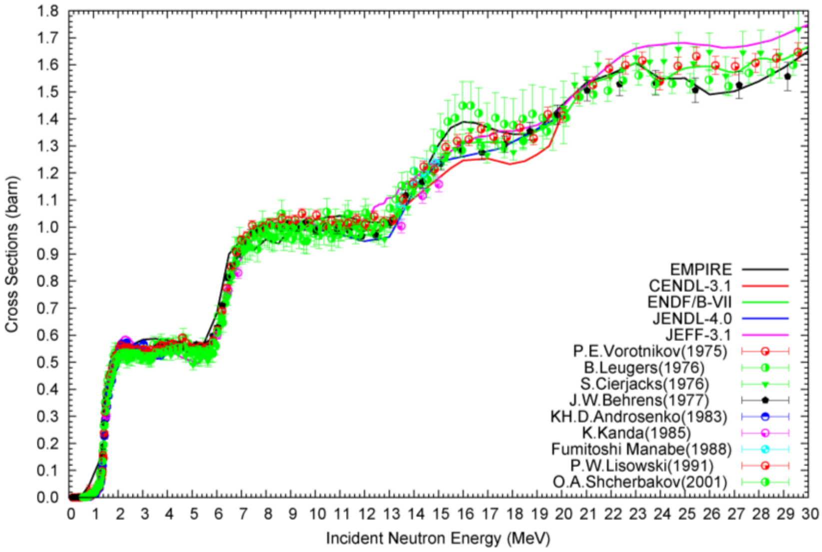


Fig. 5: Comparison of calculation with evaluations and measurements for (n, f) reaction

The calculated result of (n, inl) is compared with the evaluated data and measurements as shown in **Fig. 6**. There are taken into account 27 discrete levels and the directly inelastic scattering contribution of the 1^{st} and 2^{nd} band state using couple channel model calculation. The calculated inelastic scattering cross section is fit well with the measurements and evaluated data in shape and values. For ^{238}U, there are exist some experimental information on the 1^{st}, 2^{nd}, 3^{rd} and 6^{th} excited state inelastic scattering cross section. The comparison of calculation with evaluations and measurements for discrete level inelastic scattering reaction cross section is shown in **Fig. 7**. In general, the calculated result is fit well with the measurements in the whole energy range.

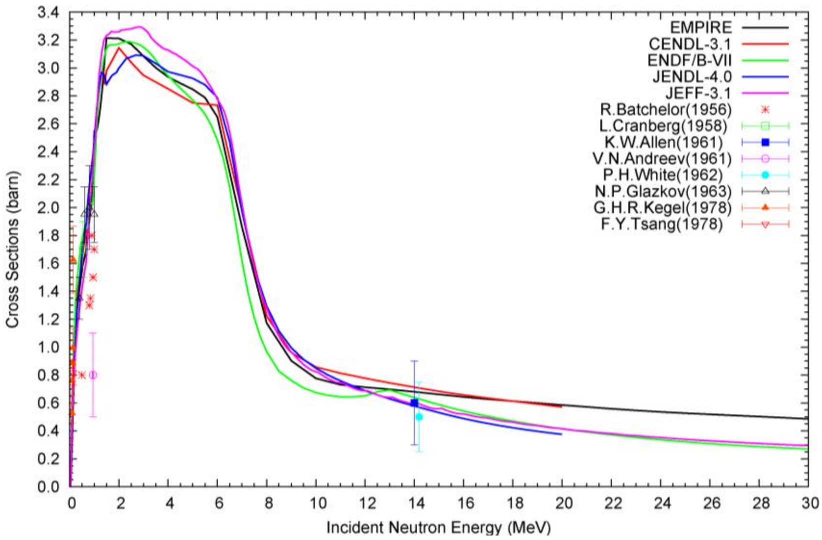
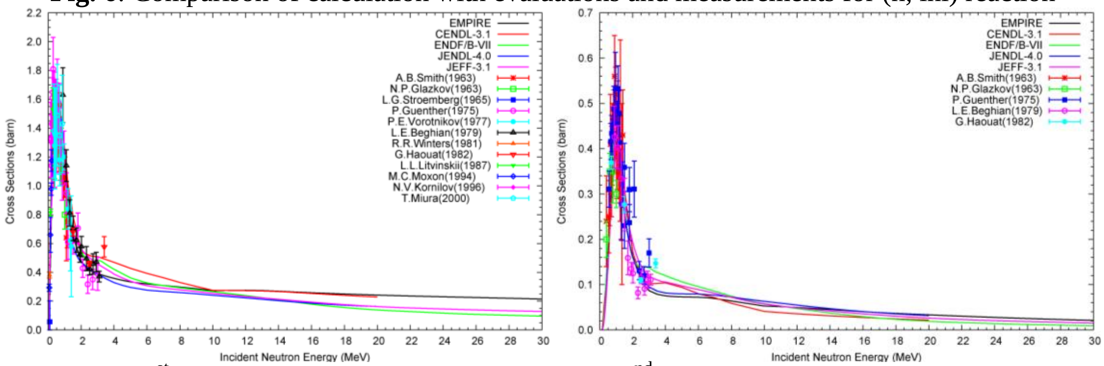


Fig. 6: Comparison of calculation with evaluations and measurements for (n, inl) reaction



(a) 1st excite state inelastic scattering (b)2nd excite state inelastic scattering

Fig. 7: Comparison of calculation with evaluations and measurements for discrete level inelastic scattering reaction

The calculated result of elastic angular distribution is compared with the evaluated data and measurements as shown in **Fig. 8**. In general, the calculated result is fit well with the measurements.

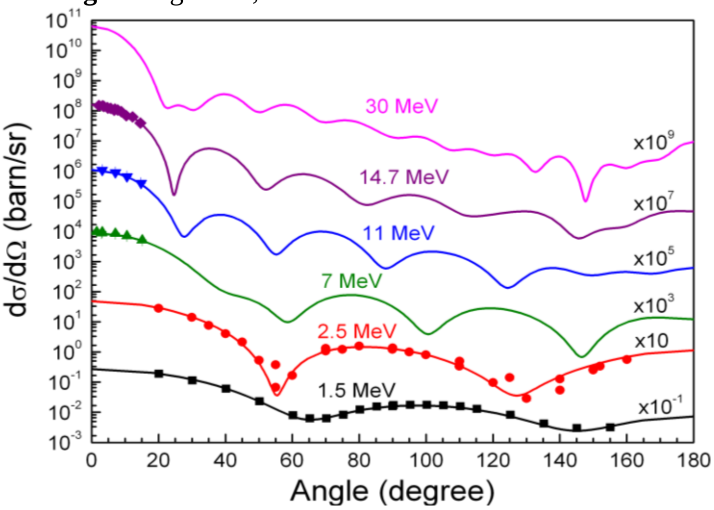


Fig. 8: Comparison of calculation with measurements for elastic scattering angular distribution

3. Conclusion

EMPIRE code system was adopted to do the model calculation for n+^{238}U below 30 MeV. According to the special characteristics of neutron induced reaction of actinide nuclei, and choosing proper reaction mechanisms, the model parameters were adjusted and reasonable neutron reaction data were obtained based on the experimental data. Comparing the EMPIRE calculation results with the data of evaluations and measurements, it is found that EMPIRE can obtain reasonable results for n+^{238}U reaction up to 30 MeV.

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Recent Activities of Nuclear Data Physics Centre of India

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Bhabha Atomic Research Centre is involved in the design of advanced reactor systems such as Advanced Heavy Water Reactor (AHWR), Compact High Temperature Reactor (CHTR) and Innovative High Temperature Reactor (IHTR) for hydrogen production where nuclear data plays an important role. To cater to various needs of department, the Nuclear Data Physics Centre of India (NDPCI) was formed which has been successful in pursuing all aspects of nuclear data, viz, measurements, analysis, compilation and evaluation involving national laboratories and universities in India. The NDPCI is evolving a streamlined and coherent activities of all nuclear data activities in India. The NDPCI has been very successful in bringing out people in various fields and students and staff from various Universities across India covering both experimentalists and theoreticians on a single platform. Our scientists are involved in nuclear data measurements using pelletron/FOTIA accelerator facility. They have carried out a number of cross-section studies using ^{7}Li(p,n) reaction as mono-energetic neutron source, surrogate technique for unstable targets and also using reactors. We have also used 14 MeV neutron generator both at Pune university and at BARC for cross-section measurements. The electron accelerators at Khargarh, India and Pohang, Korea have been used for photon induced cross-section studies. We have also carried out extensive measurements of charged particle reactions. It is also planned to carry out measurement of prompt neutron spectra in neutron induced fission reaction under CRP of IAEA. VECC is setting up facility for TAGS studies for decay heat data using BaF2 detectors. We are also involved in nuclear theory and simulations related to nuclear data for AHWR and other advanced reactors and criticality benchmark studies for various reactors. We have involved some of the universities in EXFOR compilations and have organized a series of theme meetings on EXFOR compilations. The NDPCI has awarded many projects to different universities on topics relevant to nuclear data. The NDPCI was instrumental in developing general geometry Monte Carlo code M3C for neutronics calculations based on point data and fuel cycle analysis code ADWITA which can generate isotopic inventory based on irradiation history and calculate radioactivity and decay heat for extended period of cooling. The talk will cover the progress of recent activities in the field of nuclear data mentioned above.

International Collaboration of Hokkaido University Nuclear Reaction Data Centre

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The Hokkaido University Nuclear Reaction Data Centre (JCPRG) cooperates in nuclear data researches with foreign institutes. In this report, we present such cooperative activities with the International Network of Nuclear Reaction Data Centres (NRDC) [1], institutes among Asian countries, and the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), respectively.

The NRDC has 13 member institutes worldwide and collaborates in compilation of experimental nuclear reaction data under the auspices of the International Atomic Energy Agency (IAEA). The compiled data are stored as the EXFOR (EXchange FORmat) database [1] and freely accessible through the Internet. The JCPRG is a member of the NRDC since 1975 and contributes about 10 percent of the data on charged-particle nuclear reactions in the EXFOR database.

In the NRDC, there are five institutes in Asia; China Nuclear Data Centre (CNDC), China, Bhabha Atomic Research Centre (BARC), India, Hokkaido University Nuclear Reaction Data Centre (JCPRG) and JAEA Nuclear Data Center, Japan, and Korea Nuclear Data Center (KNDC), Korea. The four centres, CNDC, BARC, JCPRG and KNDC, are in charge of compilation of domestic nuclear reaction data. The centre heads of the four institutes cooperates to promote nuclear data activities under the support of the 'R&D' Platform Formation of Nuclear Reaction Data in Asian Countries (2010-2013), the Asia-Africa Science Platform Program, the Japan Society for the Promotion of Science (JSPS) from April 2010 to March 2013. During the period, annual workshops were held and devoted to sharing information about their activities, to strengthen collaboration among the NRDC members in Asia and to promote the dissemination and improvement of data compilation techniques. Even though the JSPS support had been finished since April 2013, the fourth and fifth workshops were held at Al-Farabi Kazakh National University, Kazakhstan in October 2013 and at the BARC, India in September 2014. The workshop series are very fruitful for participants.

One of the results in the promotion, institutes and researchers other than NRDC members are encouraged. Central Asian countries, such as Kazakhstan and Uzbekistan, have a long history of nuclear research, however, there was no member in the NRDC. Recently, Central Asian Nuclear Reaction Database (CANRDB) jointly consisting of institutes in Kazakhstan and Uzbekistan started to compile nuclear reaction data obtained in their own countries. Thus, nuclear data activities in Asia are increasing under the promotion.

An important research topic in nuclear data is nuclear medicine. Radioisotopes are available for a variety of applications, e.g., radiotherapy and diagnostics in medicine. Production cross sections of the radioisotopes is one of important nuclear data. However, there still exist a lack of data and data with large errors. Therefore, it is necessary to perform experiments to obtain more accurate and reliable data for medical application. Recent technical development of accelerators and detectors enables us to reach such data.

The ATOMKI group has accumulated experience to measure production cross sections for medical radioisotopes. The collaborative research with the ATOMKI group was proposed to obtain nuclear reaction data for medical purposes. The JSPS Bilateral Program "Measurement and Evaluation of Important Nuclear Data for Diagnosis and Therapy Treatments" with ATOMKI was successfully accepted for two years between Apr. 2014 to Mar. 2016. In Apr. 2014, we have performed an experiment at ATOMKI to obtain the cross section of $^{100}Mo(p,2n)^{99m}Tc$ reaction. The result was published in a peer-reviewed journal [2]. In addition to the experiment, we continuously performs experiments at ATOMKI and RIKEN under the program.

As shown above, JCPRG energetically cooperates with the foreign institutes. The cooperation hopefully extends to other institutes.

Acknowledgement

These works are supported by Grant-in-Aid for Publication of Scientific Research Results (No. 257005), JSPS; “'R&D' Platform Formation of Nuclear Reaction Data in Asian Countries (FY2010-2012)”, Asia-Africa Science Platform, JSPS; “Measurement and Evaluation of Important Nuclear Data for Diagnosis and Therapy Treatments (FY2014-2015)”, under the Japan - Hungary Research Cooperative Program, JSPS and HAS; International Atomic Energy Agency (IAEA).

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Evaluation of the photoabsorption cross section of few-nucleon systems with time-dependent method

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Nuclear photoabsorption cross sections are important data to investigate nuclear structure. Since a nucleus is excited to discretized and continuum states, one faces the difficulty in treating many-body continuum states. The time-dependent method [1] is one of the methods developed to avoid this problem. The time-dependent Schrodinger equation is solved with basis expansion method using complex-range Correlated Gaussian functions. With these methods, we can calculate photo absorption cross sections of few-nucleon systems without *ad hoc* assumptions.

Calculated photoabsorption cross sections of ^{3}H and ^{3}He are shown in the figure with experimental data. The experimental values are reproduced up to the high energy region at around 80 MeV in the case of ^{3}He. However, in the case of ^{3}H, we find that our calculation does not agree with the measurement in the energy region at around 16 MeV. Further investigation is needed to resolve this discrepancy.

In this talk, we will explain our method in more detail, and also present the result for ^{4}He.

