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EANDC (J) 7 "L"

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NOT FOR PUBLICATION

JAPANESE PROGRESS REPORT TO THE EANDC

(March to December, 1966 inclusive)

January 1967

edited by

T. Momota

Japanese Nuclear Data Committee

Japan Atomic Energy Research Institute

Tokai Research Establishment

Tokai-mura, Ibaraki-ken, Japan

Errata

Page	Line (place)	Incorrect	Correct
2	from top 8	200_ - ohm	2000 - ohm
4	from top 2	N. Shikuzono	N. Shikazono
8	from top 10	Y. Nak_jima	Y. Nakajima
20	from top 10	rediochemically	radiochemically
27	from bottom 7	from	form
29	from bottom 11	progress	Progress
36	from top 8	targetrs	targets
41	from bottom 3	et al..	Ommit one period.

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Editor's Note

This report is prepared for presentation to the Tenth Meeting of the European-American Nuclear Data Committee which is to be held on 20-25 February, 1967 in Istanbul, Turkey. The editor asked forty-four physicists to submit reports on those research work which pertained to Nuclear Data in the sense used in the EANDC.

The individual reports, which were submitted to the editor, are all included herein without selection. They are not intended to be complete or formal, and must not be quoted in publications without the permission of the authors.

CONTENTS

CONTENTS (cont'd)

I. Japan Atomic Energy Research Institute

A. Neutron Experiments - Reactor

I-A-1. Analysis of the 0.098-eV Neutron Resonance in ^{149}Sm

Y. Ohno, T. Asami, K. Okamoto, and K. Ideno

The neutron transmission of ^{149}Sm and natural samarium samples have been measured with the JAERI neutron crystal monochromator and the neutron velocity selector over the energy range from 8 x 10^{-4} to 1 eV. Results are shown in the follwing figure.

The parameters of the 0.098-eV neutron resonance in ^{149}Sm are being analysed by the shape method.

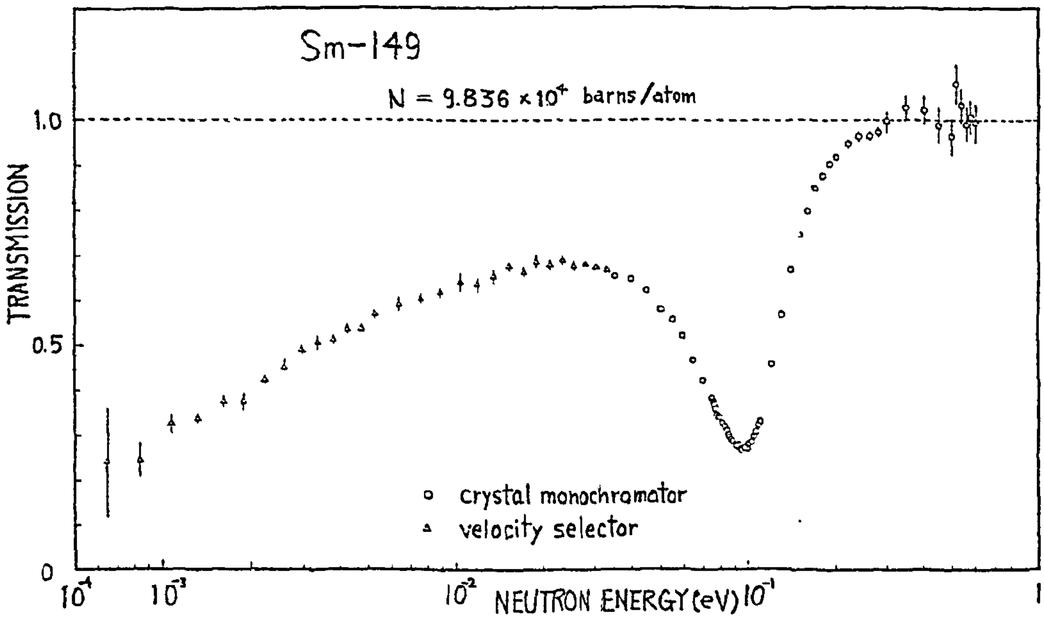


Fig.1

I-A-2. The Thermal-Neutron Induced (n, α) Reactions in Rare-Earth Elements

K. Okamoto

The (n, α) reactions induced by thermal neutrons in the rare-earth elements are being investigated.

The reaction cross sections and the spectra of alpha particles have been measured for Sm^{147}, Sm^{149}, and Nd^{143} by a surface barrier detector (200-ohm resistivity) in a neutron flux from the thermal column of JRR-2 reactor.

Fig. 1, 2, and 3 show the spectra of alpha particles in Sm^{149}-, Sm^{147}-, and Nd^{143} (n_{th}, α) reactions, respectively.

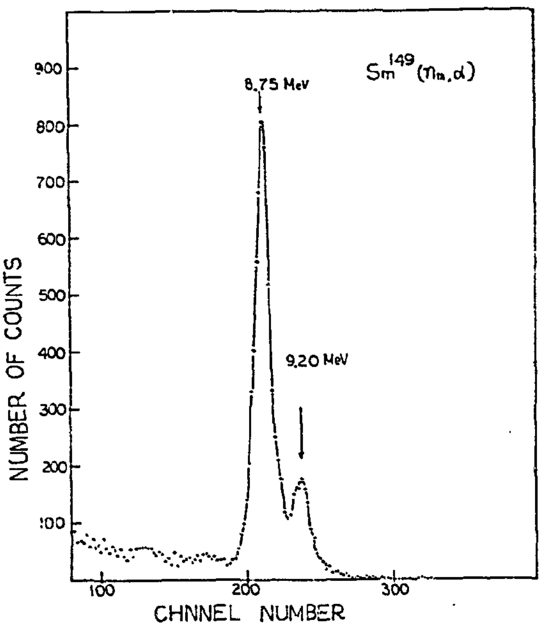


FIG. 1

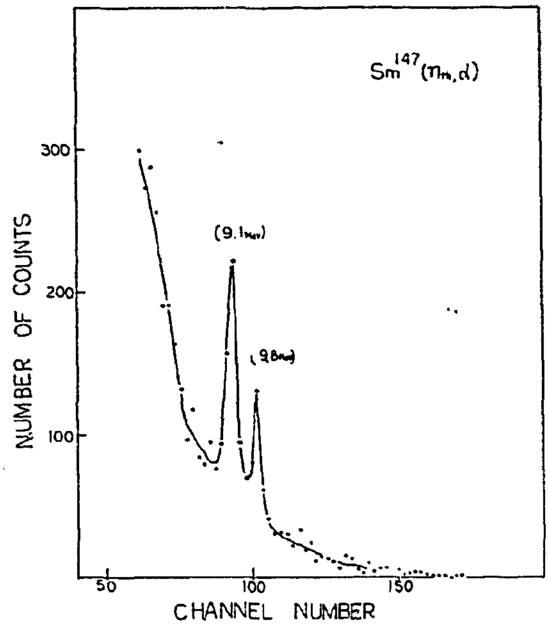
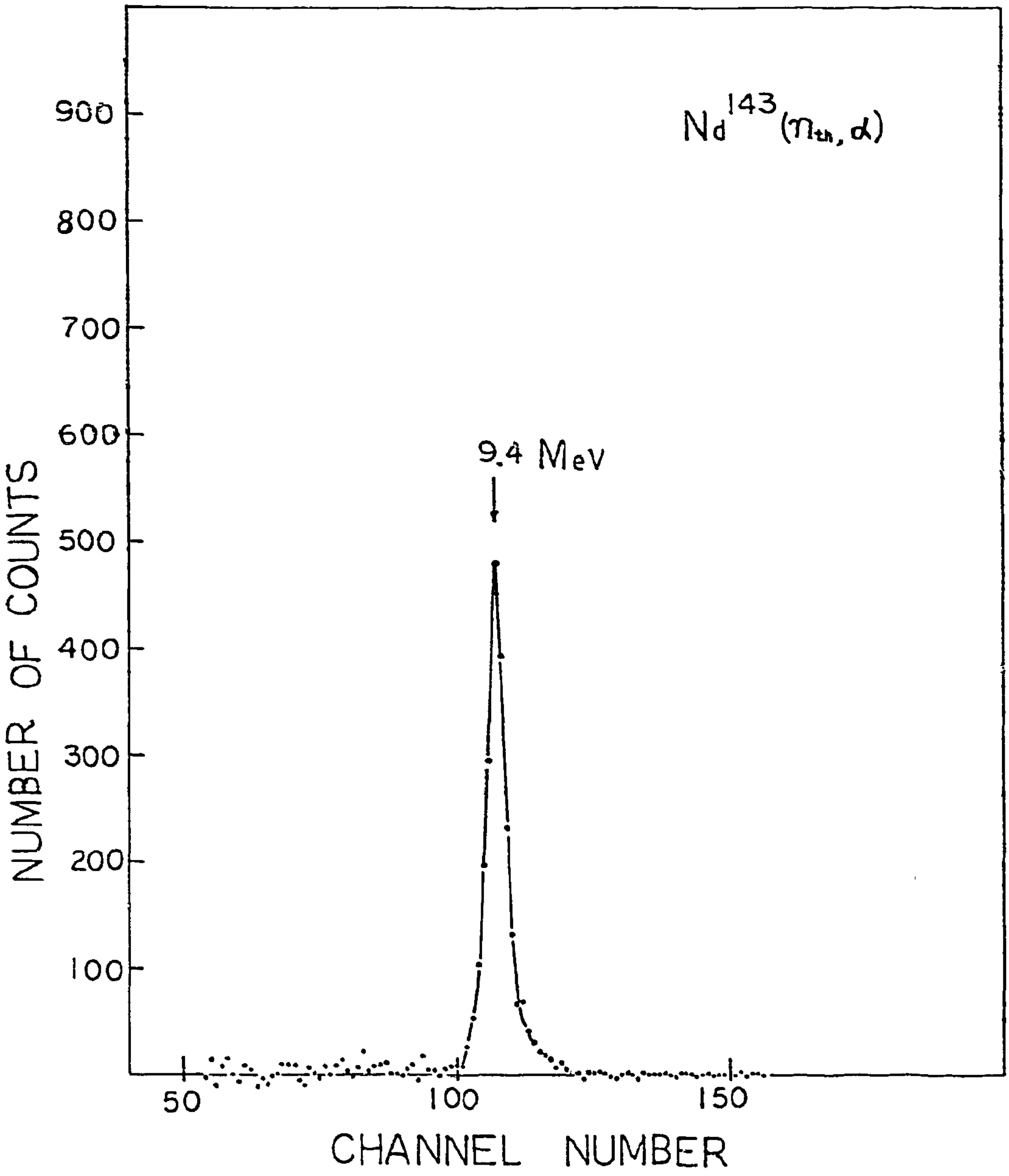


