## PROGRESS REPORT

(July 1994 to December 1995 inclusive)

March 1996

Editor
J. Katakura

Japanese Nuclear Data Committee

Japan Atomic Energy Research Institute<br>Tokai Research Establishment<br>Tokai-mura, Ibaraki-ken, Japan

## Editor's Note

This is a collection of reports which have been submitted to the Japanese Nuclear Data Committee at the committee's request. The request was addressed to the following individuals who might represent or be in touch with groups doing researches related to the nuclear data of interest to the development of the nuclear energy program.

Although the editor tried not to miss any appropriate addressed, there may have been some oversight. Meanwhile, contribution of a report rested with discretion of its author. The coverage of this document, therefore, may not be uniform over the related field or research.

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## I. Electrotechnical Laboratory

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## A. Quantum Radiation Division

# I-A-1 $\quad\left(\gamma_{\text {pol }}, \gamma\right)$ Reactions with Laser-Compton Backscattering 

H.Ohgaki, T.Noguchi, S.Sugiyama, T.Mikado, M.Chiwaki, K.Yamada, R.Suzuki, N.Sei, T.Ohdaira, and T.Yamazaki

Polarized gamma-rays are of interest in the field of nuclear physics, because the real photon has a high spin selectivity and a polarized beam assigns an unambiguous parity. Several facilities have used partially polarized photon beams from off-axis bremsstrahlung to investigate photonuclear reactions ${ }^{1)}$. However, the polarization of these photon beams was too poor to determine the parity assignment of the weak level. Another way to assign the parity is being investigated using a Compton polarimeter ${ }^{2)}$. It measures the polarization of outgoing photons by Nuclear Resonance Fluorescence. Unfortunately, this technique can be used in a low energy region, because the Compton polarimeter cannot analyze a high energy photon. So highly polarized photon beam is desired in this field.

Nowadays we can use a high quality and high current electron beam circulating in a storage ring, and we can also use an intense photon beam produced by a conventional laser. These circumstances allows us to produce photon beams using Compton backscattering ${ }^{3)}$. Compton scattering between a relativistic electron beam and a laser beam enhances the energy of the laser photons in head-on collisions. So these photons can be called Laser Compton Photons (LCPs). An LCP is a highly monochromatic gamma-ray that is energy tunable. Moreover, the most important characteristic of the LCP is its high polarization, because of the small spin-flip amplitude in the Compton scattering in the head-on collision. We have developed a linearly polarized LCP to investigate the multipolarities in a nucleus.

Our LCP facility uses a conventional Nd:YAG laser with electrons circulating in the electron storage ring TERAS at ETL. TERAS stores electrons up to 400 mA and the electron energy ranges from 200 to 800 MeV . A linearly polarized laser beam generated by a Q-switched Nd :YAG laser of $\lambda=1064 \mathrm{~nm}$ enters the vacuum window of the bending magnet and collides head-on with the electron beam in the straight section. The laser beam is focused on the colliding point into a few millimeters' diameter. The LCP energy can be varied by changing the energy of the electrons circulating the storage ring or changing the wavelength of the laser. In our case, we observed LCP energies of 1 to 10 MeV with the Nd:YAG laser. The LCP energy spread was also measured to be $1 \%$ FWHM for 1 MeV LCPs and to be $4 \%$ FWHM for 10 MeV LCPs with a 0.056 mrad collimator that defined the scattering cone ${ }^{4}$.

We tried to use the LCPs for a nuclear fluorescence experiment to assign the parities of $J=1$ levels in a nucleus. If we use a polarized laser beam, we can easily obtain polarized LCPs ${ }^{5}$. Then we measure the asymmetry,

$$
\begin{equation*}
A(\theta)=\frac{1}{p}\left(\frac{\sigma\left(\theta, 0^{\circ}\right)-\sigma\left(\theta, 90^{\circ}\right)}{\sigma\left(\theta, 0^{\circ}\right)+\sigma\left(\theta, 90^{\circ}\right)}\right) \tag{2}
\end{equation*}
$$

so we can easily assign the parity of the nucleus. In this expression, $\theta$ is scattering angle, $p$ is polarization of incident photons, $\sigma\left(\theta, 0^{\circ}\right)$ is the yield for the elastically scattered photons in the plane parallel to the electric vector of the incoming photons and $\sigma\left(\theta, 90^{\circ}\right)$ is that in the perpendicular plane. The theoretical calculation ${ }^{6)}$ predicts the asymmetry to be +1 for the positive parity state and -1 for the negative parity state under the condition of $\theta=90$ degree,
$p=100 \%$, and an even-even nucleus. This means that the elastically scattered photons are observed only in the $\sigma\left(\theta, 90^{\circ}\right)$ plane for the negative parity state in an even-even nucleus.


Fig. 1 Energy spectra of the ${ }^{208} \mathrm{~Pb}\left(\gamma_{\mathrm{pol}}, \gamma\right)$ reaction. The incident gamma-ray energy was 5.52 MeV and its energy spread was $2.9 \%$ FWHM. Upper part of this figure shows the elastically scattered photon in the plane parallel to the electric vector of the incident polarized gamma-ray and the lower one show that in the perpendicular plane.


Fig. 2 Energy spectra of the ${ }^{208} \mathrm{~Pb}\left(\gamma_{\text {pol }}, \gamma\right)$ reaction. The incident gamma-ray energy was 4.85 MeV and its energy spread was $2.7 \%$ FWHM. Upper part of this figure shows the elastically scattered photon in the plane parallel to the electric vector of the incident polarized gamma-ray and the lower one show that in the perpendicular plane.
${ }^{208} \mathrm{~Pb}\left(\gamma_{\text {pol }}, \gamma\right)$ reactions have been studied to check the system and to assign the parities of $J=1$ levels. Figure 1 shows the energy spectra of the ${ }^{208} \mathrm{~Pb}\left(\gamma_{\mathrm{pol}}, \gamma\right)$ reaction at the incident photon energy of 5.52 MeV . We measure the elastically scattered photon in the direction of $90^{\circ}$ by a 155 cc pure Ge detector. The upper part of fig. 1 shows the elastic scattering photons against the parallel polarized photons. The lower one shows the elastic scattering photons against the perpendicularly polarized photons. The measured asymmetry is $-0.950 \pm 0.047$ after background subtraction. The error in the asymmetry is only from statistical error. We can clearly determine the parity of the 5.514 MeV level to be negative by using the linearly polarized LCPs. Next we tried to measure the elastically scattered photons from ${ }^{208} \mathrm{~Pb}, E x=4.841 \mathrm{MeV}, J=1$ state. Figure 2 shows the energy spectra of the ${ }^{208} \mathrm{~Pb}\left(\gamma_{\text {pol }}, \gamma\right)$ reaction at the incident photon energy of 4.85 MeV . One can clearly see that the parity of $E x=4.841 \mathrm{MeV}, J=1$ states is negative ${ }^{7}$.

We also tried to measure the parity of an even-odd nucleus, ${ }^{11} \mathrm{~B}(E x=4.4451 \mathrm{MeV})$. The asymmetry is predicted to be +0.226 for $5 / 2^{\circ}$ state. In contrast to a high asymmetry in an odd-odd nucleus, the asymmetry of the even-odd nucleus is rather low. So the parity assignment for the even-odd nucleus was difficult for a poor polarization gamma-ray. Figure 3 shows the elastically
scattered photons from the ${ }^{11} \mathrm{~B}\left(\gamma_{\text {pol }}, \gamma\right)$ reaction. The measured asymmetry is +0.21 after
 background subtraction. This shows a good agreement with the theoretical prediction. We should emphasize that the polarized gammaray from laser-Compton backscattering is quite a useful gamma source in this field, because we can use highly, almost completely, polarized gamma-rays. So, we can conclude that the linearly polarized LCP beams can assign the parity for any nucleus.

Fig. 3 Energy spectra of the ${ }^{11} B\left(\gamma_{p o l}, \gamma\right)$ reaction. The incident gamma-ray energy was 4.47 MeV and its energy spread was $2.7 \%$ FWHM. Upper part of this figure shows the elastically scattered photon in the plane parallel to the electric vector of the incident polarized gamma-ray and the lower one show that in the perpendicular plane.

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## II. Fuji Electric Co., Ltd

## A. Nuclear Engineering Division

## II-A-1 Excitation-dependent Properties of Paired Nucleons System

Hisashi Nakamura

At the present time the most statistical theory calculations of nuclear reactions are carried out by using the semiempirical level density formula proposed by Gilbert and Cameron ${ }^{1)}$ in 1965, which is based essentially on the Fermi-gas (FG) model and seems to be enough to predict the level densities at the narrow range of excitations. However, it has been in fact well established ${ }^{2)}$ that the extrapolation of this formula to a wide range of excitation energies is subject to large errors, and that washing out of shell and pairing effects should be considered. Among the semiempirical models which account for the energy-dependent shell correction of the nuclear level density, the Kataria,Ramamurthy and Kapoor (KRK ) model ${ }^{3)}$ is considered as the typical one. On the other hand, the energy-dependent pairing corrections with the shell-pairing correlation seems to be correctly considered only by means of the microscopic Fermi-gas model ${ }^{4)}$, which has, however, still an inaccuracy due to the formalism in the superconducting phase ${ }^{2)}$.