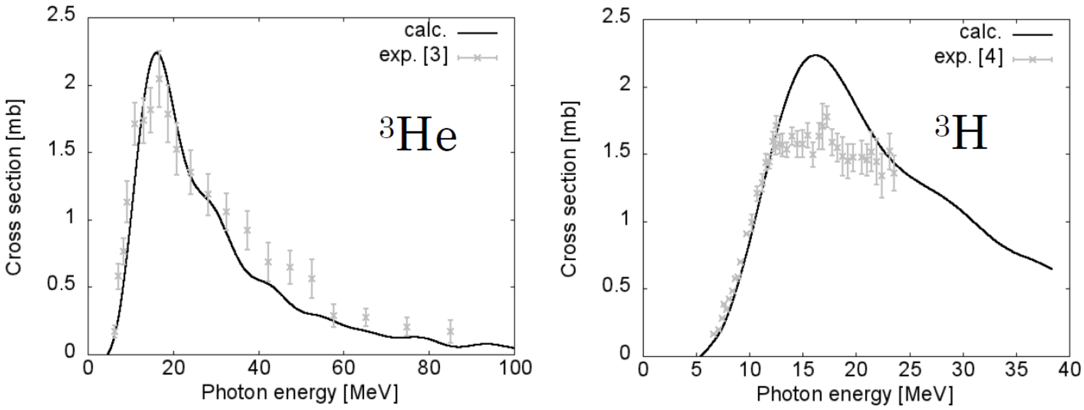

Figure Photo absorption cross sections of ^{3}He, ^{3}H are shown with the experimental data.

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The scattering cross sections for ^{7}Li + *n* reactions

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Abstracts

We investigate the continuum-discretized coupled-channel analysis to the integrated elastic and inelastic scattering cross sections for ^{7}Li at incident neutron energies below 14.1 MeV by using optical model potential and above 14.1 MeV by using the Jeukenne-Lejeune-Mahaux effective nucleon-nucleon interaction. The calculated elastic and inelastic scattering cross sections with observed incident energies are almost in good agreement with experimental and evaluated data.

1. Introduction

The Li + *n* reactions are important not only from the basic interest but also from the application point of view. Lithium isotopes will be used as a tritium-breeding material in *d-t* fusion reactors. Therefore accurate nuclear data are required for n- and p-induced reactions.

In the previous works [1-3], we have successfully studied cross sections for the ^{6,7}Li + *n* elastic and inelastic scattering angular distributions and neutron spectra applying the continuum-discretized coupled-channel method (CDCC) method [4] with (α - d) + n and (α - t) + n models. It was found that the observed cross section data for incident energies from 7.47 to 24 MeV can be reproduced by the present cluster model with one normalization parameter for the imaginary part of the Jeukenne-Lejeune-Mahaux effective nucleon-nucleon (JLM) [5] interaction. More recently, H. Guo et al. [6] have analyzed both neutron and proton scatterings from ^{6,7}Li in wide incident energies up to 150 MeV, and demonstrated the applicability of CDCC to nucleon scatterings from ^{6,7}Li. They analyzed neutron total cross sections, proton reaction cross sections and differential cross sections for nucleon elastic and inelastic scatterings. However, it is still difficult to reproduce low energy data below 14.1 MeV in these frameworks.

In this work, we extended the CDCC analysis to the integrated elastic and inelastic scattering cross sections for ^{7}Li at incident neutron energies below 14.1 MeV by using optical model potential (OMP) [7,8] and above 14.1 MeV by using JLM. We adjust the normalization constants for the OMP, because the agreement of the calculated cross sections with the data in very low incident energies of the neutron is insufficient without any adjustments. The energy dependent normalization constants, real part λ_v and imaginary part λ_w, of the OMP and JLM are determined explicitly from the integrated elastic cross section data, respectively. Comparing the results of calculations with experimental data, we discuss that the present CDCC calculations, which reproduce the experimental data observed in incident energies higher than 14.1 MeV with the single folding potential of the JLM and in lower energies with introducing the normalization factors for the cluster folding potential of the OMP.

2. The Method and Model

We prepare the wave functions of the bound and α-t scattering states of ^{7}Li in the similar way as the previous work [3] in the CDCC method. The binding energy of the 3/2$^-$ and 1/2$^-$ bound states are observed as -2.47 MeV and -1.99 MeV, respectively, with respect to the ^{7}Li$\rightarrow$ α + t threshold, and the low-energy part of the α-t scattering phase shifts in the *P*-wave

(ℓ =1) and *F*-wave (ℓ =3) have been obtained experimentally. The excited 7/2$^-$ and 5/2$^-$ states of ^{7}Li are observed at 4.65 MeV and 6.60 MeV, which are considered to be the triplet resonance state in the α-*t* relative motion with the *F*-wave. According to the cluster model, the wave functions for the bound states and the scattering states are written as

$$\phi_{\ell I}(^7Li; k) = A\left\{\varphi(\alpha)[\varphi_{1/2}(t)\otimes u_\ell(k,\ r)]_I\right\}, \quad (1)$$

Here, $\varphi(\alpha)$ and $\varphi_{1/2}(t)$ stands for the internal wave functions of the alpha and triton clusters, respectively.

The potential between α and *t* clusters is chosen ℓ -dependently so as to reproduce well the energies of the ground state, and the excited states, and the α-*t* scattering phase shifts. It consists of central and spin-orbit potentials, which are parametrized by a two-range Gaussian form and by a two-range Gaussian-derivative form, respectively;

$$\left\{\begin{array}{l} V_{t\alpha}(r) = V^{CE}{}_\ell(r) + V_\ell^{SO}(r), \\ V^{CE}{}_\ell(r) = \upsilon_{1,\ell}e^{-(r/r_{1,\ell})^2} + \upsilon_{2,\ell}e^{-(r/r_{2,\ell})^2} + V_{CL}(r), \\ V_\ell^{SO}(r) = \upsilon_{1,\ell}^{SO}re^{-(r/r_{1,\ell})^2} + \upsilon_{2,\ell}^{SO}re^{-(r/r_{2,\ell})^2}, \\ V_{CL}(r) = \begin{cases} Z_1Z_2e^2/r, & r \geq R_{CL}, \\ \left(Z_1Z_2e^2/(2R_{CL})\right)\left(3 - r^2/R_{CL}{}^2\right), & r < R_{CL}. \end{cases} \end{array}\right. \quad (2)$$

The parameters are listed in Table 1.

Table 1. The parameters of the effective central and spin orbit potentials between α and *t* for ℓ =1 and 3

Parameters	$r_{1,\ell}$ (fm)	$r_{2,\ell}$ (fm)	$\upsilon_{1,\ell}$ (MeV)	$\upsilon_{2,\ell}$ (MeV)	$\upsilon_{1,\ell}^{(SO)}$ (MeV)	$\upsilon_{2,\ell}^{(SO)}$ (MeV)	$r_{1,\ell}^{(SO)}$ (fm)	$r_{2,\ell}^{(SO)}$ (fm)
ℓ = 1 (3/2$^-$)	2.447	--	-84.70	--	-0.99	-0.67	4.900	2.447
ℓ = 1 (1/2$^-$)	2.447	--	-89.50	--	-0.30	-0.11	4.900	2.447
ℓ = 3	2.608	--	-75.65	--	-1.05	--	2.466	

The ^{7}Li + *n* scattering is described by using an (*n* - α) + *t* three body model. The Schrödinger equation is written as

$$\left[K_R + H(^7Li) + K_r + V_{t\alpha}(r) + U_{tn}(r_{tn}) + U_{\alpha n}(r_{\alpha n}) - E\right]\Psi_{JM}^{CDCC} = 0, \quad (3)$$

where *E* is the energy of the total system, vectors $\vec{r}$ and $\vec{R}$ are the relative coordinate between α and *t*, and between the center of mass of the *t*-α pair and *n*, respectively, and $\vec{r}_{tn}$ $(\vec{r}_{\alpha n})$ denotes the relative coordinates between two particles *t*(α) and *n*. Operators K_r and K_R are kinetic energies associated with $\vec{r}$ and $\vec{R}$, respectively. The total wave function with the total angular momentum *J* and its projection *M* on *z*-axis, Ψ_{JM} , is expanded in terms of the orthonormal set of eigenstates of *H*(^{7}Li) which is the Hamiltonian of the α-*t* system. The detailed explanations are given in Refs. [1-3]

The interaction U_{tn} ($U_{\alpha n}$) between *t*(α) and *n* is taken to be the optical potential for the *t*+*n* (α+*n*) scattering (Table 2). For simplicity, the spin dependence of the interaction is neglected. In this study, we adopt *p* + α scattering at 31 MeV [7] instead of *n*-α interactions. For *n* + *t* scattering, we used a neutron potential parameter set presented by Wilmore et al. [8] at lower incident energies. However, these optical potentials cannot reproduce the experimental cross sections. Therefore, we introduce normalization parameters for real and imaginary parts. We also use the JLM interaction based on a single folding model in the incident neutron energy region above 14.1 MeV. In the previous works [1-3], we reported the CDCC calculation with the JLM interaction.

Table 2. Parameters of the optical potentials for t+n and α+n at half the neutron incident energy.

System	V_0(MeV)	r_0(fm)	a_0(fm)	W_D(MeV)	r_{WD}(fm)	a_{WD}(fm)
$t + n$	50.35	2.146	0.144	0.520	2.164	0.378
$\alpha + n$	47.00	2.098	0.660	9.520	2.009	0.280

3. Results and discussion

In this calculation, we analyze the integrated elastic and inelastic scattering cross sections of the ^{7}Li+n collision at incident neutron energies below 14.1 MeV by using the optical model potential (OMP) and above 14.1 MeV by using the JLM ^{7}Li-n folding potential. For the JLM single-folding potential, we take the normalization factors λ_v=1.0 and λ_w=0.2 for the real and imaginary parts, respectively. These values of the normalization factors indicate that the small imaginary potential is needed while the real part has no any adjustment parameter.

We determine normalization factors, real part λ_v and imaginary part λ_w, of the cluster folding ^{7}Li-n potential using α-n and t-n OMPs from the integrated elastic cross section data. For the OMP cluster-folding potential, we assume λ_w= 0 for all incident neutron energies lower than 14.1 MeV. The normalization factor λ_v is determined at each incident energy below 5 MeV and introduced a linear energy-dependent form from 5 MeV to 14.1MeV. The obtained results of λ_v are presented in Table 3.

The left hand panel of Fig. 1 shows the differential cross sections of the ^{7}Li + n elastic scattering with incident energies between 2.3 and 24.0 MeV. One can see that the results of the CDCC calculation represented with solid lines are in good agreement with the experimental data. The angular distributions show rather flat in low energy cases in comparison with high energy ones. It seems to be due to increase of the s-wave contribution. For inelastic scattering, the right hand panel of Fig.1 also shows the angular distributions to the 7/2$^-$ resonance state of ^{7}Li for E_n=8.17, 10.27, 11.5, 14.1, 18.0 and 24.0 MeV. The calculated differential cross sections are obtained by integrating the breakup cross section to several discretized 7/2- solutions obtained around the resonance energy region. We can see that the CDCC calculation can also reproduce the inelastic observed cross sections together with the elastic ones.

1.0	0.760
1.5	0.740
2.0	1.050
2.5	1.117
3.0	1.220
3.5	1.400
4.0	1.360
4.5	1.340
5.0	1.000
5.5≤ E_n≤ 14.1	1.7–0.07E_n

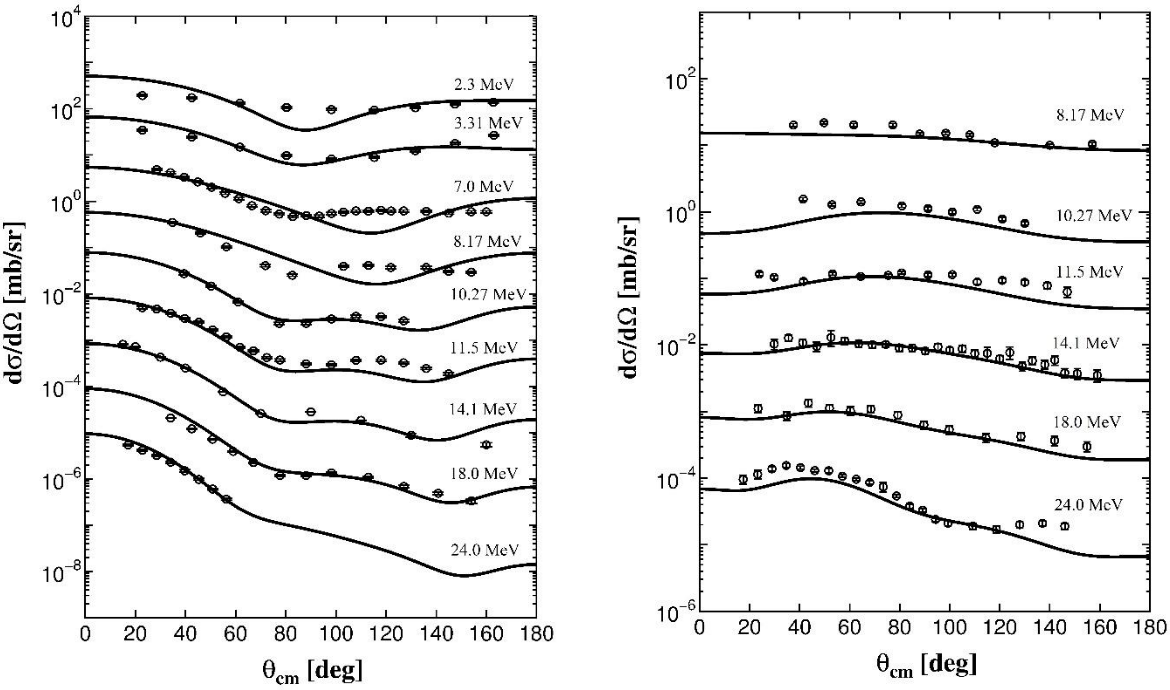

Figure 1. Elastic and inelastic angular distribution of the differential cross sections for the ^{7}Li + n scattering for incident energies between 2.3 and 24.0 MeV. The solid lines and open circles correspond to the calculated data and experimental data. The data are subsequently shifted downward by a factor 1/10.