FIG. 2



$Nd^{143}(n_{th}, \alpha)$
9.4 MeV
NUMBER OF COUNTS
900
800
700
600
500
400
300
200
100
50
100
150
CHANNEL NUMBER

FIG. 3

I-A-3. Thermal Neutron Capture Gamma Rays of Ti and Al

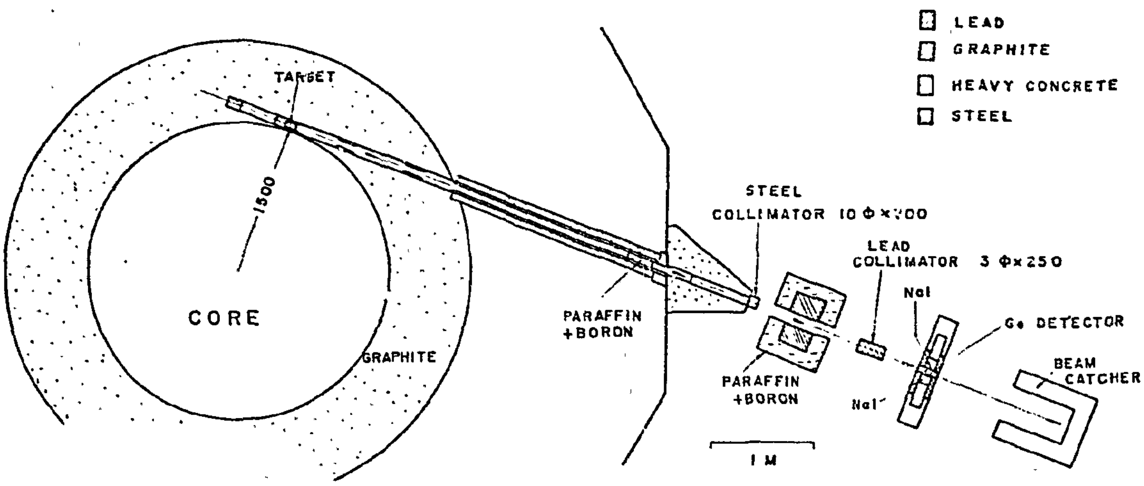
H. Takekoshi, Y. Kawarasaki, and N. Shikuzono

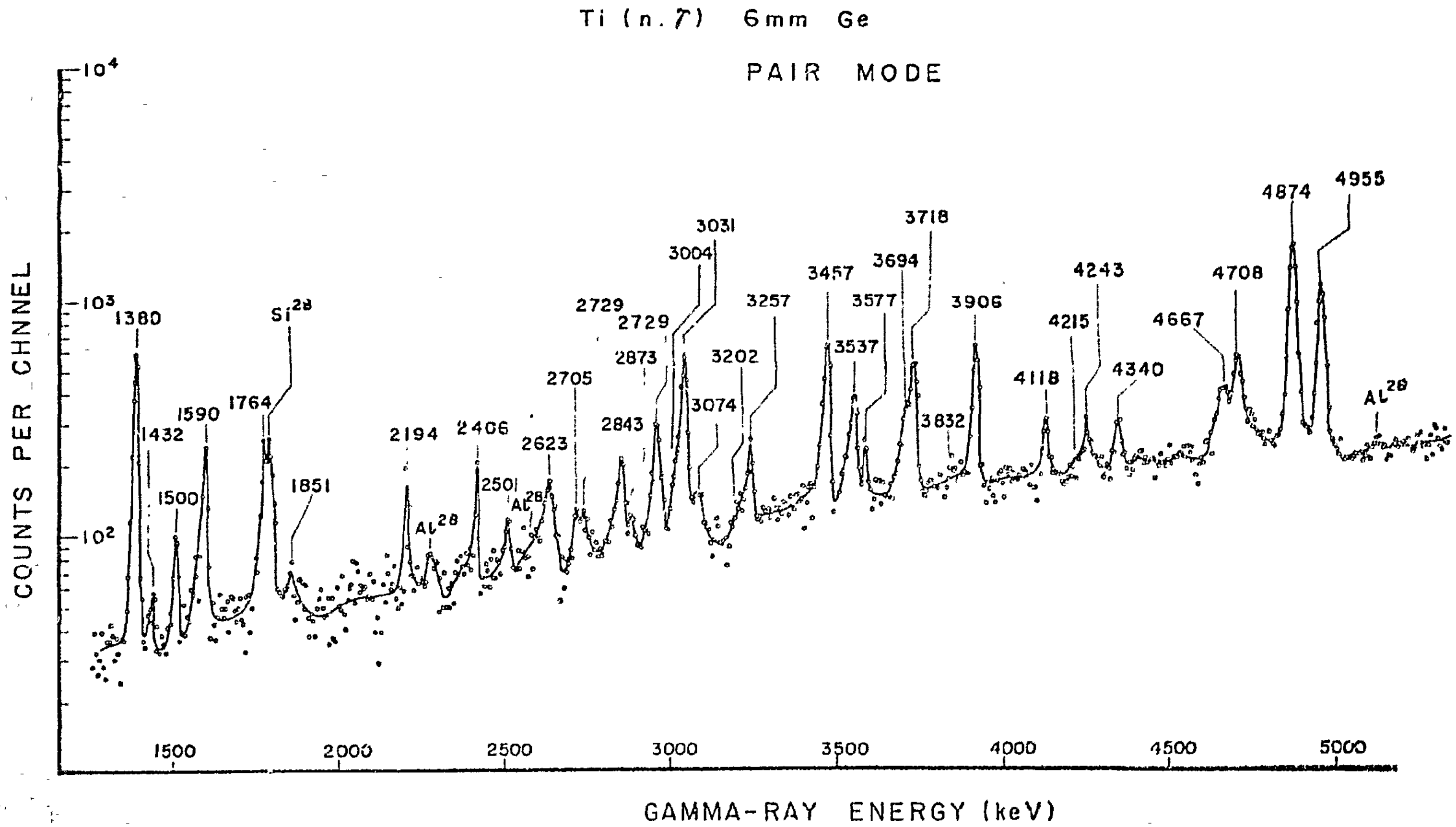
The thermal neutron capture gamma-ray spectra of titanium and aluminium have been measured with a three-crystal pair spectrometer. A lithium-drifted Ge detector was used as the central crystal of the spectrometer and 3" ØX 3" NaI (Tl) detectors as the side crystals.

The preliminary results are shown in the follwing figures. Several new lines were found in either spectrum of titanium and aluminium above 1 MeV.

Further studies, including an improvement of the apparatus, are now in progress.

EXPERIMENTAL ARRANGEMENT





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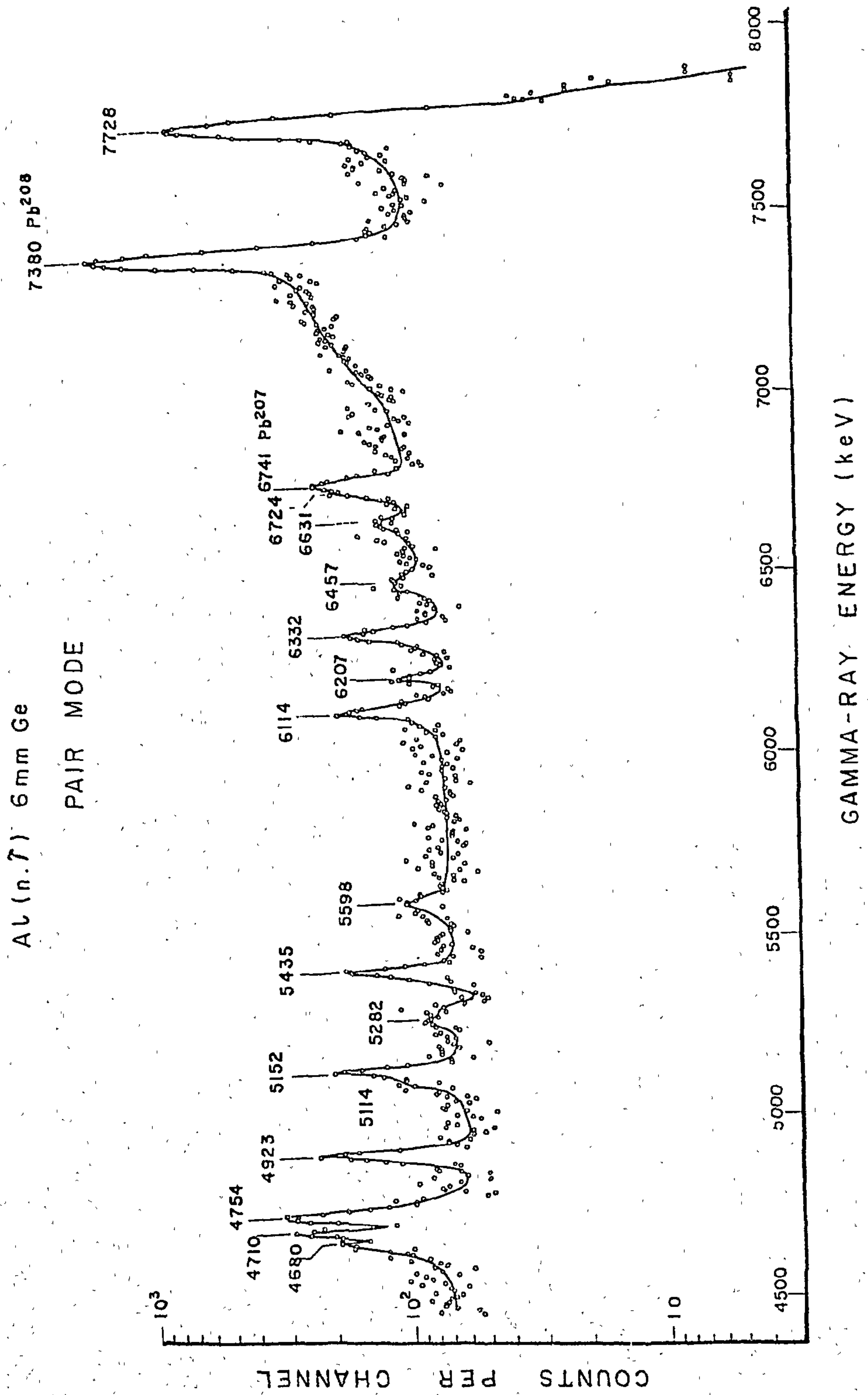
Al (n.γ) 6 mm Ge
PAIR MODE
7728
7380 Pb208
6741 Pb207
6724
6631
6457
6332
6207
6114
5598
5435
5282
5152
5114
4923
4754
4710
4680
4500
5000
5500
6000
6500
7000
7500
8000
GAMMA-RAY ENERGY (keV)
10³
10²
10
COUNTS PER CHANNEL