The purpose of the current work is to obtain the new systematics on parameters of the level density formula. In the model,the analytical expressions of the single-particle state density are adopted not only for the energy-dependent shell-effect, but, in particular, for the energy-dependent pairing correction with the shell-pairing correlation, and so we call it 'SPC' (Shell-Priring Correlation) model.

A nuclear level density formula is derived from the Fourier expansion of singleparticle state density, considering only a fundamental harmonic for the main-shell with the sub-shell associated to the pairing interaction:

$$
\begin{equation*}
\mathbf{g}(\varepsilon)=\sum \mathbf{g}_{0 \mathrm{X}}\left[1+\mathbf{f}_{\mathrm{X}} \cdot \cos \left\{\omega\left(\varepsilon-\varepsilon_{\mathrm{X}}\right)\right\}\right] \cdot\left[1-\cos \left\{\omega_{\mathrm{P}}(\varepsilon-\lambda)\right\}\right], \tag{1}
\end{equation*}
$$

where $\omega$ = frequency related to the main-shell spacing, $\omega_{\mathrm{P}}=$ frequency related to the pairing energy, $\varepsilon_{\mathrm{X}}=$ main-shell position, $\lambda=$ Fermi level, $\mathrm{g}_{0 \mathrm{X}}=$ average singleparticle state density (2-fold degenerate), and $f_{x}=$ amplitude of main-shell, $x=$ stand for proton $(=\mathrm{z})$ or neutron( $=\mathrm{n}$ ) shell.

In Eq.(1) the main-shell terms are just those of the KRK model ${ }^{3)}$, and when $\mathrm{f}_{\mathrm{x}}=0$ the so-called quasi-particle state density under the pairing correlation may be written as

$$
\begin{equation*}
g(\varepsilon)=\Sigma \mathbf{g}_{0 \mathrm{X}}\left[1-\cos \left\{\omega_{\mathrm{P}}(\varepsilon-\lambda)\right\}\right], \tag{2}
\end{equation*}
$$

which is the prescription of the SPC model for the pairing correlations. A better understanding of meanings of Eq.(2) can be obtained if the thermodynamical properties of quasi-particle system are analyzed by using the traditional method of statistical mechanics. The main quantities for that are the excitation energy Ex, the entropy $S$ (Ex)
and the moment of inertia I;

$$
\begin{equation*}
E x=a_{0} t^{2}-E_{P}\left\{h_{1}\left(\mathrm{~T}_{\mathrm{P}}\right) \mathrm{h}_{2}\left(\mathrm{~T}_{\mathrm{P}}\right)-1\right\} \tag{3}
\end{equation*}
$$

where $t=$ thermodynamic temperature, $\mathrm{T}_{\mathrm{P}}=\pi \omega_{\mathrm{P}} \mathrm{t}, \mathrm{h}_{1}\left(\mathrm{~T}_{\mathrm{P}}\right)=\mathrm{T}_{\mathrm{P}} \cdot \operatorname{cosech}\left(\mathrm{T}_{\mathrm{P}}\right), \quad \mathrm{h}$ ${ }_{2}\left(\mathrm{~T}_{\mathrm{P}}\right)=\mathrm{T}_{\mathrm{P}} \cdot \operatorname{coth}\left(\mathrm{T}_{\mathrm{P}}\right), \mathrm{a}_{0}=$ asymptotic level density parameter $\left\{=\left(\pi^{2} / 3\right) \mathrm{g}_{0}\right\}, \mathrm{g}_{0} \equiv$ ( g $\left.0_{0}+g_{0 n}\right), E_{P}=$ pairing correction energy at the ground state $\left(=g_{0} / \omega_{P}{ }^{2}\right)$.

$$
\begin{align*}
& \mathrm{S}(\mathrm{Ex})=2 \mathrm{a}_{0} \mathrm{t}-\mathrm{t}^{-1} \mathrm{E}_{\mathrm{P}} \mathrm{~h}_{1}\left(\mathrm{~T}_{\mathrm{P}}\right)\left\{\mathrm{h}_{2}\left(\mathrm{~T}_{\mathrm{P}}\right)-1\right\},  \tag{4}\\
& \mathrm{I}=\mathrm{I}_{0}\left[1-(1 / 2)\left(\delta_{2}+\delta \mathrm{n}\right) \mathrm{h}_{1}\left(\mathrm{~T}_{\mathrm{P}}\right)\right], \tag{5}
\end{align*}
$$

where $I_{0}=I_{r}$ (for spherical nuclei), $I_{r}=0.015 \mathrm{~A}^{5 / 3}$ (Fermi-gas moment of inertia), $\mathrm{A}=$ nuclear mass-number, $\delta=1$ (even protons or neutrons), $=0$ (odd). In the above formulation of Eqs.(3)~(5) the small correction terms due to the energy dependence of Fermi level $\lambda$ is ignored as the previous KRK model.

The main feature of the current prescription for pairing correlations can be seen on the basis of the simple version ${ }^{5,6)}$ of the superconductivity theory of $\mathrm{BCS}^{7)}$, where the following relations were used :

$$
\begin{align*}
& 2 \Delta_{0} / \mathrm{t}_{\mathrm{c}}=3.50, \quad \mathrm{E}_{\mathrm{P}}=1 / 2 \mathrm{~g}_{0} \Delta_{0}{ }^{2} \quad 2 \Delta_{0}, \\
& \operatorname{Ex}=\operatorname{Exc}\left(1-\phi^{2}\right), \quad S=\operatorname{Sc}\left(t{ }_{c} / t\right)\left(1-\phi^{2}\right), \\
& \mathrm{I}=\mathrm{I}_{0}\left(\mathrm{t}{ }_{\mathrm{c}} / \mathrm{t}\right)\left(1-\phi^{2}\right), \quad \phi=\tanh \left\{\left(\mathrm{t}_{\mathrm{c}} / \mathrm{t}\right) \phi\right\}, \quad\left(\mathrm{t} \leqq \mathrm{t}_{\mathrm{c}}\right), \\
& E x=\mathrm{a}_{0} \mathrm{t}^{2}+\mathrm{E}_{\mathrm{P}}, \quad \mathrm{~S}=2 \mathrm{a}_{0} \mathrm{t}, \quad\left(\mathrm{t}>\mathrm{t}_{\mathrm{c}}\right) \tag{6}
\end{align*}
$$

In the above notation $\Delta_{0}$ is the energy gap in the ground state, $t_{c}$ is the critical temperature of the phase transition.

Then, in FIG. 1 the entropy and in FIG. 2 the moment of inertia are compared each other with those of FG-, SPC-models and the foregoing superconductor model for the example of nucleus ${ }^{60} \mathrm{Ni}[\mathrm{Z}=28, \mathrm{~N}=32, \mathrm{~A}=60]$, with the parameter systematics from the relations in Eq.(3):

$$
\begin{align*}
& \omega_{\mathrm{P}}^{2}=\mathrm{g}_{0} / \mathrm{Ep}, \quad \mathrm{~g}_{0}=\left(3 / \pi^{2}\right) \mathrm{a}_{0}, \quad \mathrm{a}_{0}=0.137 \mathrm{~A}, \\
& \omega_{\mathrm{P}}=0.144 \mathrm{~A}^{1 / 2}, \quad \mathrm{E}_{\mathrm{P}}=2.0 \mathrm{MeV} . \tag{7}
\end{align*}
$$

As seen in FIG. 1 and FIG. 2 the properties of SPC model do not have a finite critical temperature of the phase transition, but shows the moderate energy-dependence at the vicinity of the phase transition point.

By using the full scope of the single-particle state density Eq.(1) with $f_{x} \neq 0, \quad$ the traditional statistical procedure leads to the following nuclear level density formula

$$
\begin{equation*}
\rho(\mathrm{Ex}, \mathrm{~J}, \mathrm{II})=\frac{1}{2} \Omega(\mathrm{~J}) \cdot \rho(\mathrm{Ex}) \cdot \mathrm{K}_{\mathrm{rot}}(\mathrm{Ex}) \tag{8}
\end{equation*}
$$

where the factor $1 / 2$ is assumed for equal probability of parity states $\Pi$ and $K_{r_{0}}$ is the rotational enhancement factor ${ }^{5)}$, and each factor is well known respectively. The procedures of level density parameter fitting by using the measured resonance spasings are now in progress over a wide range of nuclear masses.