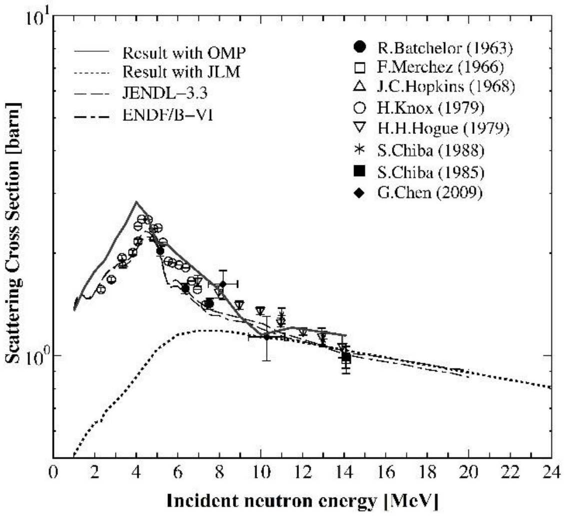

Figure 2. The integrated elastic scattering cross sections of ^{7}Li, in comparison with the evaluated data and experimental data.

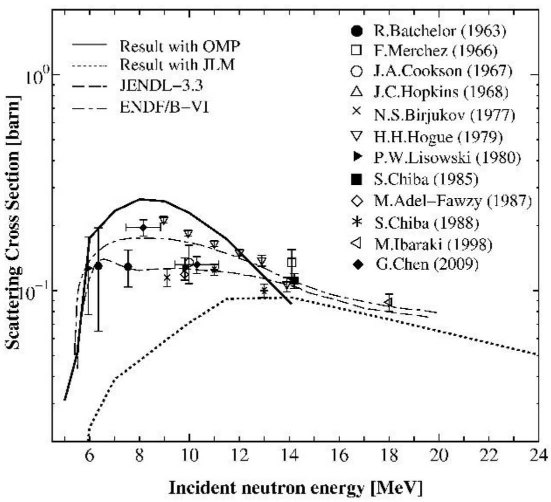

Figure 3. The integrated inelastic scattering cross sections for the 4.65 MeV state of ^{7}Li, in comparison with the evaluated data and experimental data.

We also calculate the integrated elastic and inelastic cross sections between 1.0 and 24.0 MeV. The integrated elastic cross sections for ^{7}Li almost agree with the evaluated data (JENDL-3.3 and ENDF/B-VI) and other measurements within the experimental uncertainties, as shown in Fig. 2. In Fig.3, the integrated inelastic cross-section values for the 4.65 MeV state of ^{7}Li are almost in good agreement with the evaluation data and the experimental data.

4. Summary

Applying the CDCC framework to the 7Li (α–t)+n model, we investigated the integrated neutron elastic and inelastic scattering cross sections for the ^{7}Li target at incident neutron energies below 14.1 MeV using the cluster-folding of the optical model potentials and above 14.1 MeV using the JLM single-folding potential. Energy dependence of the normalization factors, λ_v and λ_w, of the cluster folding potential is introduced and determined from measured integrated elastic cross sections. The CDCC calculation gives a satisfactorily good agreement with the experimental data.

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Upgrade of Japanese editor for EXFOR compilation

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Abstract

For about 50 years, the world-wide network of nuclear reaction data centres (NRDC) are providing data services to the scientific community. This network covers all types of nuclear reaction data, including neutron induced, charged-particle-induced, and photonuclear data used in a wide range of applications such as nuclear physics, astrophysics, nuclear engineering, nuclear medicine, etc. In this report, we present a new EXFOR editor system based on the Java programming language. The input part of the program has been developed and tested on Linux and Windows platforms, but the output and import functions of the program is still under development.

1. Introduction

Under the coordination and auspices of the International Atomic Energy Agency (IAEA), the International Network of the Nuclear Reaction Data Centers (NRDC) [1] works for storage, processing and dissemination of nuclear data on an international scale. Since the early 80s the Nuclear Reaction Data Centre of Hokkaido University (JCPRG, formerly Japan Charged-Particle Nuclear Reaction Data Group) is a member of the network [2]. The JCPRG compiles and accumulates the charged particle nuclear reaction data produced in accelerator facilities in Japan. The exchange format EXFOR (EXchange FORmat) has been developed to share experimental nuclear data [3, 4]. EXFOR is an international unified format accepted by four neutron data centers in 1970 for exchange of experimental nuclear data. Now 14 nuclear data centres of the NRDC are dividing the efforts of collection, compilation and distribution of experimental nuclear data in EXFOR according to their responsible area. The format includes details of the experimental and bibliographical information of the experiment. JCPRG also distribute nuclear data in another format, NRDF (Nuclear Reaction Data File), in addition to the data in the EXFOR format.

For the convenience of the compilation and exchange of experimental nuclear data in the countries of the third world, various editor systems have been developed within the NRDC community. ANDEX (Assisting the Nuclear Data compilation in EXfor) has been developed in the Nuclear Data Section (NDS) of the International Atomic Energy Agency (IAEA) in 1991 [5]. The main task of the ANDEX was to provide EXFOR compilers with a useful and flexible tools such as on-line EXFOR keywords and help system. ERES (EXFOR Edit System) developed by CNDC (Beijing) in 1994 [6] has functions of experimental neutron data editing, check and retrieval. EXFOR-Editor was developed at CNPD (Sarov) [7] in 2000s is currently used by many EXFOR compilers. In JCPRG, a web-based nuclear data input system HENDEL (Hyper Editor for Nuclear Data Exchange Libraries) was developed for compilation of experimental nuclear reaction data in NRDF and EXFOR formats [8], and it has been used as a standard compilation editor system at JCPRG since 2001 [9]. For beginners of EXFOR compilation, the HENDEL system is very useful because it requires very limited knowledge on EXFOR, and it is now also used by new EXFOR compilers in Kazakhstan and Mongolia.

In an EXFOR compilation workshop (6-10 Oct. 2014, Vienna) EXFOR compilers emphasized that it is important to develop an OS independent EXFOR editor system [10].

Therefore we have started development of a new OS independent EXFOR editor system ForEX using the Java programming language as a standalone application. The new EXFOR editor system was designed by the influence of the HENDEL editor. We adopted Java Swing API for building GUI (Graphical User Interface) application.

In this paper, we briefly introduce the new EXFOR editor system, user interface and executed external tools, such as CHEX and DANLO.

2. User interface and external tools

ForEX is entirely written in the Java programming language using the Swing and SwingX library. ForEX was designed for both novice and expert users to allow compilers to save the compilation time by using advanced features of the editor. Testing has been mostly performed under Windows 7, and further testing for Linux and Mac OS is in progress.

The ForEX editor main window is divided into four sections (Fig. 1). The menu bar at the top is used to perform common operations, and it includes the following menus: 'File', 'Edit'. Under the menu bar, three very frequently used controls are provided: 'DANLO' for extraction of the new dictionaries from the backup dictionary file, 'CHEX' for checking of EXFOR entries created by compiler. The main task of the 'EXFOR' button is to get EXFOR output format. At the current stage implementation of 'EXFOR' button is under construction. The left panel is used to display the content menu, which consists input forms for bibliography and information commonly applied to all data sets of the EXFOR entry (Subentry 1).

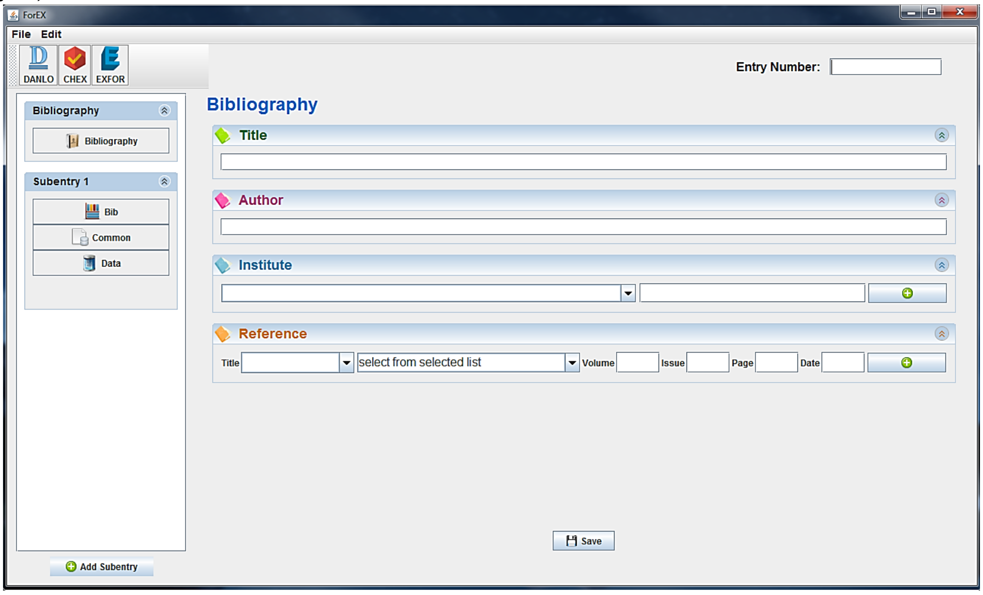

Figure 1. Main window of the ForEX graphical interface.

When the bibliography button or a button of Subentry 1 is selected, then the right-hand side panel will display the corresponding input form. The "Add Subentry" button is located under the content menu, and it allows the compiler to add new Subentries.

The right section of the window is used to input experimental nuclear data. This panel should accommodate many subpanels for different keywords, but unnecessary subpanels can be hidden by collapsing them.

The general procedure is as follows: (1) filling the input form by bibliographic and experimental information, (2) executing the external editorial and checking programs (DANLO, CHEX), and (3) exporting the edited result to an ASCII file in the EXFOR format.

Initially the ForEX editor adopted the design of input forms of HENDEL, but then it was modified so that they become more close to the EXFOR structure. Figure 2 illustrates the layout of the Bibliography, Bib, Common and Data panels. All panels offer a list of subpanels. Each subpanel can be expanded and closed by '+' and '-' buttons which are implemented by the SwingX library.

Figure 2. a) Bibliography, b) Bib, c) Common and d) Data panels.

The program is connected with external tools such as DANLO and CHEX. When the DANLO button is clicked, the FileChooser dialog box is shown. This allows extraction of a backup dictionary file (DAN_BACK_NEW.XXXX) in working directory.

Since Microsoft Windows operating systems are the most widely used computer platforms, execution of ForEX on Microsoft Windows has been considered with a priority. The program has been tested on Windows XP, 7 and 10. Executing ForEX on the GNU/Linux operating system has not been tested very often, but we confirmed it runs under Ubuntu 14.04.3 LTS. ForEX has not yet been tested on Mac OS.

ForEX is still under development, and addition of new features and bug fixes are being done on a daily basis.

3. Summary

A new EXFOR editor system, ForEX, is being developed by Java as a standalone application, which provides an environment for compilation of numerical data with its bibliographic and experimental information in the EXFOR format. The initial design was taken from its predecessor (HENDEL editor). The Swing component library was used to implement the GUI. In the current stage, the design of the user interface, coding for input forms and link with utilities (e.g., checking tools) were implemented. We have confirmed that the program works on Windows and Linux operating system. The output part is under construction. After development of the output function, we will start implementation of "Import" function, which will load existing EXFOR entries to ForEX for further editorial by ForEX.

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The container picture with two-alpha correlation for the ground state of ^{12}C

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^{12}C is one of the most important and interesting nucleus in nuclear cluster physics due to its typical 3α cluster structures [1–2]. Since 1970, the traditional microscopic cluster models have been used for exploring the rich cluster characters of ^{12}C, e.g., OCM (orthogonality condition model) calculation by Horiuchi [3], the full microscopic 3α cluster calculations by Uegaki et al, [4] and Kamimura et al. [5]. The proposed THSR(Tohsaki-Horiuchi-Schuck- Röpke) wave function in 2001 [6] has been very successful for the description of the gas-like cluster states, e.g., the Hoyle state of ^{12}C. Quite recently, we found that the THSR wave function can not only describe the gas-like cluster states with low density but also the cluster states with normal density very well, which urged us to introduce the container picture of cluster dynamics underlying the THSR wave function [7-8]. The high-percentage description of the compact ground state of ^{20}Ne by the single THSR wave function which is one of the important motivations to reconsider the squared overlap 93% between the single 3α THSR wave function of the ground state of ^{12}C and the corresponding RGM/GCM wave function. Thus, we expect to extend the original THSR to study whether the compact ground state of ^{12}C can also be described well by a single THSR wave function or not in the container picture. As for this work, see details in Ref. [9].

The constructed 2α+α THSR wave function is as follows,

$$\Phi(\beta_1,\beta_2) \propto \mathcal{A}\{\mathrm{Exp}[-\textstyle\sum_{i=1}^{2}(\frac{r_{ix}^2}{B_{ix}^2}+\frac{r_{iy}^2}{B_{iy}^2}+\frac{r_{iz}^2}{B_{iz}^2})]\phi(\alpha)\phi(\alpha)\phi(\alpha)\}.$$

Where $B_{1k}^2 = b^2+\beta_{1k}^2$, $B_{2k}^2 = b^2+\beta_{2k}^2$ and b is the size parameter of the harmonic oscillator wave function. $\phi(\alpha)$ is the α-cluster intrinsic wave function. In this 2α+α THSR wave function, 2α clusters make the motion in a container confined by the size parameter β_1 and this ^{8}Be(2α) cluster and the third α cluster can be considered to move in the other β_2-size container. Thus, the 2α correlation has been included in the constructed 2α+α THSR wave function. If we make the replacement, $\beta_1 \to \sqrt{2}\beta_0$ and $\beta_2 \to \sqrt{3/2}\beta_0$ in the above wave function, this 2α+α THSR wave function becomes the 3α THSR wave function with single β_0 parameter used by Funaki et al. in Ref. [10].