B. Neutron Experiments-Linac

I-B-1. Processing and Analysis of Neutron Transmission Data and Considerations of the Accuracy

T. Fuketa, A. Asami, M. Ohkubo, Y. Nakajima,
Y. Kawarasaki, and H. Takekoshi

A paper on this subject was submitted to the Conference on Nuclear Data, Paris, 17-21. Oct. 1966 with an abstract as follows:

The main features of the computer programmes which are being used in processing and analysing the neutron transmission data from JAERI (Japan Atomic Energy Research Institute) Linac Time-of-Flight Spectrometer are described, and the related accuracies are discussed. In these programmes, the background is formulated to a channel-dependent expression by making least-squares fitting to the raw data of the background, and the statistical error of the transmission is computed at every individual channel. Some modifications of the area-analysis programme which was originally written by S. E. Atta and J. A. Harvey of ORNL is made to expand its functions. That is, in the present programme, computations are iterated semi-automatically until the values of Γ and Γ_n satisfy the condition of self-consistency, $\Gamma = \Gamma_n + \Gamma_\gamma$, for an assumed value of Γ_γ and of the g-factor, and, in estimating the error of the $g\Gamma_n$-value, the statistical error of the transmission at individual channels and the error of the baseline under which the resonance area is defined are taken into account.

The accuracy of the final result of $g\Gamma_n$ depends not only on

the statistical errors in the transmission data but also on their systematic errors and on the adequacy of the choice of input parameters for the analysis. Some semi-empirical examinations were made on the influences of these errors upon the value of $g\Gamma_n$. A 20-per-cent systematic error in the background, whose amount was about one per cent of the open-beam counting rate, gave rise to an error of more than 4 per cent in the computed $g\Gamma_n$-value of a resonance chosen for the test.

I-B-2. Neutron Transmission Measurements

T. Fuketa, M. Ohkubo, and Y. Nak jima

Additional measurements on transmissions of natural cadmium and antimony have been made with samples at liquid-nitrogen temperature in order to improve separation of the resonance dips. Analysis of the data (including the previous data at room temperature) is not completed yet.

I-B-3. The Parameters of the 4.14-and 7.6-eV Resonances in Tungsten

K. Ideno, M. Ohkubo, and T. Asami

The neutron transmission in the neighbouring of the 4.14- and 7.6-eV neutron resonances of tungsten has been measured with a resolution of 0.04 μsec/m in order to investigate the effect of crystalline binding on the Doppler broadening in neutron resonances. W metal and WO_3 were used as the sample.

The shapes of the resonances were measured in detail at the room and the liquid nitrogen temperatures.

Using the Atta-Harvey program for shape analysis*, the following resonance parameters were obtained:

For 4.14-eV resonance of ^{182}W,

E_o=4.15 ± 0.01 eV, Γ=50 ± 2 meV, and Γ_n =1.46 ±0.02 meV.

For 7.6-eV resonance of ^{183}W,

E_o=7.64 ± 0.02 eV, Γ =70 ± 3 meV, and Γ_n =1.72± 0.05 meV.

The detailed analysis is now in progress.

* S. E. Atta and J. A. Harvey, ORNL-3205 (1961) and its addendum (1963); by courtesy of Dr. J. A. Harvey of ORNL, we recieved the resonance analysis program and rewrote it from FORTRAN II to IV.

I-C-1. Elastic and Inelastic Scattering of Neutrons from Fe, Ni and W

K. Tsukada, S. Tanaka, M. Maruyama, and Y. Tomita

In the previous progress report, EANDC (J) 3 "L" p.18, the authors reported that time spectra of neutrons scattered from Fe, Ni and W had measured as a function of the energy of incident neutrons and the direction of scattered neutrons. As the continuation of the work, the time spectra have been analysed by means of an IBM 7044 computer, and differential cross sections for the elastic and inelastic scattering have been obtained. In the analysis peeling-off process was used, when necessary. As an example Fig. 1 shows differential cross section* for the inelastic scattering of neutrons leading to the 1st excited state in ^{56}Fe.

The following corrections and analysis are now in progress: Multiple-scattering correction in the sample for the angular distribution of elastic scattering, flux-attenuation correction for inelastic scattering, parameter search of the optical potential, and comparison of the observed inelastic scattering data with those calculated on the basis of Hauser-Feshbach theory and Moldauer theory.

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* Some of the values in the figure may be changed within small amount due to the correction now in progress.

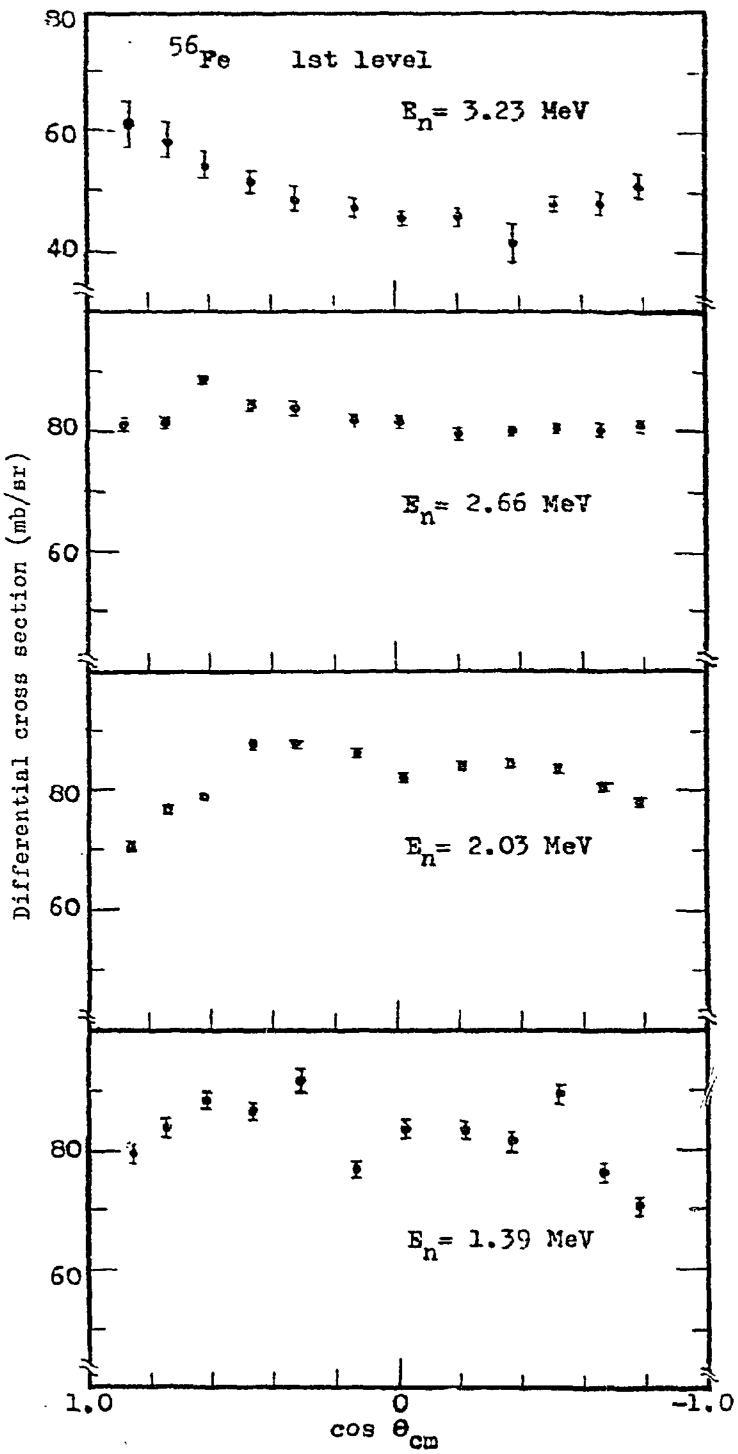

Fig. 1. Differential cross sections for the inelastic scattering of neutrons leading to the 1st level in Fe^{56}.

I-C-2. Elastic and Inelastic Scattering of Neutrons from S and Zn

K. Tsukada, S. Tanaka, M. Maruyama, and Y. Tomita

Time spectra of neutrons scattered from S and Zn have been measured at incident energies of 4.55, 5.95, 6.97 and 7.99 MeV over scattering angles from 30° to 150° with a step of 10°. The measurement was made by means of a time-of-flight spectrometer with a 5.5-MeV pulsed-beam Van de Graaff accelerator and an ion-beam bunching system. Neutrons were generated by means of the $D(d,n)^{3}He$ reaction.

The purpose of the present investigation is to study the transition between two modes of reaction in which compound-nucleus excitation and direct excitation of low-lying collective states dominates respectively. The bias of the slow side channel which cuts off the pulses of neutrons with low energy was, therefore, set comparatively high. In addition to the counting of the sample-out background, countings of background runs of sample-in and -out with the gas target evacuated were also measured, unless they were negligible.