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FIG. 1 Entropy vs. Excitation Energy


FIG. 2 Moment of Inertia vs. Excitation Energy

# III. Japan Atomic Energy Research Institute 

# A. Nuclear Data Center and Working Groups of Japanese Nuclear Data Committee 

III-A-1 Evaluation of Neutron Nuclear Data for ${ }^{9}$ Be

Keiichi SHIBATA

Evaluation of neutron nuclear data for ${ }^{9} \mathrm{Be}$ has been performed in the energy region from $10^{-5} \mathrm{eV}$ to 50 MeV . The evaluated quantities are total, elastic scattering, $(\mathrm{n}, \mathrm{p}),(\mathrm{n}, \mathrm{d}),(\mathrm{n}, \mathrm{t}),(\mathrm{n}, \alpha),(\mathrm{n}, \gamma)$ and $(\mathrm{n}, 2 \mathrm{n})$ reaction cross sections as well as neutron and charged-particle emission spectra.

The cross sections below 20 MeV were taken from the JENDL-3.2 data except the ( $n, t$ ) reaction cross section. The latest measurements ${ }^{1,2)}$ were taken into account in the evaluation of the $(\mathrm{n}, \mathrm{t})$ cross section.

Above 20 MeV , the total cross section was evaluated on the basis of the experimental data measured by Finlay et al. ${ }^{3)}$ The total reaction cross section was calculated with the microscopic optical model ${ }^{4)}$ in the energy range above 20 MeV . The reaction cross section thus obtained was divided into each partial cross section on the basis of statistical model calculations.

Double differential cross sections of emitted particles were calculated with a modified version of SCINFUL/DDX code ${ }^{5)}$ by taking account of 2- and 3-body reaction kinematics. The calculated neutron and $\alpha$-particle emission spectra are in good agreement with available experimental data.

## References

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# III-A-2 Uncertainties in Evaluated Total Cross-Section Data for 14 Nuclides Contained in JENDL-3.2 

Masahiro NAKAMURA and Keiichi SHIBATA

A paper on this subject was published as JAERI-Research 95-068 (1995) with the following abstract:

Variances and covariances of total cross sections have been estimated for 14 nuclides contained in JENDL-3.2. Least-squares analyses using the GMA code were performed to obtain them. Information on the uncertainties of those measurements, which the JENDL-3.2 evaluation was based on, was derived from the associated references and fed into the GMA code system. The results obtained from the present analysis are illustrated.

# III-A-3 Status of Nuclear Data Evaluation for JENDL High Energy File 

T. Fukahori and S. Chiba

A paper on this subject has been published in Proc. of the 2nd Specialists' Meeting on High Energy Nuclear Data, Jan. 26-27, 1995, JAERI Tokai, Japan, JAERI-Conf 95-016, p. 46 (1995) with the following abstract:

The present status of the JENDL High Energy File is reported as well as the code comparison benchmark test and discussion for the file format performed by Japanese Nuclear Data Committee. The PKA/KERMA File and the Photonuclear Data File are also introduced briefly as related topics with the JENDL High Energy File.

## III-A-4 Status of JENDL High Energy File for IFMIF

## T. Fukahori

A paper will be published in Proc. of the 1995 Symposium on Nuclear Data, 16-17 November 1995, JAERI Tokai, Japan, JAERI-Conf (1996) with the following abstract:

The JENDL High Energy File for IFMIF is a neutron nuclear data file of the phase-I of JENDL High Energy Files. The 27 elements from H to W are included in the JENDL High Energy File for IFMIF. The evaluated quantities are the total, elastic scattering, reaction, fission and isotope production cross sections, and double differential particle and $\gamma$-ray emission cross sections. The considered outgoing particles are neutron, proton, deuteron, triton, ${ }^{3} \mathrm{He}$ and $\alpha$-particles. The present status of the JENDL High Energy File for IFMIF, and preliminary results for several nuclides are reported as well as their format.

# III-A-5 Process of PKA File for FENDL from JENDL Fusion File with Effective Single Particle Emission Approximation 

T. Fukahori, S. Chiba and M. Kawai

A paper will be published in Proc. of the 1995 Symposium on Nuclear Data, 16-17 November 1995, JAERI Tokai, Japan, JAERI-Conf (1996) with the following abstract:

The code ESPERANT using an effective single particle emission approximation (ESPEA) was developed for nucleus except light mass elements as a processing method the of JENDL PKA/KERMA File from an evaluated nuclear data file. The code SCINFUL/DDX is used for light mass nuclides. As a trial task of ESPERANT usage, PKA file for the FENDL project in the energy range below 20 MeV was processed from the JENDL Fusion File. The processed PKA file was compared with results of Monte-Carlo calculation by MCEXCITON and calculated results from ENDF/B-IV. The results of three methods gave similar trends. It was concluded that the processing method with ESPEA was applicable to produce PKA File.

## III-A-6 Process of PKA/KERMA File for FENDL from JENDL Fusion File <br> T. Fukahori, S. Chiba and M. Kawai

A paper will be published in Proc. of the 3rd Specialists' Meeting on Nuclear Data for Fusion Reactors, 29-30 November 1995, JAERI Tokai, Japan, JAERI-Conf (1996) with the following abstract:

The project of JENDL PKA/KERMA File is introduced as a file for radiation damage calculations in the incident neutron energy range below 50 MeV . The code ESPERANT using an effective single particle emission approximation (ESPEA) was developed for nucleus except light mass elements as a processing method from an evaluated nuclear data file. The code SCINFUL/DDX is used for light mass nuclides. As a trial task of ESPERANT usage, PKA file for the FENDL project in the energy range below 20 MeV was processed from the JENDL Fusion File. The processed PKA file was compared with results of Monte-Carlo calculation by MCEXCITON and calculated results from ENDF/B-IV. The results of three methods gave similar trends. It was concluded that the processing method with ESPEA was applicable to produce PKA File.

## III-A-7 Systematics of Fission Cross Sections in the Intermediate Energy Region

T. Fukahori and S. Chiba

One of the purposes of developing intermediate energy nuclear data is to supply basic data to waste management system, especially to accelerator-driven waste transmutation system. The fission cross section is an important physical quantity in the transmutation system. At the intermediate energy region, nuclei lighter than the actinides also have considerable fission cross sections. Systematics of fission cross section in the intermediate energy region is under development in JAERI to obtain the values simultaneously for various projectile-target combinations by using accumulated experimental data such as measured at Los Alamos ${ }^{1)}$ and Gatchina ${ }^{2}$. In this report, the systematics of proton induced fission cross section is reported as an step of the total systematics study.

The systematics was obtained with fitting experimental data for proton induced fission cross sections of ${ }^{n a 1} \mathrm{Ag},{ }^{181} \mathrm{Ta}, ~{ }^{197} \mathrm{Au}, ~{ }^{206.207,208} \mathrm{~Pb}, ~{ }^{209} \mathrm{Bi}, ~{ }^{232} \mathrm{Th}, ~{ }^{233.235,238} \mathrm{U}, ~{ }^{237} \mathrm{~Np}$ and ${ }^{239} \mathrm{Pu}$ above 20 MeV with the following formula.

$$
\begin{gather*}
P_{f i s}(Z, A, E)=p_{1} \cdot\left[1-\exp \left(-p_{3}\left(E-p_{2}\right)\right)\right] \\
p_{i}=A^{2 / 3} \cdot \exp \left[q_{i, 1}+q_{i, 2}\left(Z^{2} / A\right)+q_{i, 3}\left(Z^{2} / A\right)^{2}\right] \tag{i=1,2,3}
\end{gather*}
$$

where $P_{\text {fis }}\left(=\sigma_{\text {fis }} / \sigma_{R}\right)$ is defined as the fissility, $\sigma_{\text {fis }}$ and $\sigma_{R}$ are fission and total reaction (compound formation) cross sections, $Z$ and $A$ are the atomic and mass number of compound nucleus, $E$ is an excitation energy $[\mathrm{MeV}], ~ q_{i, j}$ is the parameter independent of $Z$ and $A$. It seems that the $p_{1}, p_{2}$ and $p_{3}$ parameters correspond to the saturation fissility, threshold energy and increasing rate, respectively. In the case that the experimental data are only given for the fission cross section, fissility is obtained by using $\sigma_{R}$ calculated by Pearlstein's systematics ${ }^{3)}$. The low energy cross section of actinoid nuclei is omitted from systematics study, since the cross section has a complicated shape and strongly depends on characteristic of nucleus.

The numerical result of systematics is summarized in Table 1. The fission cross sections calculated by the systematics are in good agreement with experimental data. In the future work, fission cross section induced by neutron, deuteron, alpha, photon, etc. will be included to the systematics. The fragment mass distribution and neutron energy spectrum should be also considered.