In the practical calculations, two kinds of potential parameters are adopted. Force 1 represents the parameters, Volkov No.1 with Majorana parameter M =0.575 and b =1.41 fm, which is used by Uegaki et al. for 3α Brink-GCM calculation [4]. Force 2 represents the parameters, Volkov No.2 (modified version) with Majorana parameter M =0.59 and b =1.35 fm, which is used by Kamimura et al. for 3α RGM calculation [5].

By making variation calculations, the minimum energy $E_{min}= -87.28$ MeV can be obtained at the position $\beta_{1x} = \beta_{1y} = 1.5$, $\beta_{1z} = 0.1$, $\beta_{2x} = \beta_{2y} = 0.1$, $\beta_{2z} = 3.2$ fm using Force 1 and E_{min}=-89.05 MeV at the position $\beta_{1x} = \beta_{1y} = 1.5$, $\beta_{1z} = 0.1$, $\beta_{2x} = \beta_{2y} = 0.1$, $\beta_{2z} = 3.2$ fm using Force 2. These energies are much deeper than the corresponding minimum energies by using the one-deformed-β_0 THSR wave function. This indicates that the 2α correlation cannot be neglected in the compact ground state of ^{12}C. It is surprising to find that there is still large room for the improvement for the compact ground state of ^{12}C in the container picture.

Potential	$E_{min}(\beta_0)$	$E_{min}(\beta_1,\beta_2)$	Full calculations	$E_{GCM}(\beta_0)$	$E_{GCM}(\beta_1,\beta_2)$	SO
Force 1	-86.09	-87.28	-87.92	-87.81	-87.98	0.975
Force 2	-87.68	-89.05	-89.4	-89.52	-89.65	0.978

Table 1: For the ground state of ^{12}C, $E_{min}(\beta_0)$ are the obtained minimum energies by using one deformed parameter β_0 in the 3α THSR wave function and $E_{GCM}(\beta_0)$ are the corresponding GCM energy [10]. $E_{min}(\beta_1, \beta_2)$ are the obtained minimum energies by using two deformed parameters (β_1, β_2) in the 2α+α THSR wave function and $E_{GCM}(\beta_1, \beta_2)$ are the corresponding GCM energy. The squared overlaps between $\Phi_{GCM}(\beta_1, \beta_2)$ and the single normalized 2α+α THSR wave functions corresponding to their minimum energies are also listed. Here, SO= $|\langle \Phi_{min}(\beta_1, \beta_2)|\Phi_{GCM}(\beta_1, \beta_2)\rangle|$. Units of energies are MeV.

In Table 1, we can find that the calculated squared overlaps $|\langle \Phi_{min}(\beta_1, \beta_2)|\Phi_{GCM}(\beta_1, \beta_2)\rangle|$ are as high as 98% by using two kinds of potentials. It is not surprising that the wave function can be improved by increasing the number of variational parameters. However, the obtained squared overlap 98% is surprising since this simple improved single THSR wave function is now almost 100% equivalent to the full solution of 3α cluster model. Since almost all the observed quantities including those related to the ground state are reproduced very well by the RGM/RGM wave functions [1], this means that our container wave function is also well supported by experiments. Furthermore, while the previous THSR calculations for ^{12}C show that the squared overlap between the single 3α THSR wave function and the THSR-GCM wave function for the ground state is at most 93%, by introducing the 2α correlation, the corresponding squared overlap increases to 98%. This provides a strong support for the existence of the 2α correlation in the ground state of ^{12}C.

Acknowledgement

The authors would like to thank Prof. Gerd Röpke, Prof. Peter Schuck, Prof. Taiichi Yamada, and Prof. Chang Xu for helpful discussions. B.Z. wishes to acknowledge discussions with Prof. Naoyuki Itagaki, Prof. Eiji Uegaki, and Dr. Tadahiro Suhara.

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Monte Carlo simulation for thick-target yields deduced from inverse kinematics

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Transmutation of radioactive material such as long-lived fission products (LLFPs) ejected from nuclear plants, is an important technology to reduce them. The thick-target yield (TTY) of the reaction is an essential data although it is difficult to accommodate the radioactive target as LLFPs in the experiment. To avoid the experiments using the targets, we suggested an estimation of the TTY based on inverse kinematics [1].

TTY is defined as the reaction probability in a matter. The TTY Y can be describe microscopically by the beam penetration length x, the cross section σ and the number density ρ of the target matter. The definition of a differential TTY is

$$dY = \sigma \frac{N_A \rho}{A_T} dx, \tag{1}$$

where dx is the infinitesimal penetration length of projectile particles, A_T is a mass of target and N_A is Avogadro constant. Since the energy loss of the beam can be estimated by the mass stopping power $S(\varepsilon) = -\frac{A_p d\varepsilon}{d(\rho x)}$ with a mass of projectile A_P and the beam energy ($\varepsilon = E/A$), the variable of TTY is replaced into the energy. The whole TTY is obtained by integration of Eq. (1) with the $S(\varepsilon)$,

$$Y(\epsilon_{\mathrm{i}}) = \frac{N_A A_P}{A_T} \int_0^{\epsilon_{\mathrm{i}}} \frac{\sigma(\epsilon)}{S(\epsilon)} d\epsilon, \tag{2}$$

where ε_{i} is an incident energy. We assume that the incident particle is stopped inside the target, which gives the zero of the bottom energy in the integration.

The inverse kinematics which is to replace target and projectile in the reaction system is often applied especially to unstable nuclear system. We apply the inverse kinematics to investigate the TTY of radioactive targets. The target and projectile in a “forward reaction” are shown as the T and P. The inverse kinematics of the reaction is named the “inverse reaction”. Physical values such as TTY of “forward” and “inverse” are denoted by the “for” and “inv” subscripts, for instance Y_{for} and Y_{inv}. Therefore, the ratio between differential TTYs is represented as

$$\frac{dY_{\mathrm{for}}(\varepsilon)}{dY_{\mathrm{inv}}(\varepsilon)} = \frac{A_P^2 S_{\mathrm{inv}}(\varepsilon)}{A_T^2 S_{\mathrm{for}}(\varepsilon)} \equiv R(\varepsilon), \tag{3}$$

with the same energy ε. The Y_{for} can be deduced from the ratio and the dY_{inv}, are given. The TTY on the radioactive target is converted from its inverse kinematics such as using RI beam. The stopping powers of forward and inverse reaction is evaluated by SRIM code [2], and hence the ratio is easily derived as shown in Fig. 1.

The conversion method is applied to the reaction ^{nat}Cu(^{12}C,X)^{24}Na [3] to confirm the relation between ^{nat}Cu(^{12}C,X)^{24}Na forward and ^{12}C(^{63,65}Cu,X)^{24}Na inverse kinematics reactions. The $\sigma(\varepsilon)$ and $S(\varepsilon)$ are needed to calculate the Y_{for} and Y_{inv} from Eq. (2). The energy dependence of the cross section is prepared by the spline interpolating of experimental data [3] (shown in Fig.2), and the stopping powers are computed using SRIM code [2]. The stopping powers and the ratio in Eq. (3) are shown in Fig. 3 (a) and (b), respectively. The TTYs are evaluated from Eq. (2) using these data and the mass A_T(^{nat}Cu) = 63.564 with the energy ε_{i}=40 and 100 MeV/nucleon cases. On the other hand, $Y_{\mathrm{for}}(\varepsilon)$ can be obtained from the integration of $R(\varepsilon)dY_{\mathrm{inv}}(\varepsilon)$ in Eq. (3) and vice versa. Here, we note that the ratio $R(\varepsilon)$ in Fig. 3 (b) converges on a constant value at the high energy over 50 MeV/nucleon. The cross section in Fig. 2 is small in the low energy region since such fragmentation reaction requires a large amount of energy. This simple behavior of $R(\varepsilon)$ and the small $\sigma(\varepsilon)$ allows us to utilize a more convenient method as:

$$Y_{\mathrm{for}}(\varepsilon_{\mathrm{i}}) = \tilde{R}Y_{\mathrm{inv}}(\varepsilon_{\mathrm{i}}), \qquad (4)$$

where the $\tilde{R}$ is a constant value of ratio at high energy over 50 MeV/nucleon in this case. The value $\tilde{R}$=1.1 and the $Y_{\mathrm{inv}}(\varepsilon_{\mathrm{i}})$ which is estimated from Eq. (2) give the $Y_{\mathrm{for}}(\varepsilon_{\mathrm{i}})$ immediately. We show the results of $Y_{\mathrm{for}}(\varepsilon)$ from Eqs. (2) and (4) in Table 1 and of $Y_{\mathrm{inv}}(\varepsilon)$ form Eq. (2) in Table 2. The result in the simple conversion agrees with that of Eq. (2) especially at 100 MeV/nucleon.

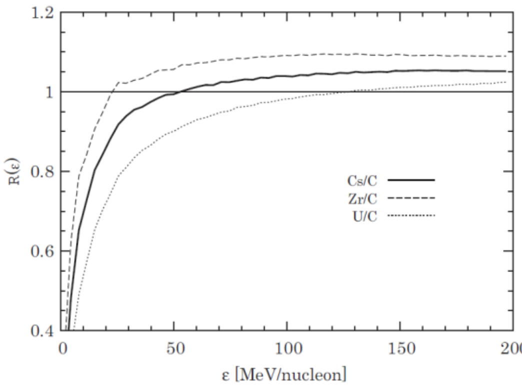

Fig.1 : $R(\varepsilon)$s for Cs on C (Cs/C), Zr on C (Zr/C) and U on C (U/C) are simulated by SRIM code [2].

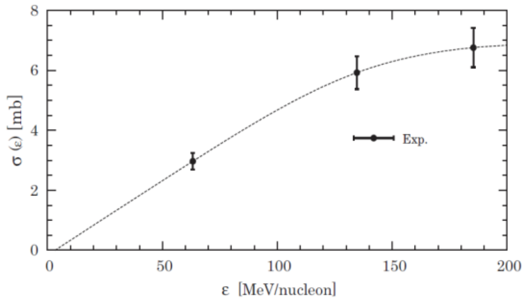

Fig.2 : Cross section with respect to ε of the ^{nat}Cu(^{12}C,X)^{24}Na reaction taken from the experimental data [3] with the spline fitting (dashed).

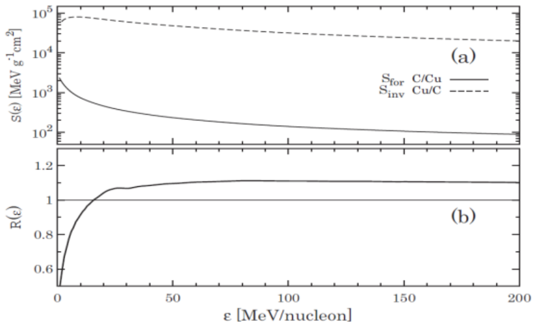

Fig.3 : (a) Stopping powers $S_{\mathrm{for,inv}}(\varepsilon)$ and (b) ratio $R(\varepsilon)$ of the Cu + C system by SRIM2008 [2].

Table 1: TTYs for the forward reaction $Y_{\mathrm{for}}(\varepsilon)$ evaluated from Eqs. (2) and (4) at the ε_{i}=40 and 100 MeV/nucleon.

Forward reaction	40 MeV/nucleon	100 MeV/nucleon
Eq. (2)	0.91×10^{-5}	1.14×10^{-4}
Eq. (4)	0.94×10^{-5}	1.13×10^{-4}

Table 2: TTY for the inverse kinematics $Y_{\mathrm{inv}}(\varepsilon)$ evaluated from Eq. (2) at the ε_{i}=40 and 100 MeV/nucleon. This result is used in Eq. (4) to estimate $Y_{\mathrm{for}}(\varepsilon)$.

Inverse reaction	40 MeV/nucleon	100 MeV/nucleon
Eq. (2)	0.86×10^{-5}	1.03×10^{-4}

The above results are derived under a simple assumption neglecting the effect of second particles. To check the effect, we perform a Monte Carlo simulation on the $^{63}Cu(^{12}C,X)^{24}Na$ reaction with the Particle and Heavy Ion Transport code System (PHITS)[4]. We consider ^{63}Cu instead of ^{nat}Cu, since the natural abundance of capper is known as about 70%. We can separate the effects of scattering particles by Light (n, p, d, triton, ^{3}He and alpha) and Heavy (others: ^{12}C, ^{63}Cu etc.). The yield of ^{24}Na in both of "forward" and "inverse reaction" systems are simulated by 10^5 trials. The results are shown in Table 3 and 4. The effects of the secondary particle seem small on the TTY, which indicates that the contribution is also small in the conversion between Y_{for} and Y_{inv} although it might depend on the reaction system.

Table 3: The effect of secondary particles simulated by PHITS in forward reaction.

Forward reaction	40 MeV/nucleon	100 MeV/nucleon
w/ Light and Heavy	1.760×10^{-5}	1.618×10^{-4}
w/ Light	1.760×10^{-5}	1.618×10^{-4}
w/ Heavy	1.760×10^{-5}	1.616×10^{-4}

We suggest the conversion method for TTY based on inverse kinematics. According to the method, the TTY of radioactive nuclide can be deduced without a direct experiment by radioactive target. We confirm the feasibility of out method to apply to the $^{nat}Cu(^{12}C,X)^{24}Na$ reaction system [3]. The conversion relation is simplified to the linear relation Eq. (4) in high energy. The effect of secondary particles is checked using PHITS simulation and found that it might be small on the method. The conversion method will be applied to specific radioactive nuclide such as LLFP.

Table 4: The effect of secondary particles simulated by PHITS in inverse reaction.

Forward reaction	40 MeV/nucleon	100 MeV/nucleon
w/ Light and Heavy	1.530×10^{-5}	1.538×10^{-4}
w/ Light	1.540×10^{-5}	1.538×10^{-4}
w/ Heavy	1.530×10^{-5}	1.548×10^{-4}

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RECENT CHARGED-PARTICLE INDUCED REACTION DATA MEASUREMENTS PERFORMED IN KAZAKHSTAN

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This is the second year as the Kazakhstan team is actively engaged in the compilation of articles to EXFOR database. Since our report in the 5th AASPP workshop (Mumbai, September 2014 [1]), the following six articles have been compiled. All articles report charged-particle induced reaction experimental works performed by using the U-150M cyclotron in Almaty or the DC-60 cyclotron in Astana.