Fig. 1 shows typical time spectra of neutrons scattered from S in directions of 60° and 90° at a bombarding energy of 7.99 MeV. The spectra are corrected for the background and live time, efficiency, etc. of the detector system. The ordinates are given in the scale of cross section per channel (mb/sr/channel), which were measured relative to the well-known cross sections of the H(n,n) H reaction. From the figure one can see a fact that the cross sections for the inelastic scattering leading to low-lying states vary remarkably with two scattering angles.

Analysis of the data obtained is now in progress.

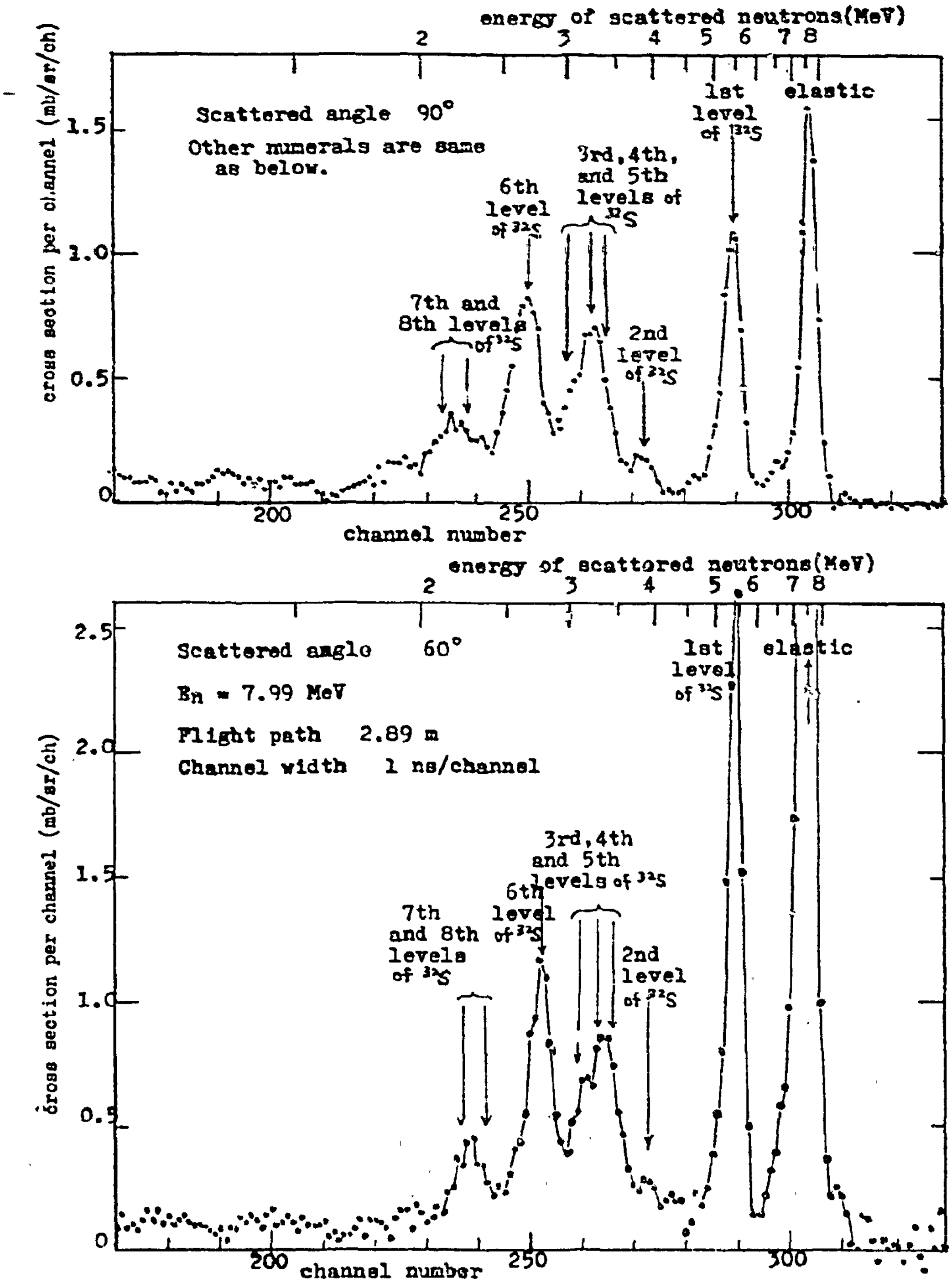

Fig. 1. Time spectra of neutrons scattered from S in directions of 60° and 90°.

I-C-3. High Resolution Measurements of Gamma Rays from Neutron Inelastic Scattering

S. Kikuchi, Y. Yamanouchi, and K. Nishimura

Measurements of gamma rays from neutron inelastic scattering in iron, copper, nickel, zinc, and tin have been made with a lithium-drifted germanium detector. The germanium crystal has an area of about 3 cm^2 and a thickness of 0.5 cm. The ring geometry is used as in the previous experiment[1].

A typical example of the gamma-ray spectra obtained with a sample of natural zinc is shown in Fig. 1. It is obvious that three gamma-ray peaks corresponding to the transitions from the first to the ground states in ^{64}Zn, ^{66}Zn, ^{68}Zn nuclides are clearly separated.

Estimation of cross section values of (n, n', γ) reaction in above five elements is now in progress.

Reference 1) K. Nishimura, K. Okano, and S. Kikuchi, Nuclear Physics 70 (1965) 421

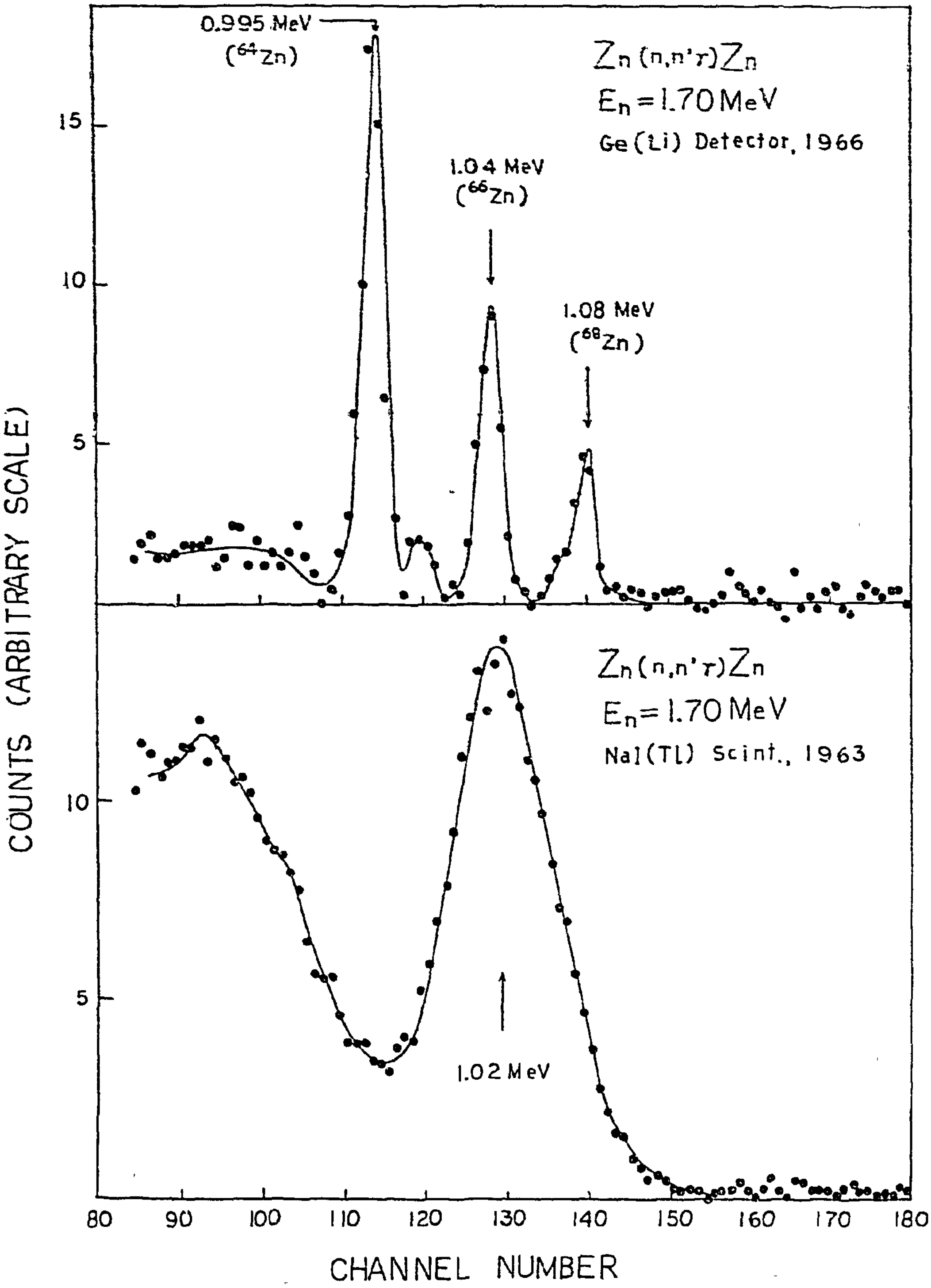

Fig. 1 GAMMA RAY SPECTRA FROM ZINC

I-C-4. Neutron Total Cross-Section of ^{139}La

K. Nishimura, S. Kikuchi, and Y. Yamanouchi

Total neutron cross-sections of natural lanthanum have been measured in the keV region with a high energy resolution. By using a thin lithium metal target and a narrow neutron beam collimator, an energy resolution of about 2.5-3.5 keV was obtained in the neutron energy of approximately 100-200 keV.

Preliminary results on ^{139}La show a resonance structure in this energy region.

Further measurements in the energy region extended both to the lower and higher sides are in progress.

I-C-5. Energy Dependence of the Nuclear Level Density below the Neutron Binding Energy

K. Tsukada, S. Tanaka, M. Maruyama, and Y. Tomita

A report on a part of this work, which was outlined in the previous report (EANDC (J) 3 "L"), was published in the Nucl. Phys. 78 (1966) 369-384.