## References

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Table 1 The result of systematics for proton induced fission cross section result error (\%) Correlation Matrix


## III-A-8 A Code Guidance System for Integrated Nuclear Data Evaluation System

T. Fukahori and T. Nakagawa

Evaluated nuclear data files are necessary to many applications, and nuclear data evaluation is required to obtain the most reliable data sets. The evaluation must be done by using experimental data and by many complicated theoretical calculations with various physical data such as optical potential parameters, level density parameters, and level scheme. Japanese Evaluated Nuclear Data Library, version 3 (JENDL-3) ${ }^{1)}$ released in 1989 was accomplished by great efforts of many evaluators with a lot of intricate work.

Integrated Nuclear Data Evaluation System (INDES) ${ }^{2)}$ is being developed to keep their accumulated experiences of JENDL-3, to store basic data of nuclear physics used for the JENDL-3 evaluation, and to support new evaluations. Roughly classified, INDES functions are of three categories; to select the most suitable set of theoretical calculation codes, to retrieve data needed for the theoretical calculation codes from the database in INDES, and to set up input data of theoretical calculation codes automatically. For the first function, a guidance system in INDES, which is called 'Evaluation Tutor (ET)', has been developed by applying knowledge engineering technology, which is based on the similar method to 'example-base reasoning'. ET consists of an inference engine, calculating modules of certainty factors, two example-bases, frames, and a rule-base. The theoretical calculation codes for nuclear data evaluation considered in ET are DWUCKY ${ }^{3 \text { 3 }}$, ECIS $^{4)}$, CASECIS, JUPITOR ${ }^{(5)}$, EGNASH2 ${ }^{3)}$, TNG $^{6)}$, PEGASUS ${ }^{7}$, ALICE- $F^{8)}$, CASTHY2 ${ }^{9)}$, ELIESE- $3^{(1)}$, RESCAL and HIKARI, and it is easy to add new codes. The information concerning the theoretical calculation codes is stored in frames.

The two example-bases are used to obtain 'certainty factors' of the theoretical calculation codes from their frequencies of use in the previous nuclear data evaluation. One example-base has been created from the experiences of the JENDL-3 evaluation work. Another is a supplementary example-base which stores results of code selection performed by ET, in order to be used in the next selection and to supply 'learning function'.

The 'rules' stored in the rule-base are used in the inference engine to select the theoretical calculation codes. The rules are classified into four types according to nuclear reaction processes; the direct, preequilibrium, compound and other processes. The latest version of ET has 14 rules.

The typical execution scheme is following. Firstly, the user specifies the basic information such as a target nucleus, a projectile and an incident energy range. Then, certainty factors are calculated for all the registered theoretical calculation codes by counting the number of uses in two example-bases. The rules in the rule-base are executed to make a preliminary decision of code selection. All the codes in the frames are classified into four reaction processes. If a process is judged not to be needed, the codes corresponding to the process are omitted from the selection. The candidate which has the largest certainty factor is selected as the recommended theoretical calculation code for each reaction process. For the codes requiring other auxiliary codes, the auxiliary codes are added to the set of recommended codes.

The rule-base and the theoretical calculation codes contained in ET will be expanded to treat more detailed procedures.

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## III-A-9 Status of PKA, KERMA and DPA Files of JENDL

T. Fukahori, S. Chiba, K. Shibata, Y. Watanabe, T. Murata, N. Yamano, Y. Ikeda, T. Aruga and M. Kawai

A paper on this subject will be presented at the 9th International Symposium on Reactor Dosimetry, Sep. 2-6, 1996, Autokongrescentrum Prague, Czech Republic with following abstract

In the Japanese Nuclear Data Committee, the PKA/KERMA file containing PKA spectra, KERMA factors and DPA cross sections in the energy range between $10^{-5} \mathrm{eV}$ and 50 MeV is prepared from the evaluated nuclear data in the JENDL-3.2 ${ }^{1)}$ and JENDL High Energy Files ${ }^{23}$, for reactor dosimetry and the International Fusion Material Irradiation Facility (IFMIF) which is an FMIT-type accelerator facility using Li(d,n) neutron source for a material irradiation test. The processing code ESPERANT was developed to calculate quantities of PKA, KERMA and DPA from evaluated nuclear data for medium and heavy elements by using the single particle emission approximation. For light elements such as $\mathrm{Li}, \mathrm{Be}, \mathrm{B}, \mathrm{C}$, N and O , the PKA spectra are evaluated by the SCINFUL/DDX and EXIFON codes, simultaneously with other neutron cross sections.

The file of PKA spectra for 69 nuclides from ${ }^{19} \mathrm{~F}$ to ${ }^{209} \mathrm{Bi}$ in the energy region up to 20 MeV has been generated for fusion application in the spring of 1995, and the KERMA and DPA data are calculated from the PKA spectra. The evaluation of nuclear data for JENDL High Energy File is now in progress. Finally, the PKA/KERMA file will contain the data for 78 isotope of 29 elements: $\mathrm{H}, \mathrm{Li}, \mathrm{Be}, \mathrm{B}, \mathrm{C}, \mathrm{N}, \mathrm{O}, \mathrm{Na}, \mathrm{Mg}, \mathrm{Al}, \mathrm{Si}, \mathrm{Cl}, \mathrm{K}, \mathrm{Ca}, \mathrm{Ti}, \mathrm{V}, \mathrm{Cr}, \mathrm{Mn}$, $\mathrm{Fe}, \mathrm{Co}, \mathrm{Ni}, \mathrm{Cu}, \mathrm{Ge}, \mathrm{Zr}, \mathrm{Nb}, \mathrm{Mo}, \mathrm{W}, \mathrm{Pb}$ and Bi up to 50 MeV .

The benchmark test of the KERMA data for $\mathrm{C}, \mathrm{Ti}, \mathrm{Cu}, \mathrm{Mo}$ etc. will be made by using the FNS experiments ${ }^{3)}$ of nuclear heating. After the test, the PKA/KERMA file will be released in 1998.

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## III-A-10

Japanese Evaluated Nuclear Data Library Version 3 Revision-2: JENDL-3.2

T. Nakagawa, K.Shibata, S.Chiba, T.Fukahori, Y.Nakajima, Y.Kikuchi, T.Kawano, Y.Kanda, T.Ohsawa, H.Matsunobu, M.Kawai, A.Zukeran, T.Watanabe, S.Igarasi, K.Kosako and T.Asami

A paper on this subject was published in J. Nucl. Sci. Technol., 32, 1259 (1995) with the following abstract:

The revision work of JENDL-3 has been made by considering feedback information of various benchmark tests. The main revised quantities are the resonance parameters, capture and inelastic scattering cross sections, and fission spectra of main actinide nuclides, the total and inelastic scattering cross sections of structural materials, the resonance parameters, the capture and inelastic scattering cross sections of fission products, and the $\gamma$-ray production data. The revised data were released as JENDL-3.2 in June 1994. The preliminary Benchmark tests indicate that JENDL-3.2 predicts various reactor characteristics more successfully than the previous version of JENDL-3.1.

## III-A-11 Evaluation of Nuclear Data of ${ }^{244} \mathrm{Pu}$ and ${ }^{237} \mathrm{Pu}$

## Tsuneo NAKAGAWA and Valentin A. KONSHIN

A paper on this subject was published as JAERI-Research 95-67 (1995) with the following abstract:

The evaluation of nuclear data for ${ }^{244} \mathrm{Pu}$ and ${ }^{237} \mathrm{Pu}$ was made in the neutron energy region from $10^{-5} \mathrm{eV}$ to 20 MeV . For the both nuclides, the total, elastic and inelastic scattering, fission, capture, ( $n, 2 n$ ) and ( $n, 3 n$ ) reaction cross sections were evaluated on the basis of theoretical calculation. The resonance parameters were given for ${ }^{244} \mathrm{Pu}$. The angular and energy distributions of secondary neutrons were also estimated for the both nuclides. The results were compiled in the ENDF-5 format and will be adopted in JENDL Actinoid File.