Entry #	**First author**	**Article**	**Lab.**	**Status***
D0744	A.Duisebaev	J,BAS,78,(7),601,2014	Almaty	EXFOR
D0745	B.N.Gikal	J,PPN/L,11,(4),462,2014	Astana	EXFOR
D0751	Sh.Hamada	J,IMP/E,22,1350058,2013	Astana	EXFOR
D0770	N.A.Mynbayev	J,JET,119,(4),663,2014	Almaty	Compiled
D0771	N.Burtebayev	J,PAN,59,(1),29,1996	Almaty	Compiled
D0773	K.G.Kuvatov	J,SNP,14,45,1972	Almaty	Compiled

*
EXFOR: Accessible through the EXFOR web retrieval systems.
Compiled: Compiled and waiting transmission to other centres.
Short description of each article:

D0744: This experimental work measured the double differential cross sections for (p,xp) and (p,xα) reactions on the ^{209}Bi nucleus at Ep = 30.0 MeV.

D0745: This experimental work measured the thick target yields of neutrons emitted from light materials (Be, C, Al, Al_2O_3, and LiF) irradiated by heavy ions (Ar, Kr, Xe) at 0.7 to 1.8 MeV/nucleon.

D0751: This experimental work measured the angular distributions of ^{16}O ion beam elastically scattered by ^{16}O nuclei at 20, 24 and 28 MeV.

D0771: This experimental work measured the angular distributions of alphas elastically and inelastically scattered by ^{6}Li and ^{7}Li at 50 MeV..

D0770: This experimental work measured the excitation function of the ^{13}C + ^{4}He elastic scattering by the thick target inverse kinematics method (TTIK). The main feature of this work is using the method to observe resonances by TTIK.

For all entries, their numerical data were received from the authors or taken from the tables of the articles *without digitization*. We would thank to all authors who submitted the numerical data for compilation.

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CANRDB: current activities, issues and prospects

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The history of nuclear physics and nuclear research facilities started in Kazakhstan more than 60 years ago. Considerable part of it in the past was related to military tests of nuclear bombs and other activities at located here Semipalatinsk test site. Today the consequent problem of lands decontamination and radiation safety is a very important problem in our country. Rapid development of information technologies is common to various areas of science and research; it is particularly noticeable in nuclear physics. The amount of data obtained and used in modern nuclear physics is huge and continuously increases with time. Creation in 2013 of the Central Asian Nuclear Research Data Base (CA-NRDB) was therefore very important for the whole region of Central Asia.

The CA-NRDB group carries out an important work on the creation of specialized programs and data protection. New data sectors were created:

- Data on nuclear reactions for astrophysics;
- Data on neutron resonances for nuclear physics and nuclear astrophysics;
- Data on nuclear chemistry applications and on radio-active elements.

The important sector for nuclear medicine is at the beginning of creation and development. Our university already has agreements with research centers in South Korea. We started the collaboration with Hokkaido University, Osaka University and JAEA. New international scientific ties have emerged and strengthened (France, USA, Italy, etc.).

Traditionally, al-Farabi Kazakh National University supports the close relations and cooperation with the Institute of Nuclear Physics (Almaty) and L.N. Gumilyov Eurasian National University (Astana), where main accelerators and basic experimental facilities for nuclear physics are located:

- isochronous cyclotron
- the small-sized cyclotron
- the accelerator of heavy ions DC-60
- electrostatic recharging accelerator UKP-2-1
- research nuclear reactor WWR-K, etc.

Joint research groups in nuclear physics conduct new experiments and take part in international collaborations with JINR (Dubna, Russia) and CERN, where our students acquire practical skills and gain experience.

The accelerator of heavy ions DC-60. It was manufactured in Flerov Laboratory of nuclear reactions of the Joint Institute for Nuclear Research (Dubna, Russian Federation). Physical start of the accelerator took place on September 21st, 2006 in Astana. This is the first in the Central Asia powerful accelerator of heavy ions which consists of an injector-implanter based on ECR-source, a cyclotron and channels of transportation of heavy ions. The injector-implanter allows to produce bunches of ions with energies up to 40 keV per charge. One of the main components of the cyclotron is a source of heavy ions. It can work as a heavy ion injector in cyclotron for generating high energy ion beams or operate in autonomous regime in experiments with low energy beams.

National Nuclear Center of the Republic of Kazakhstan was founded at beginning of 90' at the former Semipalatinsk test site. Now NNC operates several facilities and has the departments: Tokamak KTM, Park of Nuclear Technologies, Radiation Technologies Complex and Museum of former Semipalatinsk nuclear test site, etc.

The current CA-NRDB activities

The CA-NRDB of the characteristics of nuclear reactions and properties of atomic nuclei is replenished with the database of hazardous chemical and radioactive substances. Following the suggestions of radio ecologists, we started to form a sector in the Database on hazardous chemical and radioactive substances.

The Ministry of Education and Science of Kazakhstan funded our database in 2013-2015. We plan to prepare and submit a new project related to the development of CA-NRDB for the next three years.

Fig. 1: Main page of CANRDB cite

Currently, our team is actively working on expansion of the database, improvement of the website productivity, further development of the specialized software, and fostering partnership with international nuclear physicists. We already developed our website with ergonomic graphical interface and own database structure. CA-NRDB website is available in three languages – Kazakh, English and Russian at http://canrdb.kaznu.kz/. Our database is designed to support educational activities and scientific research. An extensive electronic library was also created to incorporate textbooks, presentations, lecture materials, scientific papers, etc.

Below is a list of latest changes in the CA-NRDB website and database:
Server components have been replaced by a newer version: IIS (Internet Information Services) 7 to IIS 8; Created a new connection string script to improve a website connection speed; Added sections for "Nuclear Data Editor" and "Neutron Resonance Data"; Added and filled a section "Publications"; Created a graphical interface of the database: GNUI MySQL and etc…

We also improved the efficiency of the database. As a result, CA-NRDB now has multi-level streaming and relational I/O massive data. The sector (http://canrdb.kaznu.kz/) was established in the Information department of KazNU. The database is constantly updated and has already proved to be useful for students specializing in physics and nuclear physics.

It was important for the KazNU to create the special educational sector of the CA-NRDB which included the following:

- Nuclear Reaction Database for Education (for students and teachers);
- Virtual Laboratories: Computer laboratory practice "Interaction of particles with matter" (created by T.S. Ramazanov, A.V. Yushkov, V.V. D'yachkov et. al.); Computer laboratory practice "Study of gamma rays and neutrons produced in nuclear reactions" (F.B. Baimbetov, A.H. Abuldaev, V.V. D'yachkov et. al.);
- Electronic handbooks (A.V. Yushkov, V.V. D'yachkov)
    - Nuclear Data Base Reviewer & Calculator (Yushkov, V.V. D'yachkov and Yu. A. Zaripova)
- Data on interaction of gamma rays with matter; alpha particles with matter
- a Handbook of atomic nuclei, etc.

Our CA-NRDB team maintains friendly cooperative relations with many data centers in different countries. We look forward to our fruitful cooperation with the team of Hokkaido University and we are planning to upload all the noticeable domestic papers into the EXFOR by the next technical meeting in Beijing on 26-29 April, 2016.

We thank the MSU database team and prof. V.V. Varlamov for their support and useful advices. The main objective of the CA-NRDB is the development and formation in Kazakhstan of open and user-friendly database on nuclear reactions with further incorporation of this database into the international network of nuclear databases under the IAEA.

This year our database was significantly improved and we recreated a database data structure by using a SQL Server technology from Microsoft Corporation.

The CA-NRDB team has participated in the technical meeting of NRDC under the auspices of the IAEA held in Vienna (Austria) on April 21-23, 2015. Participation in this meeting was of particular importance for the CA-NRDB team and allowed to present our activities among experienced colleagues from other centers with nuclear databases.

Fig. 2: Young scientists at JAEA training seminars 2015

Neutron resonances at crystalline structures in the thermal range

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In this work, we propose investigating the neutron resonances employing piezo-crystals with Cd isotopes, which have resonances in the thermal range. It is noticeable that Cd crystals demonstrate piezo electric features what allows changing the crystal parameters. Recently, neutron resonances at low thermal energy were found for the few isotopes, including ^{113}Cd (see Table 1 and details at the site [1]).

Table 1. Isotopes with resonances in the low thermal range

Isotope	Abundance (%)	Wavelength (Å)	Energy (meV)
Gd-155	14.800	6.44	1.97
Gd-157	15.650	6.18	2.14
Sm-149	13.820	6.02	2.26
Cd-113	12.220	5.44	2.77
Hf-177	18.600	4.03	5.04
Sm-152	26.750	2.74	10.93

New neutron resonances are formed at re-scattering of a neutron on a subsystem of heavy nuclei [2]. Such neutron resonances become stronger at specific distances between the nuclei and the resonances vanish if the distances are larger or less than these resonance distances [3, 4].

For example, the isotopes ^{113}Cd are considered because the corresponding the electric piezo effect allows to vary the distances between the nuclei in the range.

Theoretical background

The quantum scattering theory for three-body systems is based on Faddeev equations

$$T_{ij} = t_i\,\delta_{ij} + \sum_k t_i\, G_0\, \bar{\delta}_{ik}\, T_{kj} \quad , \quad i, j, k = 1,2,3\,, \tag{1}$$

where the conditions of existence and uniqueness of solutions are satisfied (i, j, k is the number of pair). In the case of resonance in two-body subsystem, we can write in the resonance energy region the two-body *t*-matrix in the Breit-Wigner form:

$$t_i(k_0;\vec{k},\vec{k}') = \bar{\nu}_i(\vec{k})\cdot\eta_i(k_0)\cdot\nu_i(\vec{k}')\,, \quad \eta_i^{-1}(k_0) = (E_0 - E_{R;i} + i\Gamma_i/2)\,. \tag{2}$$

$E_{R;i} = k_{res}^2/2m$ is the energy of two-body resonance, Γ_i is the width of the resonance.

For the three-body resonance scattering we can write the elements of *T*– matrix also in the simple form [3, 4]:

$$T_{ij} = \frac{1}{k_0 m}\sqrt{\Gamma_i}\,M_{ij}\sqrt{\Gamma_j} \quad , \tag{3}$$

$$M_{ij} = M_{ij}(\vec{r},\vec{r}\,') = M_{ij}^{+}(\vec{r})\delta(\vec{r}+\vec{r}\,') + M_{ij}^{-}(\vec{r})\delta(-\vec{r}+\vec{r}\,') \quad , \tag{4}$$

$$M_{i,j}^{+}(\vec{r},k_0) = \frac{1}{D_{i,i}(\vec{r},k_0)}\,J_{i,j}(\vec{r},k_0) \quad , \tag{5}$$

$$M_{i,j=i}^{-}(\vec{r},k_0) = \frac{1}{D_{i,i}(\vec{r},k_0)}\,J_{i,l}(\vec{r},k_0)\eta_l(k_0)J_{l,j}(-\vec{r},k_0) \quad , \tag{6}$$

$$J_{i,j}(\vec{r},k_0) = 2m\int d\vec{k}\exp(i\vec{k}\vec{r})\frac{\nu_i(k)\bar{\nu}_j(k)}{k_0^2 - k^2 + i\gamma} \quad , \tag{7}$$

$$D_{i,i}(\vec{r},k_0) = \delta_{ij} - \sum_l J_{i,l}(\vec{r})\eta_l(k_0)J_{l,j}(-\vec{r})\,. \tag{8}$$

Here $D_{i,i}(\vec{r},k_0)$ is the diagonal element, because $D_{i,j}(\vec{r},k_0) = 0$ if $j \neq i$ [3].

In the case of the neutron scattering at the system of two heavy nuclei the three-body *T*-matrix can take the form:

$$< T > = \sum_i \bar{\nu}_i\eta_i\nu_i + \sum_{i,j} \bar{\nu}_i\eta_i < M_{i,j} > \eta_j\nu_j \quad , \tag{10}$$

The $< T >$ form means that the *M*-matrix is taken in the brackets of the free wave functions $\overline{\Psi}_i$ and Ψ_j, then $< M_{i,j} >= M_{i,j}(\vec{r}_i) = M_{i,j}(-\vec{r}_j)$ [3-5], where, for simplicity, we omit the indices and take: $\vec{r}_i = \vec{r}$ and $\vec{r}_j = \vec{r}\,' = -\vec{r}$. Then the modulus of enhancement factor can be written as

$$F(k_0;\vec{r}) = \left| \sum_{i,j} \bar{\nu}_i\eta_i < M_{i,j} > \eta_j\nu_j / t_i \right|^2 \tag{11}$$

Our goal is the study of the three-body resonance effects in the scattering of neutrons at subsystem of two isotopes in the dependence of distances between these heavy nuclei.

In order that the distance between the nuclei in the target has been unchanged during the neutron irradiation, we propose to use the crystal target, and the distance between the nuclei to change using the piezoelectric effect.

Determination of crystal parameters

We determined the lattice parameters for the selected isotopes. These nuclei have piezoelectric properties. Isotope 113 Cd has the more suitable properties.

Table 2 contains the parameters of $Cd\,S$ and $Cd\,Se$ crystals with a hexagonal (h) and a face-centered cubic (c) structures [5]. The d is the distances between two neighboring Cd nuclei, r = d/2.

Table 2. Parameters of Cd crystals

Phase	a = b (Å)	c (Å)	d (Å)
$Cd\,S$; h	4.13	6.71	4.116
$Cd\,S$; c	5.3	5.3	3.748
$Cd\,Se$; h	4.29	7.01	4.292
$Cd\,Se$; c	5.54	5.54	3.917

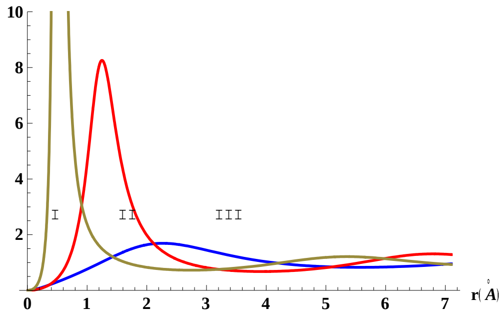

Figure 1.
F(k0,r); the system n + [113]Cd + [113]Cd;
here I, II, III correspond to the cases with
k_0 = 0.988; 1.15; 1.278.