I-C-6. Average Level Width of the Compound Nucleus

K. Tsukada, and T. J. Lee

A full paper of this work, which was outlined in the previous report (EANDC (J) 1 "L"), was published in the Nucl. Phys. 83 (1966) 274-288.

D. Others

I-D-1. An Empirical Formula for the Number of Neutrons as a Function of Mass and Total Kinetic Energy for Spontaneous Fission of Cf-252⁺

Eiko Takekoshi

The properties of the prompt neutrons associated with the spontaneous fission of Cf-252 were reported by H. R. Bowman et al..[1] In this report, the number, energy and angular distribution of neutrons were analysed as a function of the mass and kinetic energy of the fission fragments before the emission of the prompt neutrons, and the results on the number of the prompt neutrons were presented graphically; the variation of the number of neutrons per fission as a function of fission mass pair, the average number of neutrons per fragment as a function of fragment mass for selected kinetic energy intervals, and the number of neutrons vs. total kinetic energy for selected fragment masses.

The above mentioned relationships can be expressed in a convenient way by means of a formula. The formula also gives the number of prompt neutrons as a function of the fission mass pair and the total kinetic energy. The following empirical formula was obtained by fitting the original experimental data of the above reference.

$$\nu\,(M,\,E_T) = A(M)\,e^{-B(M)\,(E_T\,-\,150)}$$

where M is the mass of a fission mass pair and E_T is total kinetic energy in MeV. The two parameters, A(M) and B(M), were obtained for selected fission mass pairs by means of a least squares fit.

As shown in the figure this empirical formula fits the data very well. If the formula is applicable to other cases of fission, it may be useful in resolving some essential problems concerning fission mechanisms, where the relationships between total kinetic energy and excitation energy, and total energy release are involved.

+ The initial part of this work was done under the auspices of the U. S. Atomic Energy Commission, at the Lawrence Radiation Laboratory, University of California, Berkeley, California, U. S. A.

REFERENCE

1). H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki; UCRL-10139 (1962), Phys. Rev. 129 (1962), 2133.

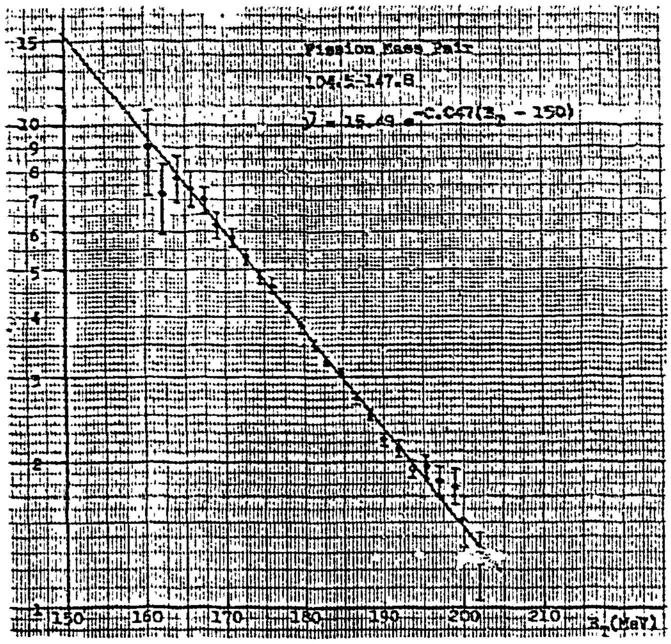

Fig. 1. Fitting between experimental data and the empirical formula for a fission mass pair of average mass, 104.5-147.8.

M	A(M)		B(M)	±△A(M)		±△B(M)
90.6-162.0	1.051142E	01	3.175789E-02	1.145673E	00	5.587937E-03
93.3-159.1	1.298356E	01	4.047030E-02	1.119826E	00	4.320221E-03
96.0-156.1	1.036345E	01	3.418736E-02	1.062659E	00	2.219159E-03
98.9-153.2	1.059153E	01	3.551356E-02	1.073524E	00	2.417977E-03
101.7-150.4	1.411688E	01	4.568359E-02	1.049548E	00	1.557781E-03
104.5-147.8	1.548740E	01	4.709535E-02	1.043418E	00	1.295249E-03
107.1-145.3	1.711756E	01	4.757485E-02	1.045976E	00	1.306369E-03
109.6-142.8	1.908681E	01	4.711096E-02	1.040042E	00	1.105750E-03
112.3-140.2	1.613277E	01	3.966645E-02	1.072244E	00	1.902963E-03
114.9-137.7	2.186056E	01	4.468517E-02	1.084261E	00	2.137312E-03
117.4-135.3	1.961045E	01	4.037683E-02	1.075005E	00	1.855199E-03
119.7-133.0	1.978643E	01	3.740538E-02	1.096399E	00	2.375969E-03
123.8-128.5	1.607475E	01	2.703174E-02	1.099831E	00	2.607426E-03

I-D-2. Radiochemical Studies of ^{238}U Fission Induced by 12-55 MeV Protons

H. Natsume, H. Amano, E. Takekoshi, F. Ichikawa, H. Umezawa, H. Goto, H. Baba, T. Suzuki, S. Baba, and T. Sato

Proton-induced fission of ^{238}U is being studied by radiochemical techniques for the energy range from 12 MeV to 55 MeV. Eleven targets of uranium which was of natural isotopic composition were stacked and irradiated for 10-20 hours with 55-MeV protons from the cyclotron of the Institute for Nuclear Study, University of Tokyo. After irradiation each target was analyzed rediochemically for ^{72}Zn, ^{86}Rb, ^{89}Sr, ^{91}Y, ^{99}Mo, ^{112}Pd, ^{115g}Cd, ^{115m}Cd, ^{132}Te, ^{127}Te, ^{136}Cs, ^{134}Cs, ^{137}Cs, ^{140}Ba, ^{141}Ce, ^{144}Ce, ^{143}Pr, ^{147}Nd, ^{149}Pm, ^{148g}Pm, ^{148m}Pm, ^{153}Sm, ^{156}Eu, ^{160}Tb, and ^{161}Tb as the fission products and for ^{238}Np, ^{236}Np, ^{234}Np, and ^{237}U as the spallation products.

Determination of the yields of the spallation and fission products are being carried on.

I-D-3. Fabrication of Thick Germanium Detectors

M. Ishii, T. Tamura, N. Shikazono, and H. Takekoshi

Lithium-drifted germanium detectors with a depletion layer of up to 8 mm and a diameter of about 19 mm have been made from pulled, indium-doped, p-type singls crystals. The detectors have an energy resolution of 4 to 5 keV (FWHM) for gamma rays from ^{60}Co, when they are used with a conventional low-noise preamplifier. The procedure of fabrication is described in detail in JAERI 1131 which is now in press.

I-D-4. Diffusive Motion of Light and Heavy Molecules

Y. Gotoh and H. Takahashi

The scattering laws of light and heavy water have been calculated based on the Nelkin or Butler models in which the translational, rotational and vibrational motions are assumed to be those of free molecules.

In this diffusion model, the atoms in the molecule are considered to receive the stochastic force from the surrounding molecules, but the coupling among the various types of motions is assumed to be negligible. The hindered rotational motions of a molecule in the potential field of its neighbors are treated here as the torsional oscillation with a proper frequency.

In Fig. 1., the scattering laws of the light water which are calculated by the UNCLE-code are displayed. Friction constant of hydrogen atoms, $\frac{\beta_Y}{m_Y}$=0.048 (eV) corresponds to the diffusion constant, $D=1.8 \times 10^{-5}$ $cm^2 sec^{-1}$. It seems to be likely that the scattering laws evaluated by this model with a reasonable diffusion constant agree well with the experimental ones. In the case of the heavy water, the generalized spectrum is shown in Fig. 2. where the friction constant $\frac{\beta_Y}{m_Y}$=0.043 (eV).

(Figures appear on the following page.)

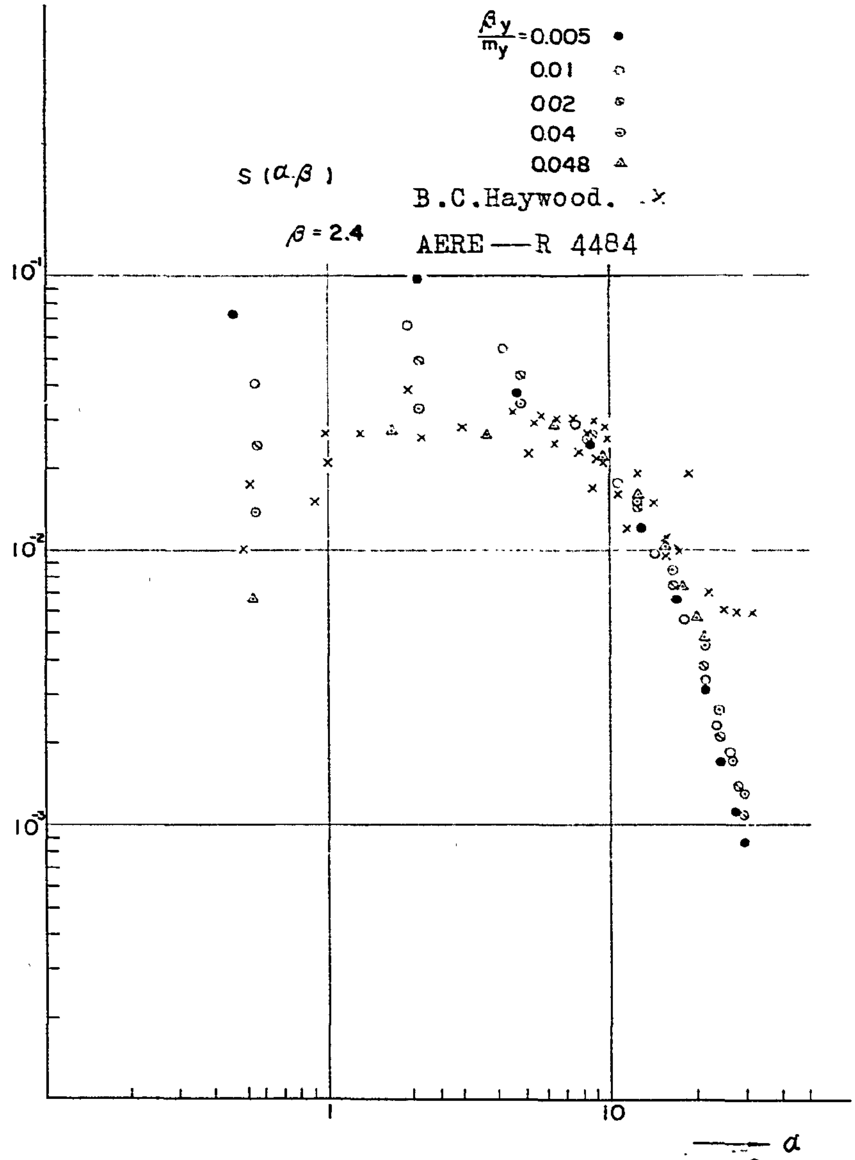

Fig. 1. Scattering law for H_2O at 295°K.