## III-A-12

# Calculations of Neutron and Proton Induced Reaction Cross Sections <br> for Actinides in the Energy Region from 10 MeV to 1 GeV 

## V.A. KONSHIN

A paper on this subject was published as JAERI-Research 95-036 (1995) with the following abstracts:

Several nuclear model codes were applied to calculations of nuclear data in the energy region from 10 MeV to 1 GeV . At energies up to 100 MeV the nuclear theory code GNASH was used for nuclear data calculation for neutrons incident for on ${ }^{238} \mathrm{U},{ }^{233-236} \mathrm{U},{ }^{238-242} \mathrm{Pu},{ }^{237} \mathrm{~Np},{ }^{232} \mathrm{Th}$, ${ }^{241-243} \mathrm{Am}$ and ${ }^{242-247} \mathrm{Cm}$. At energies from 100 MeV to 1 GeV the intranuclear cascade exciton model including the fission process was applied to calculations of protons and neutrons with ${ }^{233} \mathrm{U}$, ${ }^{235} \mathrm{U},{ }^{238} \mathrm{U},{ }^{232} \mathrm{Th},{ }^{232} \mathrm{~Pa},{ }^{237} \mathrm{~Np},{ }^{238} \mathrm{~Np},{ }^{239} \mathrm{Pu},{ }^{241} \mathrm{Am},{ }^{242} \mathrm{Am}$ and ${ }^{242-248} \mathrm{Cm}$. Determination of parameter systematics was a major effort in the present work that was aimed at improving the predictive capability of the models used. An emphasis was placed upon a simultaneous analysis of data for a variety of reaction channels for the nuclei considered, as well as of data that are available for nearby nuclei or for other incident particles. Comparisons with experimental data available on multiple reaction cross sections, isotope yields, fission cross sections, particle multiplicities, secondary particle spectra, and double differential cross sections indicate that the calculations reproduce the trends, and often the details, of the measurements data.

## III-A-13

# Consistent Calculations of Fast Neutron Induced Fission, ( $\mathrm{n}, 2 \mathrm{n}$ ) and <br> ( $\mathrm{n}, 3 \mathrm{n}$ ) Cross-Sections for 71 Isotopes of $\mathrm{Th}, \mathrm{Pa}, \mathrm{U}, \mathrm{Np}, \mathrm{Pu}, \mathrm{Am}, \mathrm{Cm}, \mathrm{Bk}$ and Cf 

## V.A. KONSHIN

A paper on this subject was published as JAERI-Research 95-010 (1995) with the following abstract:

The neutron cross-sections for fission, ( $\mathrm{n}, 2 \mathrm{n}$ ) and ( $\mathrm{n}, 3 \mathrm{n}$ ) reactions have been calculated consistently for ${ }^{227-234} \mathrm{Th},{ }^{229-233} \mathrm{~Pa},{ }^{230-240} \mathrm{U},{ }^{235-239} \mathrm{~Np},{ }^{236-247} \mathrm{Pu},{ }^{239-245} \mathrm{Am},{ }^{238-251} \mathrm{Cm},{ }^{245-249} \mathrm{Bk}$ and ${ }^{249-252}$ Cf using the Hauser-Feshbach statistical model code STAPRE. The main parameter of the pre-equilibrium exciton model was tested against the experimental data for the secondary neutron spectra for ${ }^{238} \mathrm{U}$. Shell, superfluid and collective effects in nuclear level density have been taken into account. Neutron transmission coefficients were calculated using the coupled-channel code ECIS. All experimental data available for fission and ( $\mathrm{n}, 2 \mathrm{n}$ ) reactions for the above isotopes have been used for model testing. Due to a lack of experimental data for the majority of the nuclei considered theoretical prediction of neutron cross-sections has been made.

## III-A-14

# Impacts of Data Transformations on the Least-Squares Solutions and Their Significances in Data Analysis and Evaluation 

Satoshi Chiba and Donald L. Smith

A paper on this subject was published in Journal of Nuclear Science and Technology, Vol. 31, pp.770~781(1994) with the following abstract;

In order to illustrate a potential problem which lies implicitly in the least-squares method, an anomaly known as Peelle's Pertinent Puzzle is introduced which appears in obtaining a leastsquares average of two strongly-correlated data. This anomaly is then generalized as a change of least-squares solution when data and associated covariance matrix are transformed by nonlinear functions. Reason of the change of the least-squares solution with respect to such data transformations is explained by the inconsistency in transforming the data covariance and sensitivity matrices. General criteria which can resolve this anomaly are derived. It is shown that if either one of these criteria is satisfied, the least-squares method gives the correct answer even if the data are discrepant, strongly correlated and the number of data points is small. Effects of data truncations are illustrated by a numerical example, which give an explanation on another aspect of Peelle's Puzzle. An approximate method is also proposed which should be applied when the correct method derived in this paper is not feasible.

## III-A-15

## Photonuclear Angular Distribution Systematics in the Quasideuteron Regime

Mark B. Chadwick, Phillip G. Young and Satoshi Chiba

A paper on this subject was published in Journal of Nuclear Science and Technology, Vol. 32, pp.1154~1158(1995) with the following abstract;

We describe an applications-oriented method for determining continuum photonuclear angular distributions for emission of light particles ( $n, p, d, t,{ }^{3} \mathrm{He}$ and $\alpha$ ) in the quasideuteron regime ( 40 $\leqq \mathrm{E}_{\text {inc }} \leqq 140 \mathrm{MeV}$ ). Based on theoretical considerations by Chadwick and Oblozinsky for the angular forward-peaking in preequilibrium reactions, Kalbach's 1988 angular distribution systematics for a neutron projectile can be straightforwardly modified for use in photon-induced reactions. This results in photonuclear angular distributions which are less forward-peaked than their nucleon-induced counterparts, due to the small momentum carried by a photon. Our predictions are compared against double-differential monochromatic ${ }^{12} \mathrm{C}(\gamma, \mathrm{xp})$ data at 60 and 80 MeV and are seen to describe the measurements fairly well.

## III-A-16 Concepts of Nuclear Data Measurement Center

## Satoshi Chiba

A paper (in Japanese) on this subject was published in JAERI-Conf 95-017, pp.71~76 with the following abstract;

Concepts of nuclear data measurement center, which will be constructed as one of the research facilities of the Proton Engineering Center, are described. The nuclear data measurement center will be designed so as to have a capability of offering experiments for low-to-medium energy neutrons (keV to MeV ) and medium-to-high energy neutrons ( MeV to 1.5 GeV ) by spallations induced by $1.5-\mathrm{GeV}$ protons, and variable-, mono-energy protons and pions below 1.5 GeV .

## III-A-17

Mass Chain Evaluation of $\mathrm{A}=118$-129

## ENSDF Group*

ENSDF group of Japan has been continuously evaluating the masschain data from $A=118$ to $A=129$. In 1995 the new evaluation of $A=118$ was finished and was published as an update mode in Nuclear Data Sheet ${ }^{1)}$. The evaluation includes all data avallable before November 1992 except for ${ }^{118} \mathrm{Pd}$ and ${ }^{118} \mathrm{Ag}$ which has been updated to February 1993. The data types included in the evaluation as new ones are shown in Table 1.

Table 1 Data Types Contained in $\mathrm{A}=118$ Evaluation

| Nuclide | Data Type | Nuclide | Data Type |
| :---: | :---: | :---: | :---: |
| ${ }^{118} \mathrm{Pd}$ | Adopted Levels | ${ }^{118} \mathrm{Sb}$ | ${ }^{118} \mathrm{Te}$ \& Decay |
| ${ }^{118} \mathrm{Ag}$ | Adopted Levels, Gammas |  | ${ }^{115} \operatorname{In}(\alpha, \mathrm{n}),{ }^{118} \mathrm{Sn}(\mathrm{p}, \mathrm{n}) \ldots$ |
|  | ${ }^{118} \mathrm{Pd} \beta^{-}$Decay |  | ${ }^{115} \ln (\alpha, n \gamma)$ |
| ${ }^{118} \mathrm{Cd}$ | Adopted Levels, Gammas |  | ${ }_{118} \operatorname{Sn}(\mathrm{p}, \mathrm{n} \gamma)$ |
|  | ${ }^{118} \mathrm{Ag}^{-}{ }^{-}$Decay ( 3.76 s ) |  | ( $\mathrm{H}, \mathbf{x} \mathbf{n} \boldsymbol{\gamma}$ ) |
|  | $118 \mathrm{Ag}{ }^{-}$Decay ( 2.0 s ) | ${ }^{118} \mathrm{Te}$ | Adopted Levels, Gammas |
|  | ${ }^{238} \mathrm{U}\left({ }^{7} \mathrm{~L}, \mathrm{~F}\right)$ |  | ${ }_{118} 1 \beta^{+}$Decay ( 13.7 min ) |
| ${ }^{118}$ In | Adopted Levels, Gammas |  | ${ }^{116} \mathrm{Sn}(\alpha, 2 \mathrm{n} Y$ ) |
| ${ }^{118} 8 \mathrm{Sn}$ | Adopted Levels, Gammas |  | ${ }^{117} \mathrm{Sn}(\alpha, 3 \mathrm{n} \gamma)$ |
|  | ${ }^{118} \mathrm{In} \beta^{-}$Decay ( 4.45 min ) |  | ( $\mathrm{H}, \mathbf{x n} \mathrm{y}$ ) |
|  | ${ }^{118} 8 \mathrm{Sb}^{\text {e Decay ( }} 3.6 \mathrm{~min}$ ) | ${ }^{118}$ I | Adopted Levels, Gammas |
|  | 118 Sb \& Decay ( 5.00 h ) |  | ${ }^{118} \mathrm{Xe} \beta^{+}$Decay |
|  | $117 \mathrm{Sn}(\mathrm{n}, \gamma) \mathrm{E}=$ res |  | ( $\mathrm{HI}, \mathrm{xn} \gamma$ ) |
|  | ${ }^{118} \mathrm{Sn}\left(\gamma, \gamma^{\prime}\right)$ | ${ }^{118} \mathrm{Xe}$ | Adopted Levels, Gammas |
|  | ${ }^{118} \mathrm{Sn}\left(\mathrm{e}, \mathrm{e}^{\prime}\right)$ |  | ${ }^{118} \mathrm{Cs} \beta^{+}$Decay ( $14 \mathrm{~s}+17 \mathrm{~s}$ ) |
|  | $1{ }^{18} \mathrm{Sn}\left(\mathrm{n}, \mathrm{n}^{\prime} \gamma\right)$ |  | ( H , xn Y ) |
|  | Coulomb Excitation | ${ }^{118} \mathrm{Cs}$ | Adopted Levels, Gammas |
|  | ${ }^{116} \mathrm{Cd}(\alpha, 2 \mathrm{n} \gamma),\left({ }^{7} \mathrm{LL}, \mathrm{p} 4 \mathrm{n} \gamma\right)$ |  | ( $\mathrm{H}, \mathrm{xn} \mathrm{y}$ ): Added In Proof |
| ${ }^{118} \mathrm{Sb}$ | Adopted Levels, Gammas |  |  |