In the case when the resonance energies of two isotopes are not close to each other we have the following pattern:

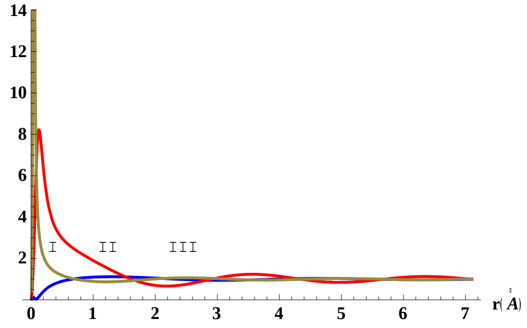

Figure 2.
F(k0,r);the system n + ^{149}Sm + ^{152}Sm;
here I, II, III correspond to the cases with
k_0 = 1.9537; 2.2955; 2.5283.

Conclusion

We calculated new neutron resonances for the systems of two nuclei in the energy range close to conventional neutron-nucleus resonances. We were focused on the study of the three-body resonance effects at scattering of neutrons on a subsystem of two isotopes when distances between these nuclei are taken into account.

All stated above opens up opportunities to use specialized piezo-crystals and to assure control over the target parameters in the experiments with thermal resonance neutrons. For example, it is possible to set up the thermal neutron scattering experiments with different targets such as *CdS* and *CdSe* crystals.

One should note that the new neutron resonances are created by interactions in three-body systems. They supplement the well-known phenomena such as Bragg's scattering (Bragg's law and neutron diffraction).

However, the new neutron resonances have a different origin - they are obliged the re-scattering of resonance neutrons on heavy nuclei. As in the Mossbauer effect, crystal structure accepts the recoil momentum, which give the strengthening of neutron resonances.

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Measurement of Charged particle-, Neutron-, and Photon-induced Reactions in Korea

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Measurement of charged particle-, neutron-, and photon-induced reactions are presented. Charged particle-induced reaction cross-sections are determined by using the stacked-foil activation technique at the MC-50 cyclotron facility in the Korean Institute of Radiological and Medical Science. Neutron-induced nuclear data were measured by using the pulsed neutron facility, which consists of an electron linear accelerator, a water-cooled Ta target with a water moderator, and a 12 m time-of-flight path. It can be possible to measure the neutron total cross-sections in the neutron energy range from 0.01 eV to few hundreds eV by using the neutron time-of-flight method and also measured the photo-neutron cross-sections by using the bremsstrahlung from the electron linac.

We collaborated with foreign researchers in India, Japan, Russia, China, and Vietnam. We also utilized foreign facilities in India, Japan, Rusia, and USA.

Overview of Compilation for the EXFOR Library in Mongolia

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For three years (Japanese FY2011-2013) one of us (MO) had training at the Hokkaido University Nuclear Reaction Data Centre (JCPRG) for compilation of charged-particle induced nuclear reaction data measured at Japanese facilities. After this training, we started our Mongolia-IAEA collaboration in 2014 for compilation of heavy-ion (A>12) induced reaction data measured in West European countries for the EXFOR library [1]. Until now we have compiled 17 EXFOR entries from articles published in 2009-2015 (Table 1). Note that the first author of the first article for our compilation (EXFOR D0731) is from Mongolia.

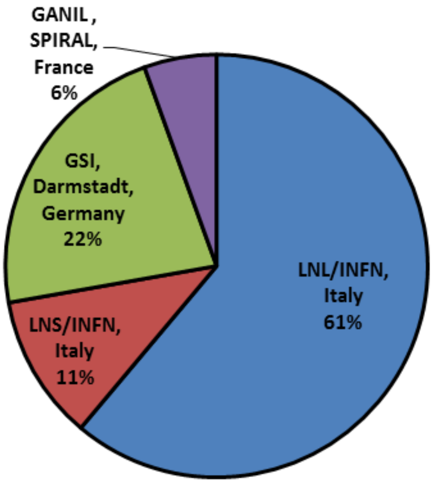

Figure 1. Laboratory’s ratio of compiled entry in 2014 and 2015

Figure 1 shows that we have mainly compiled heavy-ion induced reaction data measured at the INFN Laboratori Nazionali di Legnaro (INFN/LNL), Italy.

To maintain good quality of the EXFOR library, one of us (NO) always asks authors to provide the original numerical data. So far we have received numerical data for all cases, and it enables us to avoid compilation of digitized data. There is officially no data centre responsible for compilation of heavy-ion induced reaction data measured in West European countries, and the aim of our collaboration is to improve their completeness in the EXFOR library.

Table 1. List of compiled articles

Entry number	First author	Journal volume, page and publication year+	Laboratory, country	Year of compilation	Status*
D0731	J.Khuyagbaatar	J,PRL,112,172501,2014	GSI, Darmstadt, Germany	2014	in EXFOR
D0732	G.Benzoni	J,EPJ/A,45,287,2010	GANIL, France	2014	in EXFOR
D0736	K.Nishio	J,PR/C,82,024611,2010	GSI, Darmstadt, Germany	2014	in EXFOR
D0740	F.C.L.Crespi	J,PRL,113,012501,2014	LNL, INFN, Italy	2014	in EXFOR
D0741	C.L.Jiang	J,PRL,113,022701,2014	LNL, INFN, Italy	2014	in EXFOR
D0746	D.Bourgin	J,PR/C,90,044610,2014	LNL, INFN, Italy	2014	in EXFOR
D0747	F.Cappuzzello	J,NIM/A,763,314,2014	LNS, INFN, Italy	2014	in EXFOR
D0749	A.Estrade	J,PRL,113,132501,2014	GSI, Darmstadt, Germany	2014	in EXFOR
D0750	G.Montagnoli	J,PR/C,90,044608,2014	LNL, INFN, Italy	2014	in EXFOR
D0758	G.Montagnoli	J,PR/C,85,024607,2012	LNL, INFN, Italy	2014	in EXFOR
D0759	C.L.Jiang	J,PR/C,82,041601,2010	LNL, INFN, Italy	2014	in EXFOR
D0761	L.Pellegri	J,PL/B,738,519,2014	LNL, INFN, Italy	2015	in EXFOR
D0767	F.C.L.Crespi	J,PR/C,91,024323,2015	LNL, INFN, Italy	2015	in EXFOR
D0772	G.Montagnoli	J,PL/B,746,300,2015	LNL, INFN, Italy	2015	PRELIM
D0774	C.L.Jiang	J,PR/C,91,044602,2015	LNL, INFN, Italy	2015	PRELIM
D0775	D.Carbone	J,PR/C,90,064621,2014	LNS, INFN, Italy	2015	PRELIM
D0776	J.V.Kratz	J,PR/C,88,054615,2013	GSI, Darmstadt, Germany	2015	in Compilation

+ PRL: Phys. Rev. Lett, EPJ/A: Eur. Phys. J. A, PR/C: Phys. Rev. C, NIM/A: Nucl. Instrum. Meth. A, PL/B: Phys. Lett. B.

* "in EXFOR": The EXFOR entry is accessible through the EXFOR web retrieval systems. "PRELIM": The EXFOR entry was created and under review by other centres. "in Compilation": The EXFOR entry was created and to be reviewed.

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(n,α) REACTION CROSS SECTIONS AND ANGULAR DISTRIBUTIONS FOR SEVERAL MeV NEUTRONS

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1. INTRODUCTION

Fast neutron induced (n,α) reaction data are important for both nuclear reactor technology and the understanding of basic nuclear physics problems. For example, the (n,α) reaction leads to a buildup of residual radioactivity and radiation damage due to helium production in the structural materials. On the other hand, systematic study of such reactions depending on neutron energy allows the contributions of compound, pre-equilibrium and direct mechanisms to the studied reactions to be determined. However, for neutron energy of several MeV, where the thresholds of many of the (n,α) reactions lie, the experimental data base is rather scarce and significant discrepancies between the available results of various authors there are. In addition, essential deviations among evaluated nuclear data libraries for fast neutron induced (n,α) reaction cross sections exist.

In connection with this situation, during last ~20 years in the several MeV energy range of neutrons we (collaboration of the Nuclear Research Center, National University of Mongolia, Ulaanbaatar, Mongolia, Institute of Heavy Ion Physics, Peking University, Beijing, P.R.China and the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russian Federation) studied the (n,α) reaction for broad mass of nuclei ($6 \le A \le 149$).

In this work from the unified view point using the TALYS-1.6 code [1] we analyzed our experimental (n,α) cross sections and angular distributions at the several MeV energies of neutrons and for medium mass nuclei including 11 isotopes from ^{39}K to ^{95}Mo [2-16]. Our results are compared to other existing experimental data [17-48] and the evaluated nuclear data libraries [49], also.

2. EXPERIMENTAL METHODS

Experimental setup are composed of main three parts: the neutron source, the α-spectrometer, and the neutron detector.

Several MeV neutrons were produced on the 4.5 MV Van de Graaff accelerator of Peking University, P.R. China through the ^{3}H(p,n)^{3}He and ^{2}H(d,n)^{3}He reactions using a solid Ti-T target and a deuterium gas target, respectively.

The detector of α-particle from (n,α) reaction was a two section gridded ionization chamber with common cathode [50,51]. A mixture of Kr+(2÷3)% CO_2 was used as working gas in the ionization chamber. Two thin samples were back-to-back attached to the common cathode of the twin ionization chamber. The absolute neutron flux was determined by fission of the ^{238}U (99.999%) and for neutron flux monitor was employed a BF_3 long counter.

3. TOTAL (n,α) CROSS SECTIONS

The total (n,α) cross sections in the several MeV energy range of neutrons for 11 medium mass nuclei from ^{39}K to ^{95}Mo were measured and compared with other existing experimental data, evaluated nuclear data libraries and TALYS-1.6 calculations. Results of such analysis for ^{39}K, ^{40}Ca, ^{58}Ni and ^{64}Zn are, as example, shown in Fig.1.

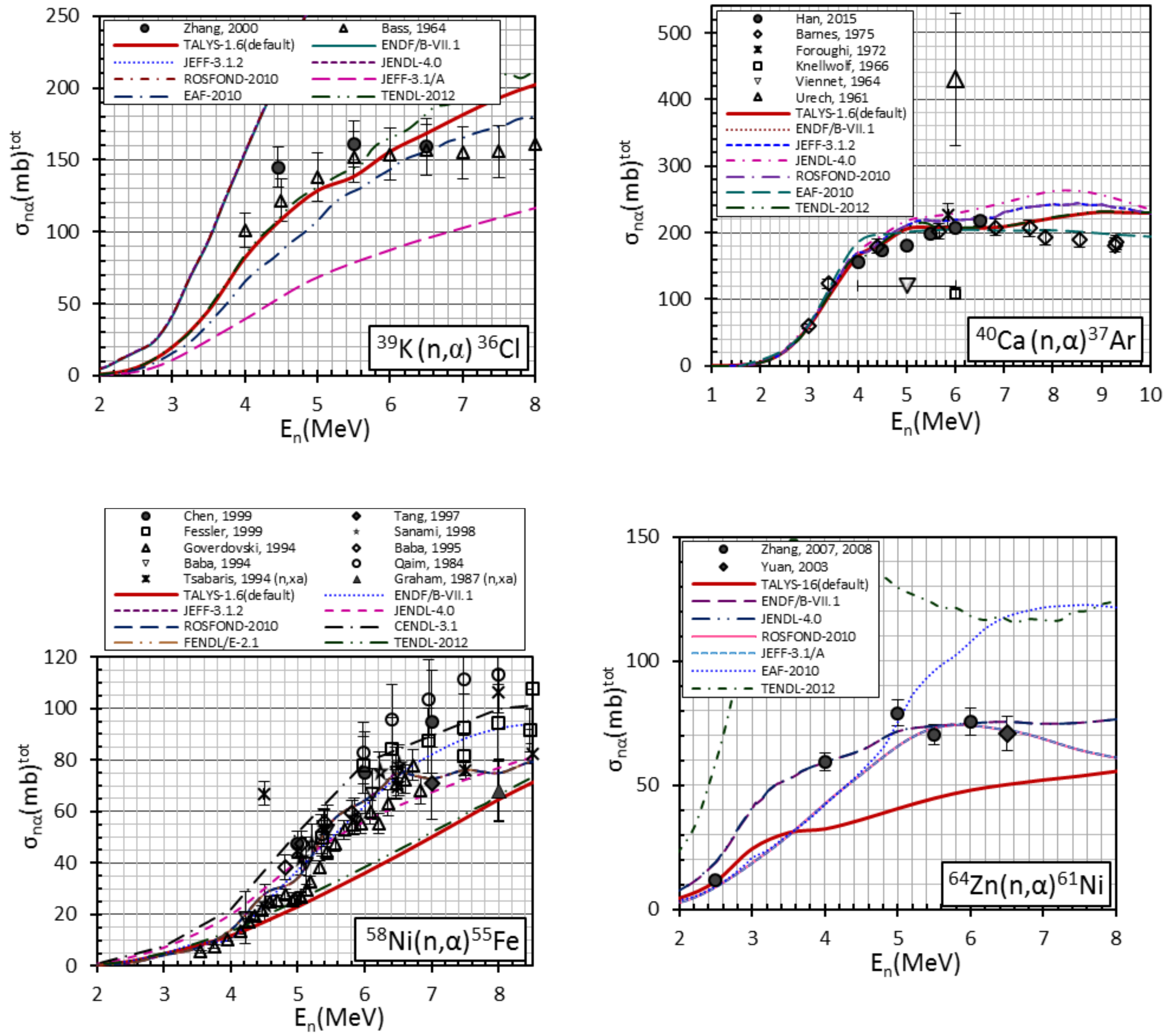

Fig.1. Total (n,α) cross sections for ^{39}K, ^{40}Ca, ^{58}Ni and ^{64}Zn.