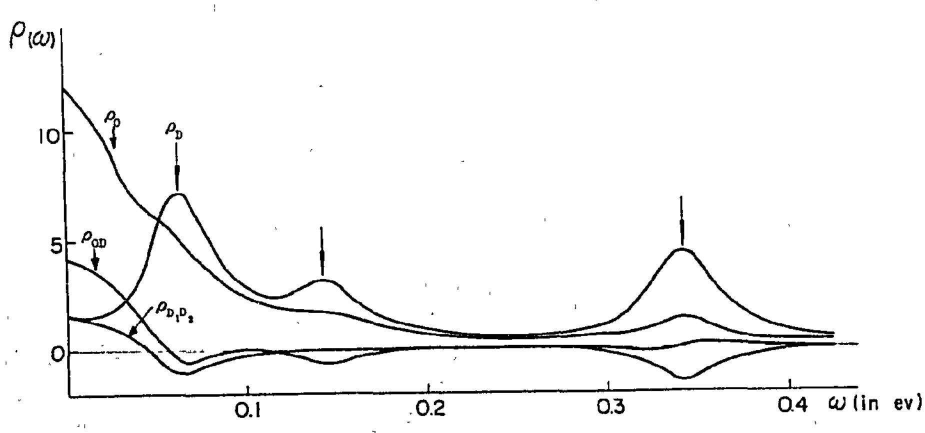

Fig. 2. Frequency spectra for D_2O.

I-D-5. Conference on the Inelastic Scattering of Neutrons

A conference was held on the inelastic scattering of neutrons at Tokai Research Establishment, JAERI, during 15-18 November, 1965. A collection of the papers presented at the Conference and the records of discussions was published in JAERI 1113 (1966).

Three of the twenty two papers are in English and the others in Japanese, but with English abstracts.

E. Japanese Nuclear Data Committee

(S. Igarasi)

The general description on the activities of the Committee are stated in a previous report, INDSWG-88, copies of which were presented to the EANDC at its 8th meeting held in May 1965.

Besides the job as the national channel for the international cooperaration in the field of nuclear data, the Committee has organized following activities:

1. Nuclear Cross Sections

1) By using the computer code, ELIESE-2, elastic and inelastic scattering cross sections of Na, Al, Fe, Zr, Pb and U were calculated taking account of probable competing processes via compound nucleus. Systematics of the optical potential parameters are being investigated. Well-depth parameters of the real and imaginary potentials are mainly looked for.
2) The computer code, STEVE-1 to be used for reaction cross section calculations based on the statistical evaporation model was developed. STEVE-2 and STEVE-3 which take account of the angular momentum effect have also been developed.
3) Computer codes RACY and STAF have been developed: the former for the calculation of neutron capture cross sections on the basis of Lane and Lynn's theory, and the latter for the calculation of fission cross sections on the basis of the statistical model.
4) A Seminar on Fast Neutron Cross-Sections was held at JAERI in the period of 18-20 August, 1966. Many reports on review and on original works were presented. Proceedings of the Seminar is to be published in January 1967.
5) Publications:

Program ELIESE-1	JAERI 1096 (also EANDC (J) 4 "S")
Proceedings of the 2nd Seminar on Fast Neutron Cross-Sections	JAERI 1126.

2. Neutron Thermalization

1) Calculations of S(α , β) have been performed by using the computer codes, UNCLE and ES. Theoretical values were fitted to the experimental data. Frequency distributions were obtained by these calculations.
   (cf. J. Nucl. Sci. and Tech. 3 (1966) 160-164)
2) Calculations and evaluations of the scattering kernels of diphenyl, D_2O and H_2O have been performed.
3) The computer code, UNCLE, was modified so as to enable it to calculate the P-1 component of the scattering kernels.
4) The computer code, ES, was modified so as to enable it to take account of the Einstein's frequency distributions.
5) The computer code, "Butler", has been modified so as to enable it to calculate the total scattering cross sections as well as the law of coherent scattering of heavy water.
6) A computer code, FREDAM-IN, has been developed in order to calculate frequency distributions by the method of interpolation.
7) Publications:

UNCLE	JAERI 1087
ES	JAERI 1094
FREE	JAERI 1084
NELKER	JAERI 1085
Survey and Problems in the Study of Thermal Neutron Scattering	JAERI 1086
Theoretical Calculation for Thermal Neutron Scattering Kernel	JAERI 1096.

3. Group Constants

A data library to be used as the input of the computer code, MUFT, was prepared. Basic nuclear data were referred to BNL-325, 2nd,ed., with its supplements as well as to A/W file. Several computer codes were developed: GROUCH-M for the conversion of nuclear data into data in the form of the library, GROUCH-R and GROUCH-R-Jr for the calculation of resonance integrals, and CROSS for the interpolation of data in the thermal energy region.

Many requests for data arose during the work. Availability of the requested data was checked with the aid of CINDA'65 and partly of CINDA'66. These requests, together with requests by other sources, were listed in Japanese List of Requests for Measurement, September 1966 (EANDC (J) 6 "AL").

II. Osaka University

II-1. Inelastic Scattering of Thermal Neutrons by Organic Moderator Molecules

T. Sekiya*, K. Sakamoto*, C. Nishida*, and Y. Watari*

The low frequency distributions of some organic moderator molecules obtained by Gläser's neutron scattering experiments, were analysed on the ground of intra-and inter-molecular potential barrier heights determined by molecular orbital calculation tables and by NMR data, respectively. As almost all the organic molecules for reactor use contain benzene rings, one of the aims of our research is to determine interaction potentials between benzene rings. We also made a calculation code ASTOM to evaluate scattering laws for asymmetric molecules under the auspices of JNDC. Thus our works may be separated into three parts:

1) Intramolecular Rotation Frequencies

[Tech. Repts Osaka Univ. 16, 431 (1966)]

In the case of gaseous diphenyl the intramolecular potential has approximately 4-fold symmetry about c-axis, and may be represented in a from as follows:

$H/2\ (\cos 4\phi - 1)$. The barrier height parameter H was determined by the consideration on two competing effects——the orthogonalizing effect of two benzene planes caused by 2-2' and 6-6' H-H repulsions and the coplanarizing effect caused by π electrons. The barrier heights so determined is H=0.95 kcal/mol=0.042 eV, and the level spacings determined from it by the method of Koehler and Dennison[1] (see Fig.)

are the same order as the low frequency peak determined by Gläser's experiments for solid and liquid diphenyl.

2) Intermolecular Rotation Frequencies

The potential barrier height of the hexad-axis rotation of benzene molecules may be determined from the NMR data of spin-lattice relaxation times T_1 for benzene and deuterobenzene.[2-3)] Almost all the experiments were made in solid states. The barrier heights were for the same order as the intramolecular one of the diphenyl gas. And we may expect the overlap between these peaks. The researches in this direction are now going on.

3) Evaluation of the Scattering Law of Asymmetric Top Molecules.

A Code ASTOM was made to evaluate the scattering law of rigid asymmetric top molecules. The principle based on Volkin's formalism.[4)] From the data structure parameters of the molecules we can evaluate $S(\kappa , \omega)$. The corrections to the classical cross section may be evaluated. It is found that the axial asymmetry effects of the diphenyl molecule at the equilibrium angle of two benzene rings may not be neglected.

References:

1) J. S. Koehler and D. M. Dennison, Phys. Rev. 57, 1006 (1940).

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3) J. K. Thompson, J. J. Krebs and H. A. Resing, J. Chem. Phys. 43, 3853 (1965).

4) H. C. Volkin, Phys. Rev. 113, 866; 117, 1029 (1960).

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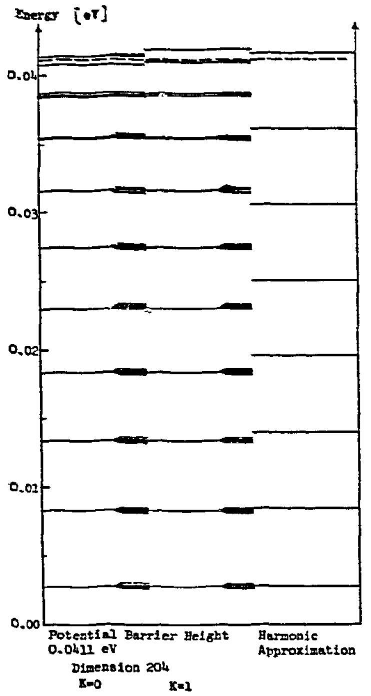

Fig. Energy levels compared with harmonic oscillator approximation.

II-2. Multiple Scattering of Neutrons and Correlation Functions

S. Sunakawa*, Y. Fukui**, and T. Nishigori***

The present note is the abstract of a paper published in progress of Theoretical Physics 35, 228 (1966).

When the wavelength of a neutron is very long, it interacts with the target system as a whole rather than with the individual atoms. The Van Hove formula for neutron scattering fails to describe such processes. In this paper, the formula is generalized to include the effects of the multiple scattering.