References:

1) K. Kitao, Nuclear Data Sheets 75, 99 (1995)
[^1]
# B. Advanced Science Research Center 

## III-B-1

# Analysis of the ( $\mathrm{N}, \mathrm{xN} \mathrm{N}^{\prime}$ ) reactions by quantum molecular dynamics plus statistical decay model 

Koji Niita, Satoshi Chiba, Toshiki Maruyama, Tomoyuki Maruyama, Hiroshi Takada, Tokio

Fukahori, Yasuaki Nakahara and Akira Iwamoto
A paper on this subject was published in Physical Review C, Vol. 52, pp.2620~2635(1995) with the following abstract;

We propose a model based on quantum molecular dynamics (QMD) incorporated with a statistical decay model (SDM) to describe various nuclear reactions in a unified way. In this first part of the work, the basic ingredients of the model are defined and the model is applied systematically to the nucleon- ( N -) induced reactions. It has been found that our model can give a remarkable agreement in the energy-angle double differential cross sections of ( $\mathrm{N}, \mathrm{xN}$ ) type reactions for incident energies from 100 MeV to 3 GeV with a fixed parameter set. A unified description of the three major reaction mechanisms of ( $\mathrm{N}, \mathrm{xN}^{\prime}$ ) reactions, i.e., compound, preequilibrium, and spallation processes, is given with our model.

## III-B-2

## Quantum molecular dynamics and multistep-direct analyses of multiple preequilibrium emission

Mark. B. Chadwick, Satoshi Chiba, Koji Niita, Toshiki Maruyama and Akira Iwamoto

A paper on this subject was published in Physical Review C, Vol. 52, pp.2800~2803(1995) with the following abstract;

We study multiple preequilibrium emission in nucleon induced reactions at intermediate energies, and compare quantum molecular dynamics (QMD) calculations with multistep-direct Feshbach-Kerman-Koonin results [M.B. Chadwick, P.G. Young, D.C. George, and Y. Watanabe, Phys. Rev. C50, 996(1994)]. When the theoretical expressions of this reference are reformulated so that the definitions of primary and multiple emission correspond to those used in QMD, the two theories yield similar results for primary and multiple preequilibrium emission. We use QMD as a tool to determine the multiplicities of fast preequilibrium nucleons as a function of incident energy. For fast particle cross sections to exceed $5 \%$ of the inclusive preequilibrium emission cross sections we find that two particles should be included in reactions above 50 MeV , three above about 180 MeV , and four are only needed when the incident energy exceeds about 400 MeV .

## C. Department of Reactor Engineering

## III-C-1

# Recurrence of Compound Nucleus in Neutron Resonance Reactions 

Makio OHKUBO
Dept. of Reactor Engineering, JAERI

A paper on this subject is in press in Physical Review C, with the following abstract.

A semi-classical model of neutron resonance reactions has been developed, where time evolution and the recurrence of the compound nuclear system are explicitly considered. We have derived an average recurrence frequency of a multiple oscillator system as a function of the total excitation energy and oscillator number involved, where the tolerable phase angle error is assumed to be 1 radian. On the compound nuclei formed by neutron resonances, we have deduced effective oscillator numbers $\mathbb{M}$ and nuclear temperatures $T$. These values agree well with the traditional ones. As regards the time evolution of compound nucleus, we have defined the 'coalescent phase' where the neutron density is high on the target nuclear surface in a time duration $\sim 10^{-21}$ s. It appears repeatedly like a pulse array with an interval of recurrence time, and continues during lifetime of resonance $\sim 10^{-14} \mathrm{~s}$. By Fourier transform of the coalescent phases, we have found the $S$-matrix, in which neutron reaction cross sections can be derived. They consist of equidistant fine structure resonances, with an envelope of a giant resonance. Triple uncertainty relations between energy and time were derived. By this model, a smooth shift from the isolated resonance region to the continuum region could be predicted.

# IV. Kyoto University 

## A. Research Reactor Institute

IV-A-1 Measurement of Fission Cross Section with Pure Am-241 Sample using Lead Slowing-Down Spectrometer<br>K. Kobayashi ${ }^{1}$, M. Miyoshi ${ }^{2, *}$, S. Yamamoto ${ }^{1}$, Y. Fujita ${ }^{1}$, I. Kimura ${ }^{2}$, I. Kanno ${ }^{2}$, S. Kanazawa ${ }^{2}$ and N. Shinohara ${ }^{3}$<br>${ }^{1}$ Research Reactor Institute, Kyoto University<br>${ }^{2}$ Department of Nuclear Engineering, Kyoto University<br>${ }^{3}$ Department of Radioisotopes, Japan Atomic Energy Research Institute

A paper on this subject was presented at the 1995 Seminar on Nuclear Data at Tokaimura, JAERI held on Nov. 16-17, 1995.

A lead slowing-down spectrometer was installed beside a 46 MeV electron linear accelerator (linac) at Research Reactor Institute, Kyoto University (KURRI). At the center of this Kyoto University Lead Slowing-down Spectrometer (KULS), we set an air-cooled Ta photoneutron target to produce pulsed fast neutrons. The characteristics of the KULS (the relation between neutron slowing-down time and its energy, and the energy resolution) were obtained by calculations with MCNP Monte Carlo code and by resonance filters using a $\mathrm{BF}_{3}$ counter and/or an Ar gas counter. The detailed descriptions have been given elsewhere ${ }^{1,2)}$.

Am-241 sample was chemically purified through an ion-exchange column. Each of the ${ }^{241} \mathrm{AmO}_{2}$ and ${ }^{235} \mathrm{UO}_{2}$ samples was electrodeposited ( 20 mm in diameter) on a stainless steel plate of 28 mm in diameter and 0.2 mm in thickness. The number of atoms in each deposit was determined by the alpha-ray spectrometry with a Si surface barrier detector. The samples were set as back-to-back type double fission chambers ${ }^{3)}$, which were filled with a mixed gas of $97 \% \mathrm{Ar}$ and $3 \% \mathrm{~N}_{2}$ at 1 atm . and put into an experimental hole covered by Bi layers in the KULS.

The linac was operated for about 250 hours with the conditions of pulse width: 10 ns , repetition rate: 200 Hz , peak current : 800 mA , and electron energy: $32 \pm 1 \mathrm{MeV}$. The ${ }^{241} \mathrm{Am}(\mathrm{n}, \mathrm{f})$ reaction cross section was obtained as follow using a standard cross section for the ${ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})$ reaction appeared in ENDF/B-VI ${ }^{4)}$.
$\sigma_{A m}(E)=\frac{\text { Fission rate of }{ }^{241} \mathrm{Am}(\mathrm{n}, \mathrm{f})}{\text { Fission rate of }{ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})} \frac{\mathrm{N}_{\mathrm{U}}}{\mathrm{N}_{\mathrm{Am}}} \sigma_{\mathrm{U}}(\mathrm{E})$
where, $N_{A m}, N_{U}$ are number of atoms for Am and U samples, respectively. $\sigma_{U}(E)$ is the reference cross section for the ${ }^{235} \mathrm{U}(\mathrm{n}, \mathrm{f})$ reaction and is broadened by the KULS energy

[^2]resolution of about $40 \%$ at full width at half maximum. Below 200 eV , since resonance peaks are found in the cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{235} \mathrm{U}$, we have employed a standard cross section for the ${ }^{10} B(n, \alpha)$ reaction instead of the ${ }^{235} U(n, f)$ reaction, making use of a $\mathrm{BF}_{3}$ counter.