It can be seen that for total (n,α) cross sections existing experimental data of medium mass nuclei are very scanty and different among themselves, and evaluated nuclear data libraries give essential various results for the same nucleus except ^{40}Ca.

From these analyses it can be concluded that our experimental (n,α) cross sections are in agreement with TALYS-1.6 calculations with default optical potential parameters for ^{40}Ca, ^{57}Fe, ^{63}Cu and ^{66}Zn. At the same time our experimental results are in disagreement with TALYS-1.6 calculations for ^{56}Fe, ^{58}Ni, ^{64}Zn, ^{67}Zn and ^{95}Mo. For ^{54}Fe and ^{39}K trend of dependence of the experimental (n,α) cross sections on the neutron energy is roughly described by TALYS-1.6 calculations. Moreover, the total (n,α) cross sections calculated by TALYS-1.6 with default parameters and Talys-based Evaluated Nuclear Data Library (TENDL-2012) for the same reaction have visible discrepancy for ^{64}Zn, ^{66}Zn, ^{67}Zn and ^{95}Mo.

4. ANGULAR DISTRIBUTIONS

The angular distributions of emitted α-particles from (n,α) reactions induced by fast neutrons were measured for ^{39}K, ^{40}Ca, ^{58}Ni and ^{64}Zn (Fig.2). These angular distributions are nearly symmetrical with respect to $\theta_{cm}=90^{\circ}$.

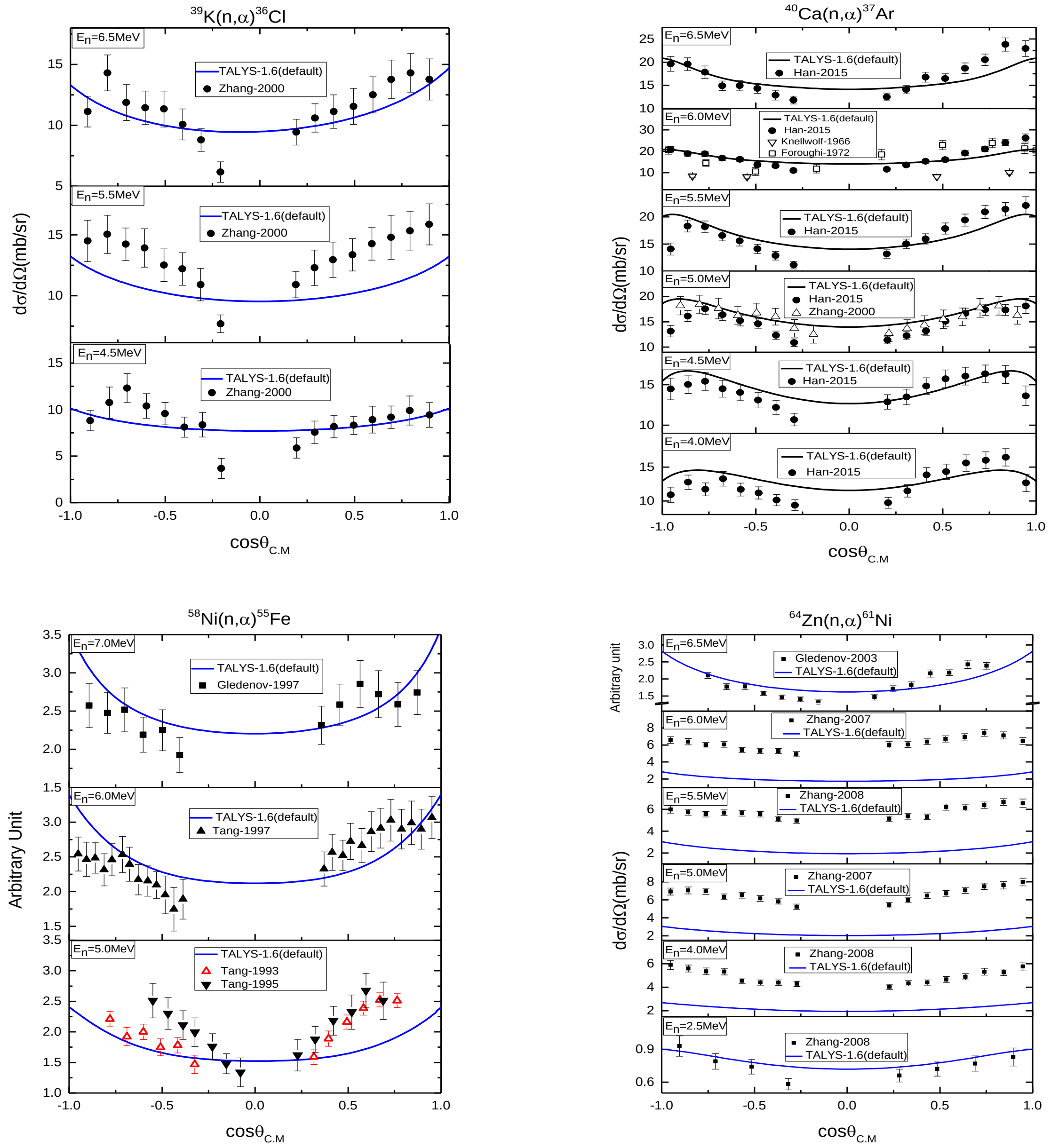

Fig.2. Angular distributions for the $^{39}K(n,\alpha)^{36}Cl$, $^{40}Ca(n,\alpha)^{37}Ar$, $^{58}Ni(n,\alpha)^{55}Fe$, and $^{64}Zn(n,\alpha)^{61}Ni$ reactions.

This fact indicates that compound mechanism predominates over the pre-equilibrium and direct reaction mechanisms in these reactions. Also, in Fig.2 our experimental angular distributions are compared with TALYS-1.6 calculations. For the $^{58}Ni(n,\alpha)^{55}Fe$ reaction the results calculated by TALYS-1.6 are normalized to experimental data at the $\theta_{cm}=90^{\circ}$ which are given in arbitrary units. It is seen that for double magic nucleus ^{40}Ca the experimental angular distributions are in agreement with TALYS-1.6 calculations with default parameters. At the same time for ^{39}K, ^{58}Ni and ^{64}Zn there are some discrepancies between the experimental data and the TALYS-1.6 calculations with default parameters.

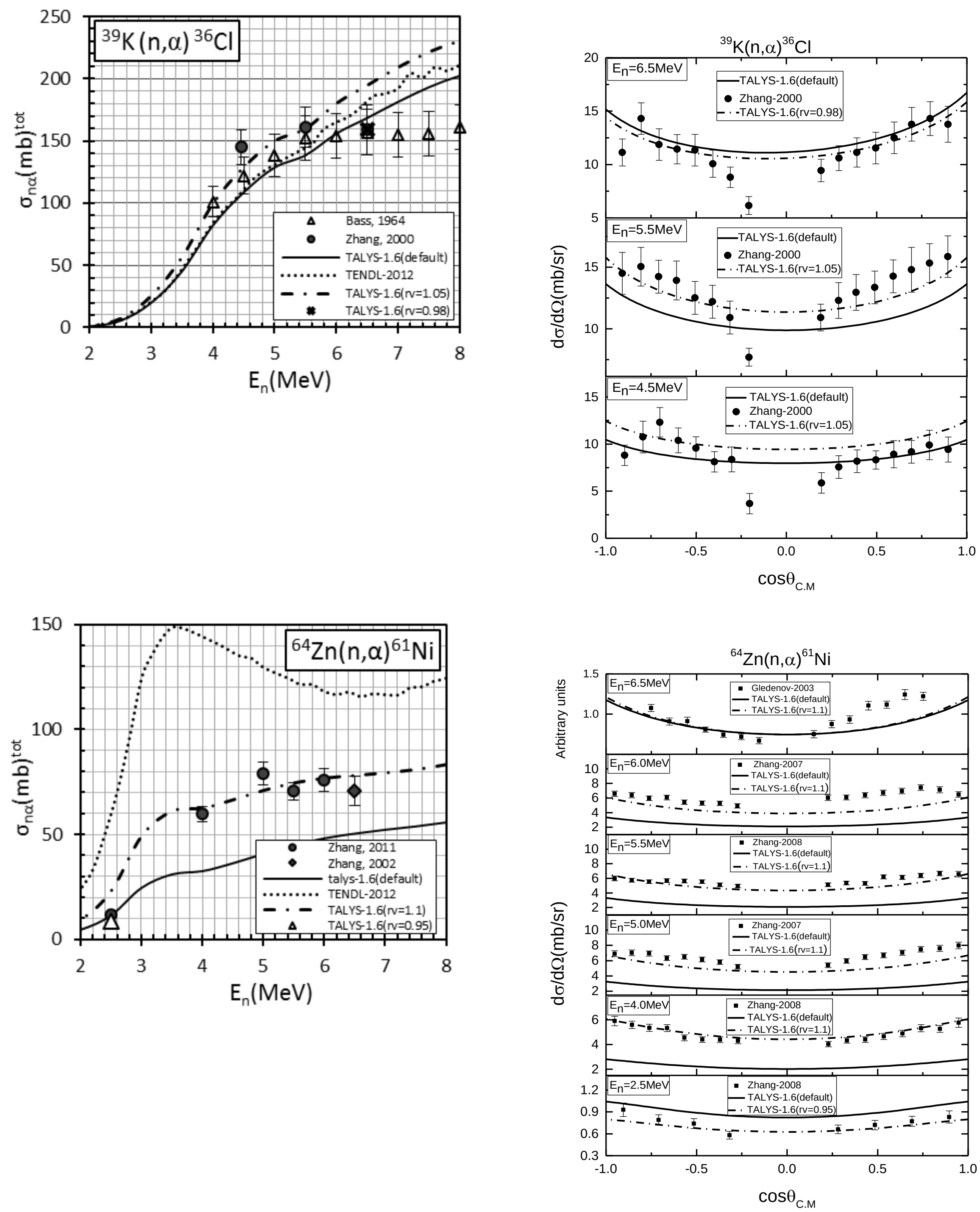

Fig.3. Total (n,α) cross sections and angular distributions for the ^{39}K(n,α)^{36}Cl and ^{64}Zn(n,α)^{61}Ni reactions. The TALYS-1.6 calculations were carried out with different parameter r_v from default one.

So, the optical model parameter r_v for the real component of the volume-central potential in the TALYS-1.6 calculation was varied to fit on experimental data. We assume that such calculations should be simultaneously carried out with the same optical model parameter r_v for cross sections and angular distributions of the same reaction. Results of these calculations are shown in Fig.3 for the total (n,α) cross sections and angular distributions of the ^{39}K and ^{64}Zn. The ^{58}Ni(n,α)^{55}Fe reaction is not considered here because experimental angular distributions are given in arbitrary units.

It is seen from Fig.3 that the total (n,α) cross sections and angular distributions are simultaneously and satisfactorily described by TALYS-1.6 calculations with optical model parameters r_v=0.98÷1.05 and r_v=0.95÷1.1 for the $^{39}K(n,\alpha)^{36}Cl$ and $^{64}Zn(n,\alpha)^{61}Ni$ reactions, respectively.

ACKNOWLEDGEMENT

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Computational cross sections of Bc absorption by hadrons

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Abstract

The cross sections of B_c absorption by mesons (pi, rho, kaon) are calculated in meson–baryon exchange model using hadronic Lagrangian based on SU(4)/SU(5) flavor symmetries. The coupling constants used in the model are determined from vector meson dominance model, QCD sum rule or SU(4)/SU(5) flavor symmetries. Cross sections are calculated with and without form factors with different cut off parameters. These results could be useful in calculating production rate of *Bc* meson in relativistic heavy ion collisions.

Investigation of the nuclear reaction $^{12}C(p,\gamma)^{13}N$ at the proton energies below $1\,MeV$

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The aim of this work is to interpolate the experimental data of the total cross section with a high precision for future using this data for the theoretical calculation of yield and astrophysical *S*-factor of the reaction.

We have analyzed all published data on the total cross sections $\sigma_t(E)$ [1-6], and reaction yield $Y(E)$ [1, 8-9] at the energies below $1\,MeV$. All data on the total cross sections are described with an analytical expression, based on the resonance formula of Breit–Wigner with the introducing of additional parameter k, depending on energy:

$$\sigma_t(E) = const\,E^k\left[(E-E_0)^2 + (\Gamma/2)^2\right]^{-1}$$

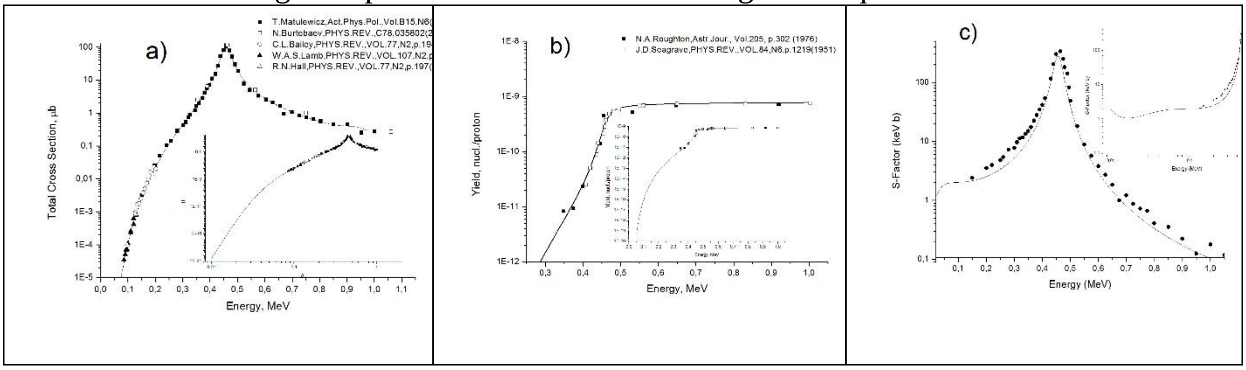
The derived expression for the total cross section is in good agreement with experimental data (see Fig. a). The total cross section is extrapolated toward lower energies up to $\sim 0.1\,MeV$, in such way that they give the extrapolated values of the astrophysical *S*-factor in [3, 7], Fig. (c).