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The cross section is written as

$$\frac{d^2\sigma}{d\Omega d\varepsilon_f} = a^2 \frac{k_f}{k_i} \sum_{m,n=1}^{\infty} \int_{-\infty}^{\infty} \frac{dt}{2\pi\hbar} e^{i(\varepsilon_f - \varepsilon_i)t/\hbar} \int dx_1 \cdots dx_m dx_1' \cdots dx_n'$$
$$\times e^{ik_f(x_1 - x_1')} e^{-ik_i(x_m - x_n')} D^*(x_m - x_{m-1}) \cdots D^*(x_2 - x_1) D(x_1' - x_2')$$
$$\cdots D(x_{n-1}' - x_n') \times G(x_m, \cdots, x_1 ; o | t ; x_1', \cdots, x_n') \qquad (1)$$

in terms of the many-particle space-time correlation functions defined by

$$G(x_m, \cdots, x_1 ; o | t ; x_1', \cdots, x_n')$$
$$= \sum_{\substack{\alpha \neq \beta \\ \mu \neq \nu}} \sum_{\substack{\alpha' \neq \beta' \\ \mu' \neq \nu'}} \langle \delta(x_m - r_\nu(o)) \cdots \delta(x_1 - r_\alpha(o)) \delta(x_1' - r_{\alpha'}(t)) \cdots \delta(x_n' - r_{\nu'}(t)) \rangle_T, \qquad (2)$$

where $D(x_i - x_j)$ is the propagation function of a neutron:

$$D(x_i - x_j) = -a \frac{e^{ik_i |x_i - x_j|}}{|x_i - x_j|} \qquad (3)$$

The first term (m=n=1) of the expression (1) coincides with that of the Van Hove formula.

II-3. Slow Neutron Scattering and Space-time Correlation Functions

S. Sunakawa*, S. Yamasaki*, and T. Nishigori**

The Van Hove formula for the scattering cross section of the neutron is written in terms of the space-time correlation functions. They have complex values on account of quantum effects, and thus one cannot give them simple physical significances.

In order to remedy this defect, we reformulate the theory of the neutron scattering. The cross section for the scattering is expressed as

$$\frac{d^2\sigma}{d\Omega d\varepsilon_f} = Na^2 \frac{p_f}{p_i} \int dr\, e^{-i\, p\cdot r/\hbar} \int_{-\infty}^{\infty} \frac{dt}{2\pi\hbar} \{ e^{i(\epsilon t + \frac{1}{2i\hbar}[\, p\cdot r_\alpha(o),\, p\cdot r_\alpha(t)])/\hbar}$$
$$\times G_s(r, t) + e^{i\epsilon t/\hbar} G_d(r, t) \}, \qquad (1)$$

where the functions G_s and G_d:

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$$G_s(\mathbf{r},t) \equiv \frac{1}{N}\sum_{\alpha=1}^{N} \langle \delta(\mathbf{r}+\mathbf{r}_\alpha(o)-\mathbf{r}_\alpha(t))\rangle_T , \tag{2}$$

$$G_d(\mathbf{r},t) \equiv \frac{1}{N}\sum_{\alpha\neq\beta} \langle \delta(\mathbf{r}+\mathbf{r}_\alpha(o)-\mathbf{r}_\beta(t))\rangle_T , \tag{3}$$

are the new quantum mechanical correlation functions proposed in the present note; the new function G_d (or G_s) is real and positive, and one can regard it as a probability of finding a displacement from a position of a particle α at a time $t=0$ to that of a particle β (or the particle α in the case of G_s) at a time $t=t$ in $\mathbf{r}$. The commutator in the exponent of the expression (1) is a c-number function of t.

In the classical approximation, we replace the commutator $[\mathbf{p}\cdot\mathbf{r}_\alpha(o), \mathbf{p}\cdot\mathbf{r}_\alpha(t)]/i\hbar$ in (1) by a classical Poisson bracket $\{\mathbf{p}\cdot\mathbf{r}_\alpha(o), \mathbf{p}\cdot\mathbf{r}_\alpha(t)\}$ and $G_s(\mathbf{r},t)$ and $G_d(\mathbf{r},t)$ by the classical space-time pair correlation functions G_{cs} and G_{cd}:

$$\left.\begin{aligned} G_{cs}(\mathbf{r},t) &\equiv \frac{1}{N}\sum_{\alpha=1}^{N}\left(\langle\!\langle \delta(\mathbf{r}+\mathbf{r}_\alpha(o)-\mathbf{r}_\alpha(t))\rangle\!\rangle_c\right), \\ G_{cd}(\mathbf{r},t) &\equiv \frac{1}{N}\sum_{\alpha\neq\beta}\left(\langle\!\langle \delta(\mathbf{r}+\mathbf{r}_\alpha(o)-\mathbf{r}_\beta(t))\rangle\!\rangle_c\right), \end{aligned}\right\} \tag{4}$$

where $\mathbf{r}_\alpha(t)$ and $\mathbf{r}_\beta(t)$ may be given as the solutions of the classical equations of motion for the target atoms, and $\langle\!\langle\cdots\rangle\!\rangle_c$ stands for the classical thermal average. The classical expression for the scattering cross section is written as

$$\frac{d^2\sigma}{d\Omega d\varepsilon_f} \simeq Na^2\frac{p_f}{p_i}\int d\mathbf{r}\; e^{-i\,\mathbf{p}\cdot\mathbf{r}/\hbar}\int_{-\infty}^{\infty}\frac{dt}{2\pi\hbar}\{e^{i(\varepsilon t+\frac{1}{2}\{\mathbf{p}\cdot\mathbf{r}_\alpha(o),\,\mathbf{p}\cdot\mathbf{r}_\alpha(t)\})/\hbar}$$

$$\times G_{cs}(\mathbf{r},t)+e^{i\varepsilon t/\hbar}G_{cd}(\mathbf{r},t)\} . \tag{5}$$

In the case of ideal gas, the result derived from the formula (5) coincides precisely with the exact quantum mechanical one. This fact indicates that the present classical cross section (5) includes correctly the recoil effects of the neutron. In the

Vineyard classical approximation, on the other hand, the contribution from the classical Poisson bracket $\{ \mathbf{p} \cdot \mathbf{r}_\alpha(0), \mathbf{p} \cdot \mathbf{r}_\alpha(t) \}$ in the exponent of (5) has been ignored inconsistently, and thus the recoil effects of the neutron are not taken into consideration.

The detail of the present note will be published in the journal: 'Progress of Theoretical Physics'.

III. Rikkyo (St. Paul's) University Institute for Atomic Energy

III-1. Gamma Rays from ^{109m}Pd*

M. Hattori, T. Nagahara, and K. Kitao**

The gamma rays from ^{109m}Pd was investigated by Stribel,[1] and Starner[2]. They obtained the value of 188 keV for the energy of the gamma rays. The purpose of the present investigation was a more precise determination of the gamma ray energy by a Ge(Li) detector.

We used a homemade Ge(Li) detector having a cross section of 1 cm x 1.5 cm and thickness of 3.5 mm. The resolution was about 4.5 keV at the 122 keV peak of ^{57}Co.

The Pd sources were obtained by 5 min. neutron irradiation of 2.7 mg natural Pd metal (99.9 %) at the rotary specimen rack ($\sim 5 \times 10^{11}$ n/cm^2. sec) of the Rikkyo University TRIGA II reactor (max. 100 kW).

The measurement was started 1 min. after irradiation. For the energy calibration, we used the values of 67.7, 84.7, 100.1, 152.4, 179.4, 198.4 and 222.1 keV of ^{182}Ta, and 122.1 and 136.4 keV of ^{57}Co. From the calibration curve, we obtained the value of 189.2 ± 0.3 keV for the gamma rays of irradiated Pd.

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* Quoted from the report IAERU-6609, Rikkyo University.

** National Institute of Radiological Science, Chiba

1) T. Stribel, Z. Naturforsch. 12a, 939 (1957)

2) J. W. Starner, Bull. Am. Phys. Soc. 4, No. 2, 99 (1959)

We measured the decay of this peak, and obtained the half-life of 4.7 ± 0.1 min.. From this value, we confirmed the 189.2 keV gamma rays come from the transition of the ^{109m}Pd to the ground state of ^{109}Pd.

IV. Nippon Atomic Industry Group Co. Ltd.

IV-1. One-Phonon Coherent Scattering of Slow Neutrons from Polycrystalline Aluminum*

Shungo Iijima

An approximate simple expression of the one-phonon coherent scattering of slow neutrons from cubic Bravais lattice was derived with the simplifying assumptions about the dispersion relations. They are:

(1) $\omega_{\lambda}(\vec{q})$ is spherical in $\vec{q}$-space and single-valued,

(2) the polarizations are strictly either transversal or longitudinal and

(3) two transverse branches are degenerate.

The scattering law was calculated for the case of aluminum, using Walker's frequency contour map and the frequency distribution. The calculation was in fair agreement with the measurement by Brugger et al. The feasibility of the usual extrapolation procedure to obtain the frequency distribution from the measured scattering law was discussed.

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* J. Nuc. Sci. & Tech. 3 p.160 (short note) (1966)

V. Tokyo Institute of Technology

V-1. The (n,α) Reactions on Heavy Nuclei with 15.1-MeV Neutrons

H. Kitazawa*, Y. Kanda*, and N. Yamamuro*

The energy distributions of the α-particles from the reactions $^{175}Lu(n,\alpha)^{172}Tm$, $^{165}Ho(n,\alpha)^{162}Tb$, $^{181}Ta(n,\alpha)^{178}Lu$, $^{141}Pr(n,\alpha)^{138}La$ and $^{197}Au(n,\alpha)^{194}Ir$ with 15.1 MeV neutrons have been measured at an angle of 0^{o} to the beam.