The relative fission cross section of ${ }^{241} \mathrm{Am}$ measured by the $\mathrm{BF}_{3}$ counter was normalized to the absolute fission cross section between 200 eV and 1 keV measured by the ${ }^{241} \mathrm{Am}$ and ${ }^{235} \mathrm{U}$ fission chambers. The present result is shown in Fig. 1 and is compared with the ENDF/B-VI ${ }^{4}$ ) and JENDL-3.2 ${ }^{5}$ data, which are broadened by the energy resolution of about $40 \%$ of the KULS. General agreement can be seen between the present measurement and the evaluated data in ENDF/B-VI and JENDL-3.2, except that both evaluated data seem to be lower by about $30 \%$ around $2-4 \mathrm{eV}$. The JENDL-3.2 data are underestimated by 1.2 to 2.3 times at energies of 22 to 140 eV .

## References:

1) A. Yamanaka, et al., J. Nucl. Sci. Technol., 30, 863 (1993).
2) K. Kobayashi, et al., JAERI-M 93-046, 360 (1993).
3) M. Obu, JAERI-M 9757 (1981).
4) R. F. Rose (Ed.), BNL-NCS-17541, 4th Ed. (ENDF/B-VI) 1991.
5) T. Nakagawa, et al., J. Nucl. Sci. Technol., Vol.32, No.12, 1259 (1995), and K. Shibata, et al., JAERI 1319 (1990).


Fig. 1 Comparison of the measured fission cross section of ${ }^{241} \mathrm{Am}$ with the evaluated data in ENDF/B-VI and JENDL-3.2.

# B. Department of Nuclear Engineering 

## IV-B-1

# Measurement of Fragment Mass Dependent Kinetic Energy and Neutron Multiplicity for Thermal Neutron Induced Fission of Plutonium-239 

Katsuhisa Nishio ${ }^{1}$, Yoshihiro Nakagome ${ }^{2}$, Ikuo Kanno ${ }^{1}$ and Itsuro Kimura ${ }^{1}$

1 Department of Nuclear Engineering, Kyoto University<br>2 Research Reactor Institute, Kyoto University

Kinetic energy and neutron multiplicity as a function of fragment mass were measured for the thermal neutron induced fission of ${ }^{239} \mathrm{Pu}$. By measuring the velocities and erergies of two fission fragments simultaneously, both of the pre-neutron emission fragment mass $m^{*}$ and the post neutron emission mass $m$ were obtained. The neutron multiplicity from specified mass $v\left(m^{*}\right)$ was deduced by subtracting $m$ from $m^{*}$. The fragment mass dependent total kinetic energy $\operatorname{TKE}\left(m^{*}\right)$ was also obtained from this data. The fragment velocity was measured by time-of-flight (TOF) method with flight path length of 28.9 cm , for which the start signal was triggered by a very thin plastic scintillation film detector (TFD) and the stop signal was obtained by a silicon surface barrier detector (SSBD) which was also used for the fragment kinetic energy determination.

The experiment was carried out at the super mirror neutron guide tube facility of the Kyoto University Reactor (KUR). The obtained results of $\operatorname{TKE}\left(m^{*}\right)$ and the individual fragment kinetic energy $E\left(m^{*}\right)$ are shown in Fig. 1 by solid squares and solid circles, respectively. For comparison, the result by Wagemans et al. ${ }^{(1)}$ is also presented in this figure. It is seen that our result agrees well with their work except in the symmetric mass region. The result of neutron multiplicity is shown in Fig. 2. In this figure, the neutron emission number from specified mass $v\left(m^{*}\right)$ is shown by solid circles and the sum of neutron multiplicity from the complementary fragment $\nu_{\mathrm{T}}\left(m^{*}\right)$ is depicted by solid squares. The result of Apalin et al. ${ }^{(2)}$ and that of Fraser et al. (3), both of which were obtained by the direct neutron detection method, are also presented. From this figure, it is seen that (1) the present result of $v\left(m^{*}\right)$ agrees well with that of Apalin et al. in the whole mass region and vith that of Fraser et al. in the light fragment region, (2) the shape of $v\left(m^{*}\right)$ in the light fragment region shows a shoulder-like structure from 100 to 110 of the fragment mass, but that in the heavy fiagmeiti region increases linearly with $m^{*}$.

We have carried out the calculation of the $\operatorname{TKE}\left(m^{*}\right)$ and $v\left(m^{*}\right)$ distributions asing BGM-model ${ }^{(4)}$ (Brosa, Großman and Müller). We assumed the two asymmetric fission channels for the present calculation. The calculated results of $\operatorname{TKE}\left(m^{*}\right)$ and $v\left(m^{*}\right)$ are shown by open circles in Fig. 1 and Fig. 2. It is said that the BGM model can reproduce the experimental data well.


Figure 1 Kinetic energy of fission fragment for ${ }^{239} \mathrm{Pu}\left(\mathrm{n}_{\text {th }}, \mathrm{f}\right)$


Figure 2 Neutron multiplicity from specified mass for ${ }^{239} \mathrm{Pu}\left(\mathrm{n}_{\mathrm{th}}, \mathrm{f}\right)$
References:
(1) Wagemans, C., et al., Phys. Rev., C30, 218 (1984).
(2) Apalin, V. F. et al., Nucl. Phys., 55, 249 (1964).
(3) Fraser, J. F., Milton, J. C. D., Annu. Rev. Nucl. Sci., 16, 379 (1966).
(4) Brosa, U., Großmann, S. and Müller, A., Phys. Reports, 197, 167 (1990).

## V. Kyushu University

## A. Deparment of Energy Conversaion Engineering

## V-A-1 Measurement of preequilibrium ( $\mathbf{p}, \mathbf{p}$ ') spectra at small angles

M. Hayashi, Y. Nakao, S. Yoshioka, M. Harada, M. Higashi, H. Ijiri, and Y. Watanabe

A paper on this subject was published in the Proccedings of the 1994 Symposium on Nuclear Data, JAERI-Conf 95-008 (1995), p. 264 with the following abstract:

A $\Delta \mathrm{E}-\mathrm{E}$ Si-detector counter telescope with an active collimator was developed in order to reduce backgrounds due to a large yield of elastically-scattered protons in measurements of continuum ( $p, \mathrm{p}^{\prime}$ ) spectra at small angles. Preequilibrium spectra of $14.1-\mathrm{MeV}$ ( $\mathrm{p}, \mathrm{p}^{\prime}$ ) for ${ }^{60} \mathrm{Ni}$ and ${ }^{93} \mathrm{Nb}$ were measured over a wide angle range from $15^{\circ}$ to $160^{\circ}$ using the developed detector system.

Recently, we have carried out the measurement of continuum $14.1-\mathrm{MeV}\left(\mathrm{p}, \mathrm{p}^{\prime}\right)$ spectra for ${ }^{56} \mathrm{Fe}$ and ${ }^{93} \mathrm{Nb}$ using the above-mentioned detector system at Kyushu University Tandem Laboratory. The data analysis is now in progress. Finally, all the experimental (p,p') data as well as the corresponding ( $\mathrm{n}, \mathrm{n}$ ') data will be analyzed using the Feshbach-Kerman-Koonin model in order to investigate whether both ( $\mathrm{p}, \mathrm{p}^{\prime}$ ) and ( $\mathrm{n}, \mathrm{n}^{\prime}$ ) data can be explained in a consistent way or not.