To calculate yield of the reaction we also approximated values of the stopping powers of protons $S(E)$ in carbon [10], which enter into the expression for yield:

$$Y(E) = const\int_0^E \sigma_t(E')\,S^{-1}(E')\,dE',$$

The corresponding experimental data of the yield in our interpolation is shown in Fig. (b).

Extrapolation of the cross section $\sigma_t(E)$ toward the low energies can lead to the values of the astrophysical *S*-factor, conforming to the theoretical calculations of [8-9]. However, this extrapolation is not unique. To obtain reliable values of the astrophysical *S*-factor in stellar energies experimental data at lower energies is required.



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Filtered neutron beam applications at the Dalat Research Reactor

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I. Introduction

The Dalat Nuclear Research Reactor (DNRR) with the nominal power of 500 kW was reconstructed and upgraded from the 250-kW TRIGA Mark-II reactor built in early 1960s. The renovated reactor was put into operation on 20th March 1984. The first fresh core was loaded with 88 fuel assemblies enriched to 36% HEU (Highly Enriched Uranium) and then partly converted to 19.75% LEU (Low Enriched Uranium) in September 2007. The full core conversion of the reactor to LEU fuel was also performed from 24th November 2011 to 13th January 2012. Recently, the DNRR has been operated with a core configuration loaded with 92 WWR-M2 LEU fuel assemblies and 12 beryllium rods around the neutron trap. The reactor has four horizontal beam ports, which provide beams of neutron and gamma radiation for a variety of experiments. Besides, the reactor also has a large thermal column with outside dimensions of 1.2m by 1.2m in cross section and 1.6m in length [1].

The neutron filter technique has been applied for extracting filtered quasi-monoenergetic keV neutron beams of 24, 54, 59, 133 and 148 keV as well as thermal neutrons at the DNRR with neutron flux about 10^5 – 10^6 n.cm^{-2}.s^{-1} and beam purity > 85%. These filtered neutron beams are very useful for nuclear data measurements and applied researches [2, 3].

II. Filtered neutron beams at the DNRR

Currently, three beam ports (No. 2, No. 3 and No. 4) and the thermal column have been used for researches and applications. The cross section view of the horizontal channels of the DNRR is shown in Fig. 1.

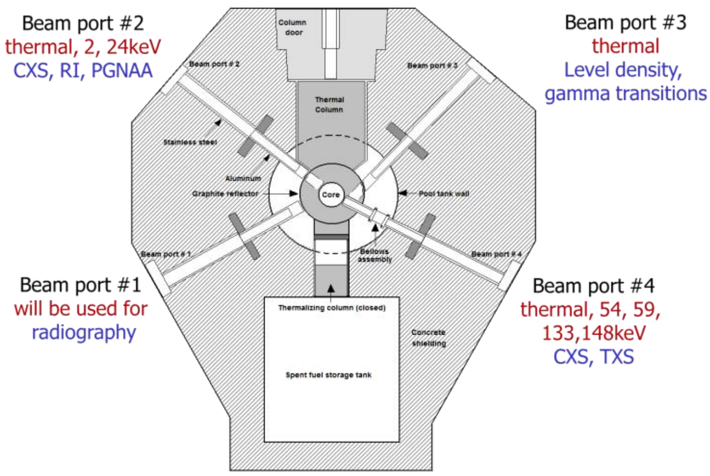

Fig. 1. Horizontal section view of the neutron beam ports of the DNRR.

At the beam port No. 2, a high quality thermal neutron beam has been created based on a silicon and bismuth filters. A BGO-HPGe gamma-rays Compton suppression spectrometer has been recently installed for PGNAA applications and experimental researches on neutron capture reactions (CXS) and resonance integrals (RI) [4]. The tangential beam port No. 3 also provided a good quality thermal neutrons with low gamma background. This beam is used for nuclear structure studies, especially for experimental determination of nuclear energy levels and level density in regions below neutron binding energy [5]. The filtered neutron beams at the piercing beam port No. 4 with quasi-monoenergies of 24, 54, 59, 133 and 148 keV are used for measurements of neutron total and capture cross sections (TXS, CXS). In addition, these neutron beams are also applied for practical study on radiation shielding design [4]. The physical parameters and neutron filter components of the beams are given in Table 1. The calculated and measured neutron energy spectra are shown in Fig. 2 and Fig. 3.

Table 1. Characteristics of the filtered neutron beams at the DNRR.

Neutron energy	Neutron flux *($n.cm^{-2}.s^{-1}$)*	R_{Cd}(Au) or I *(%)*	Filter components
Thermal[a]	1.6×10^6	420	80 cm **Si** + 6 cm **Bi**
Thermal[b]	2.4×10^5	230	60 cm **Si**
Thermal[c]	8.7×10^6	135	98 cm **Si** + 35 g/cm^2 **S** + 1 cm **Ti**
24 ± 1.8 keV	6.2×10^5	98.3	0.2 g/cm^2 **^{10}B** + 20 cm **Fe** + 30 cm **Al** + 35 g/cm^2 **S**
54 ± 1.5 keV	6.7×10^5	78.1	0.2 g/cm^2 **^{10}B** + 98 cm **Si** + 35 g/cm^2 **S**
59 ± 2.7 keV	5.3×10^5	92.3	0.2 g/cm^2 **^{10}B +** 15 cm **V +** 5 cm **Al +** 100 g/cm^2 **S**
133 ± 2.7 keV	3.3×10^5	92.9	0.2 g/cm^2 **^{10}B** + 50 g/cm^2 **Cr** +10 cm **Ni** + 60 cm **Si**
148 ± 14.8 keV	4.1×10^6	94.6	0.2 g/cm^2 **^{10}B** + 98 cm **Si** + 1 cm **Ti**

a. at the beam port No. 2. b. at the beam port No. 3. c. at the beam port No. 4.

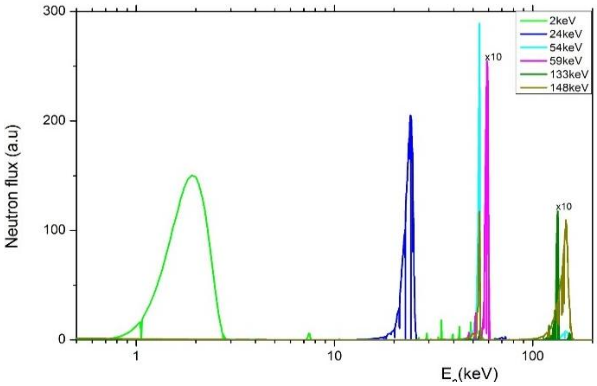

Fig. 2. The keV filtered neutron energies calculated by MCNP.

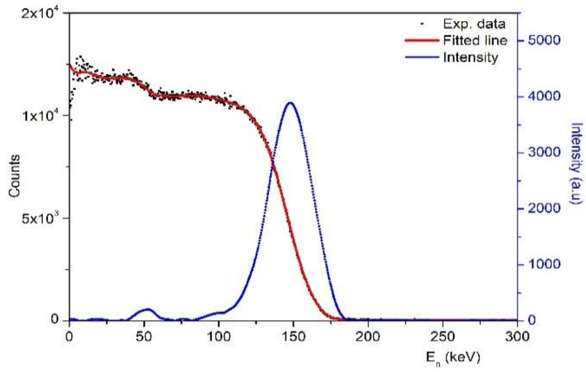

Fig. 3. The 148 keV neutron spectrum measured by a proton-recoil spectrometer.

III. Applications of the filtered neutron beams

In the keV energy region, filtered neutron beams are the most intense sources, which can be used to obtain neutron data for reactors and other applications. The following experiments have been carried out at the DNRR including:

- Measurement of total neutron cross sections of structural materials for nuclear reactors such as C, U, Nb, Al, In, Pr, Ta at monoenergetic energies of 24, 54, 59, 133 and 148 keV by the transmission technique using a proton-recoil spectrometer [6, 7] (see Fig. 4 and Fig. 5).
- Measurement of average neutron radioactive capture cross sections of ^{139}La, ^{152}Sm, ^{154}Sm, ^{69}Ga, ^{71}Ga, ^{191}Ir, ^{193}Ir, ^{185}Re, ^{187}Re and ^{51}V on filtered neutron beams of thermal, 24, 54, 59, 133 and 148 keV by the activation method using a fast-digital gamma-ray spectroscopy [8, 9] (see Fig. 6 and Fig. 7);

- Determination of relative intensities of prompt γ-rays from ^{35}Cl(n, γ)^{36}Cl and ^{48}Ti(n, γ)^{49}Ti reations with thermal neutron in the energy range of 0.5 – 8 MeV.

- Measurement and analysis of the gamma cascade transition data for nuclei of ^{239}U, ^{182}Ta, ^{153}Sm, ^{172}Yb, ^{59}Ni, ^{55}Fe, ^{49}Ti and ^{52}V on thermal neutron beam by the gamma two-step cascade (TSC) method using the event-event coincidence spectrometer [10] (see Fig. 8 and Fig. 9).

- Evaluation of nuclear structure for those nuclei based on analyzed data and theoretical models.

- Determination of the lifetime level, width level and gamma transition strength from the experimental data of gamma intensity and electromagnetic transfer selection.

- Development of prompt gamma neutron activation analysis (PGNAA) technique using the filtered thermal neutron beam in combination with the BGO-HPGe gamma-rays Compton suppression spectrometer for determination of light elements concentration such as B, H, Hg, Si, Ca, C, S, Al, Fe, Cl, Ti,...in geological, biological and environmental materials [11] (see Fig. 10 and Fig. 11).

Fig. 4. Transmission experiment.

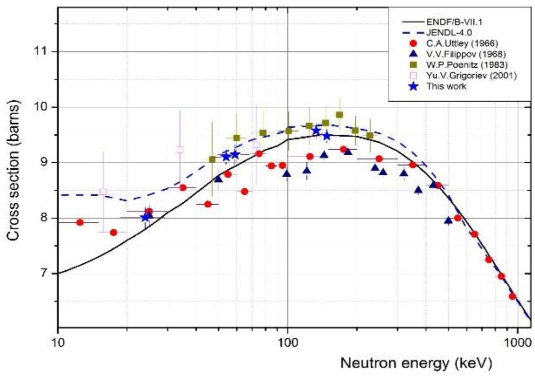

Fig. 5. Total neutron cross sections of ^{93}Nb.

Fig. 6. High efficient HPGe spectrometer.

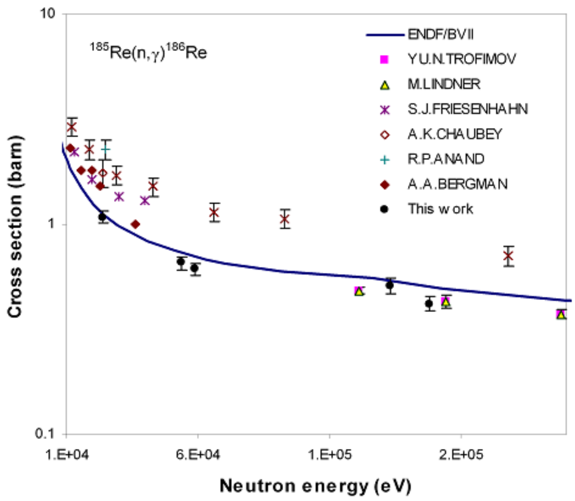

Fig. 7. Capture cross sections of ^{185}Re.

Fig. 8. Event-event coincidence spectroscopy system.

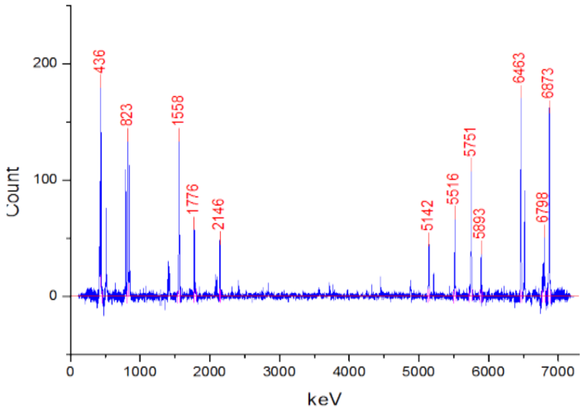

Fig 9. TSC spectrum of ^{52}V belong to final level at 0 and 18 keV.

Fig. 10. BGO-HPGe Compton suppression spectrometer.

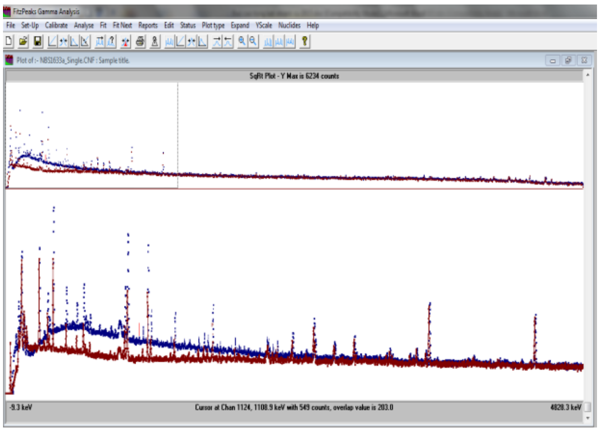

Fig. 11. Prompt γ-ray spectrums of the soil sample in single mode (blue) and Compton-suppression mode (red).

IV. Conclusions

The neutron filter technique has been applied to produce quasi-monoenergetic neutron beams of thermal (0.025 eV), 24, 54, 59, 133 and 148 keV at the Dalat Nuclear Research Reactor. These filtered beams and facilities have been used for fundamental researches on neutron-induced reaction cross sections, nuclear structure data and for applications such as boron neutron capture therapy and elemental analysis. The neutron beams in the keV energy range are also useful tools for calibration of neutron measuring devices, personal dosimeters and for investigations of radiation damage effect of structural materials of nuclear reactors as well as radiobiological effectiveness (RBE) of different energy neutrons.

The research method and facilities using the filtered neutrons will play a significant role in R&D programs of nuclear technique applications so far, as well as in preparing human resources for the nuclear data program in Vietnam in the near future.

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