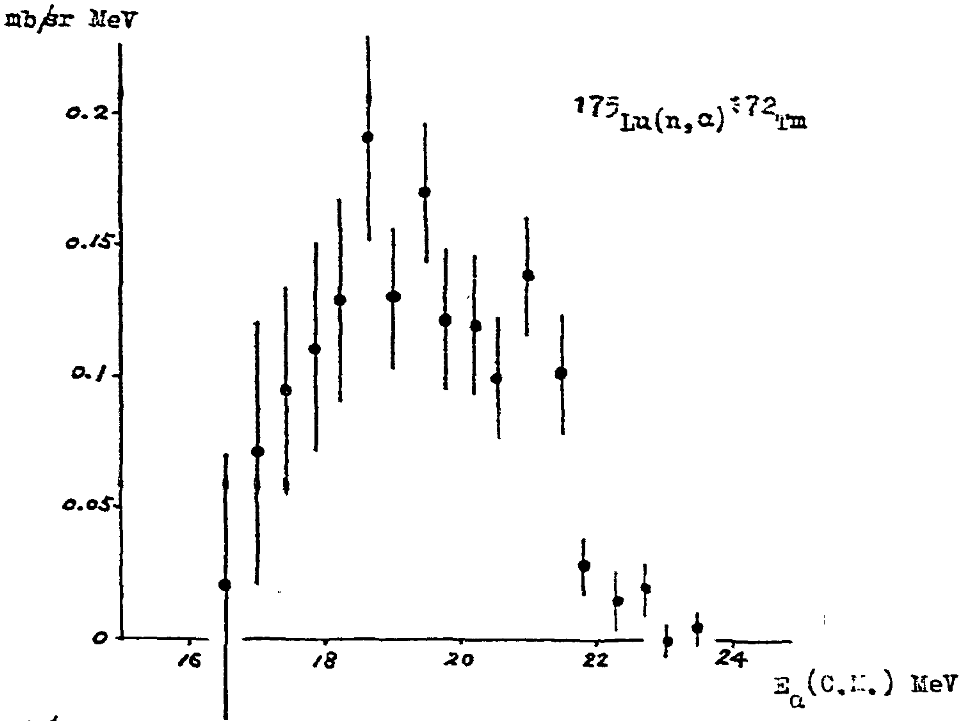
The α-particles from targetrs were detected by a silicon surface barrier detector, of 3 cm^2 sensitive area, biased 200 V. The distance between the neutron source and the target was 6 cm, and that between the target and the detector was 4 cm.

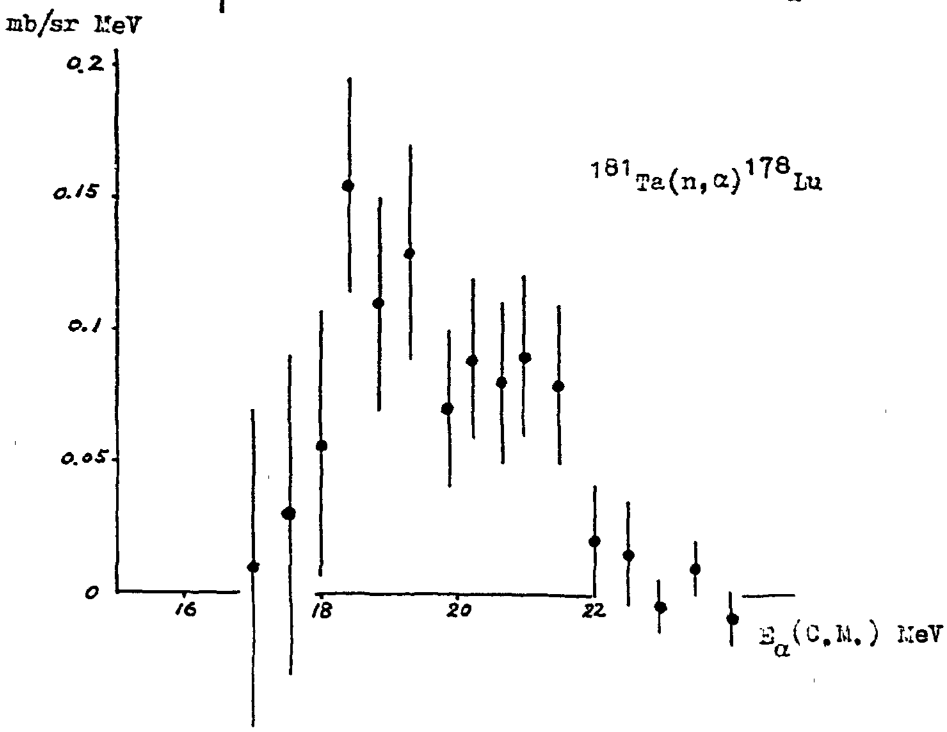
The targets of lutecium (8.4 mg/cm^2, Lu_2O_3), holmium (8.5 mg/cm^2, Ho_2O_3), tantalum (7.2 mg/cm^2, Ta_2O_3) and praseodymium (5.4 mg/cm^2, Pr_6O_{11}) were prepared by means of sedimentation.

The energy calibration of the detector was made by a Po-α source as well as by the background peaks due to $^{29}Si(n,\alpha)^{26}Mg$ and $^{28}Si(n,\alpha)^{25}Mg$ reactions.

The results for ^{175}Lu and ^{181}Ta are shown in figures. We intend to estimate the deviation from the evaporation model and to analyze it in terms of the direct interaction model.

* Reseach Laboratory of Nuclear Reactor.


mb/sr MeV
0.2
0.15
0.1
0.05
0
16
18
20
22
24
^{175}Lu(n,α)^{172}Tm
$E_α$(C.M.) MeV


mb/sr MeV
0.2
0.15
0.1
0.05
0
16
18
20
22
^{181}Ta(n,α)^{178}Lu
$E_α$(C.M.) MeV

V-2. Some Remarks on the Optical Potentials for Low Energy Neutrons

M. Igarashi, M. Kawai, and S. Igarasi *

Optical potentials for low energy neutron scattering by nuclei were briefly reviewed. The total cross sections and the differential cross sections of elastic and inelastic scattering were calculated for several target nuclei using the potentials given by Beyster et al.[1] and those of Moldauer[2] and using the Hauser-Feshbach theory of the compound nucleus process. The computations were done by ELIESE-I[3].

Neither sets were found to account for all the experimental data studied equally well. Moldauer's potential, for instance, well accounts for the data on medium weight spherical nuclei such as Ca^{40} and Y^{89} but the fit to the data on Al^{27}, Bi^{209} and U^{238} is not satisfactory.

Comparison with the potential of Auerbach and Moore[4] and with the theoretical calculation by Terasawa[5] indicates that the imaginary part of Moldauer's potential for heavy nuclei is too narrow and deep. Arguements were given for varying the imaginary potential rather rapidly with mass number, deformation, and so forth of the target nucleus.

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2) P. A. Moldauer, Nuclear Physics 47 (1963) 65
3) JAERI 1096, Nov. 1965
4) E. H. Auerbach and S. O. Moore, Phys. Rev. 135 (1964) B 895
5) T. Terasawa, Nuclear Physics 39 (1962) 563

* Japan Atomic Energy Research Institute, Tokai

V-3. Energy Spectra of Photo-Protons From Li^6

H. Hirabayashi, K. Fujioka, and Y. Oda

The proton energy spectra from the nuclear photo-reaction on Li^6 were studied with the Bremsstrahlung of maximum γ-ray energy 15.7 MeV. The protons were detected with the nuclear emulsion method. In the present case, one can expect that quite equivalent processes leading to neutron emissions also take place.

The proton energy spectra obtained show the existence of an eminent group at E_p=1.8 MeV, and the rather continuous spectra up to the maximum energy defined by the kinematics relation of the reaction. It has been confirmed that the spectrum peak is constructed only by a single group of the protons. These protons can be produced from the following two reactions. The one is the reaction $Li^6(\gamma,p)He^5$ in which the γ-rays are absorbed by the 6.63 MeV level of Li^6. The other is the reaction $Li^6(\gamma,pn)He^4$ in which the γ-rays are absorbed by the 9.0 MeV level of Li^6 and both product particles p and n have the nearly half of the available energy. It must be noted that latter level seems to have not yet the definite support for its existence. Further studies are now in progress.

VI. University of Tokyo
The Institute for Solid State Physics

VI-1. The Spin-Spin Interaction of 0.92 MeV Polarized Neutrons with Polarized ^{165}Ho Nuclei*

S. Kobayashi, H. Kamitsubo, K. Katori, A. Uchida,
M. Imaizumi, and K. Nagamine

In order to obtain a direct measure of the strength and form of the nuclear spin-spin interaction, the transmission of 0.92 MeV polarized neutrons by polarized ^{165}Ho was measured. The total cross section and relative scattering angular distribution of 0.92 MeV unpolarized neutrons through unpolarized ^{165}Ho nuclei were also measured in order to make a parameter search of the optical potential. The experimental results are analyzed with the DWBA formalism due to Davies and Satchler. The results show that the effective spin-spin interaction between a free neutron and a ^{165}Ho nucleus, is an attractive type and its strength has the order of one MeV, and the present experimental result along with other data obtained at ORNL and Stanford, can be fitted by the DWBA approach in either case of a volume and surface type of the form factor. For the further determination of the strength and form of spin-spin interaction, more precise similar experiments are needed for various different neutron energies.

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* A full paper is to appear in J. Phys. Soc. Japan 22 (1967) No. 2

VI-2. Low Energy (p,n) Reaction on ^{55}Mn and the Low-Lying Excited States of ^{55}Fe*

A. Uchida, K. Nagamine, N. Imaizumi, H. Kamitsubo, and S. Kobayashi

The (p,n) reaction on ^{55}Mn was studied with the emphasis upon the investigation of the low-lying states of ^{55}Fe. The angular distributions of each neutron groups corresponding to energy states of ^{55}Fe lower than 0.93 MeV were measured at ten different proton energies in the energy range from 2.3 MeV to 2.8 MeV. New levels of ^{55}Fe at 0.51 and 0.68 MeV reported by Kim at ORNL were not observed at least with so much intensities as he claimed. The Integrated cross section of each group corresponding to the low-lying states of ^{55}Fe was analyzed by means of the statistical theory due to Hauser and Feshbach. As a Consequence, the spin and parity of 0.41 MeV level were assigned as $1/2^-$;$3/2^-$ was excluded. This assignment is consistent with that suggested by Schiffer et al.. The measurement of the life of the first excited state at 0.41 MeV was tried as a testing of core-excitation model.

* J. Phys. Soc. Japan 21 (1966) 2115