V-A-2 Feshbach-Kerman-Koonin model analysis of preequilibrium ( $p, p^{\prime}$ ) and ( $p, n$ ) reactions at 12 to 26 MeV<br>Y. Watanabe, A. Aoto, H. Kashimoto, S. Chiba*, T. Fukahori*, K. Hasegawa*, M. Mizumoto*, S. Meigo*, M. Sugimoto*, Y. Yamanouti*, N. Koori** ${ }^{* *}$ M.B. Chadwick ${ }^{+}$, and P.E. Hodgson ${ }^{++}$

A paper on this subject was publsihed in Physical Review C 31, 1891 (1995) with the following abstract:

Double differential proton emission cross sections have been measured for protoninduced reactions on ${ }^{98} \mathrm{Mo}$ and ${ }^{106} \mathrm{Pd}$ at incident energies around 26 MeV . Several ( $\mathrm{p}, \mathrm{p}$ ) and ( $\mathrm{p}, \mathrm{n}$ ) data for both target nuclei at incident energies ranging from 12 to 26 MeV are analysed in terms of multistep direct (MSD) and multistep compound (MSC) reaction model of Feshbach, Kerman and Koonin (FKK). The strength $V_{0}$ of the effective N-N interaction is extracted from a fit of the calculated MSD spectrum to the experimental data using the subtraction method of isolating and analysing the MSD component alone. Similar analysis is also applied to ( $\mathrm{p}, \mathrm{p}^{\prime}$ ) and ( $\mathrm{n}, \mathrm{n}^{\prime}$ ) data for ${ }^{93} \mathrm{Nb}$ in the same energy region. The experimental nucleon emission spectra at 26 MeV are reproduced well by the calculation treating preequilibrium MSD and MSC emission, direct collective excitation to low lying discrete levels and Hauser-Feshbach equilibrium emission in a quantum-mechanical way. The systematic behaviour of $V_{0}$ is investigated from the viewpoint of the dependence on the incident energy and the nature of projectiles and ejectiles. In addition, the sensitivities to input parameters used in the MSD calculation (the optical model potential parameters, the pairing correction, and the non-locality correction) are examined in order to see the effect of those parameters and corrections on the determination of $V_{0}$. A possibility of gradual absorption of reaction flux from P to Q chain is also discussed through analyses of preequilibrium ( $p, p^{\prime}$ ) and ( $p, n$ ) spectra using a phenomenological phase space approach.

[^3]
## V-A-3 Applications of the Feshbach-Kerman-Koonin model to (p,p') reactions at low incident energies

Y. Watanabe

A paper on this subject was presented at International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23-27, October, 1995, and was also publsihed in acta physsica slovaca 45, 749 (1995) with the following abstract:

The Feshbach-Kerman-Koonin theory is applied to analyses of ( $\mathrm{p}, \mathrm{p}$ ) reactions on ${ }^{93} \mathrm{Nb},{ }^{98} \mathrm{Mo}$ and ${ }^{106} \mathrm{Pd}$ at incident energies ranging from 12 to 26 MeV . The subtraction method is used to isolate the multistep direct (MSD) component and analyze it alone. It is found that there is a rather strong dependence of the strength $\mathrm{V}_{0}$ of the effective $\mathrm{N}-\mathrm{N}$ interaction on incident energy compared with ( $\mathrm{n}, \mathrm{n}$ ') reactions. The multistep compound (MSC) and Hauser-Feshbach (HF) formulas are extended so that the isospin can be introduced as a conserved quantum number. The experimental data are reproduced quite well by the quantum-mechanical calculation including MSD and MSC emission, direct collective excitation to low-lying discrete levels, and HF equilibrium emission.

# V-A-4 Semi-classical distorted wave model for multi-step direct process in (p,p'x) and ( $\mathrm{p}, \mathrm{nx}$ ) reactions 

M. Kawai* , Y. Watanabe, and H. Shinohara

A paper on this subject was presented at International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23-27, October, 1995, and was also publsihed in acta physsica slovaca 45, 693 (1995) with the following abstract:

Present status of Semi-Classical Distorted Wave model (SCDW) for multistep direct (MSD) processes in ( $\mathrm{p}, \mathrm{p}^{\prime} \mathrm{x}$ ) and ( $\mathrm{p}, \mathrm{nx}$ ) at intermediate energies is discussed. A brief derivation of the cross section formulae for 1-step and 2-step processes is given and their salient features are discussed. Calculated double differential cross sections for ${ }^{58} \mathrm{Ni}\left(\mathrm{p}, \mathrm{p}^{\prime} \mathrm{x}\right)$ at 120 MeV and 200 MeV and for ${ }^{90} \mathrm{Zr}(\mathrm{p}, \mathrm{nx})$ at 120 MeV are presented and compared with experimental data. Comparison with other models of MSD is also discussed

[^4]
## V-A-5 Nuclear data evaluation for ${ }^{12} \mathrm{C}$ in the energy region more than 20 MeV and kerma factor calculations <br> M. Harada, Y. Watanabe and S. Chiba*

A paper on this subject was presented at the 1995 Symposium on Nuclear Data, November 16-17, 1995, JAERI with the following abstract:

We have developed a practical code system to calculate double differential cross sections of all emitted particles and kerma factors for the $\mathrm{n}+{ }^{12} \mathrm{C}$ reaction in the energy region from 20 to 80 MeV , and compared the results calculated using the code system with experimental data. As a result, it has been found that the code system is applicable to nuclear data evaluation of ${ }^{12} \mathrm{C}$ in JENDL high energy file.

[^5]
## V-A-6

Measurement of Helium Production Cross Section
with Helium Accumulation Method
Y.Takao, Y.Kanda, K.Yamaguchi, T.Yonemoto, H.Etoh and M.Miwa

A paper on this subject was presented at the 1994 Symposium on Nuclear Data, and published in JAERI-Conf 95-008, p.161, with the following abstract:

Helium production cross sections for aluminum at proton energies up to 17.5 MeV have been measured. Helium accumulation method has been applied to determine there cross sections. The method is a direct measurement of hellum production cross sections, because the cross sections are determined by the number of hellum atoms produced by proton irradiation in samples. An aluminum sample consists of an aluminum foll (chemical purity $99.999 \%$, size $12 \times 9 \times 0.095 \mathrm{~mm}^{3}$ ) put between two gold foils (chemical purity $99.97 \%$, size $10 \times 8 \times 0.050$ $\mathrm{mm}^{3}$ ). Ten aluminum samples were irradiated by protons of the energy range from 8.9 to 17.5 MeV with a tandem accelerator. The helium atoms were measured by the hellum atoms measurement system based on an ultra high vacuum technique. The result of this work: protoninducedhelium production cross sections of aluminum, agree with the other experimental data within the error.

## V-A-7

# Evaluation of Covariance for U-238 Cross Sections 

T.Kawano, M.Nakamura, N.Matsuda and Y.Kanda

A paper on this subject was presented at the 1994 Symposium on Nuclear Data, and published in JAERI-Conf 95-008, p.246, with the following abstract:

Covariances of U-238 are generated using analytic functions for representation of the cross sections. The covarlances of the ( $n, 2 n$ ) and ( $\mathrm{n}, 3 \mathrm{n}$ ) reactions are derived with a spline function, while the covariances of the total and the inelastic scattering cross section are estimated with a linearized nuclear model calculation.

# Covariance Matrix of Evaluated Data for $\mathrm{Fe}-54,56$ Calculated from Nuclear Reaction Models 

T.Kawano, K.Kamitsubo, T.Iwamoto, and Y.Kanda

A paper on this subject was published in Proc. of the 1994 International Conference on Nuclear Data for Science and Technology, 9-13 May, Gatlinburg, USA, p. 624 with the following abstract:

Covariance matrix of neutron induced $\mathrm{Fe}-54,56$ reaction cross sections is generated from uncertainties of the experimental data and the nuclear reaction model parameters. An optical model is used to evaluate experimental total, differential elastic scattering cross sections. The covariance matrices of these cross sections are calculated from the uncertainties of neutron optical potential parameters. Cross sections of $\mathrm{Fe}-54,56(\mathrm{n}, \mathrm{p})$, ( $\mathrm{n}, \alpha$ ), ( $\mathrm{n}, 2 \mathrm{n}$ ), ( $\mathrm{n}, \mathrm{Xp}$ ), and ( $\mathrm{n}, \mathrm{X} \alpha$ ) reactions are calculated with a Hauser-Feshbach and a precompound models, and their covariance matrices are calculated from the uncertainties of the optical potential parameters for neutron, proton, and $\alpha$-particle, level density parameters, and a precompound parameter.

## V-A-9

# Evaluation of U-238 Inelastic Scattering Cross Section 

T.Kawano, N.Fujikawa, K.Yoshida, and Y.Kanda

A paper on this subject was published in Proc. of the 1994 International Conference on Nuclear Data for Science and Technology, 9-13 May, Gatlinburg, USA, p. 652 with the following abstract:

A coupled-channels model is adopted for evaluation of U-238 direct inelastic scattering cross sections to the excited levels which belong to the vibrational bands, as well as the ground state rotational band. A band-coupling-strength $\beta$ is determined from the experimental inelastic scattering scattering cross section data. Experimental double differential cross sections (DDX) are also taken into account. The calculated level excitation cross sections and the calculated DDX reproduce consistently the available experimental data.

## V-A-10

## Cross Section Measurement of ( $\mathrm{n}, \mathrm{x} \alpha$ ) Reactions for Al and Si around 14 MeV

Y.Takao, Y.Kanda, T.Yonemoto, K.Yamaguchi, K.Yamasaki, and H.Hashimoto
Y.Ikeda and H.Maekawa (JAERI)

A paper on this subject was published in Proc. of the 1994 International Conference on Nuclear Data for Science and Technology, 9-13 May, Gatlinburg, USA, p. 929 with the following abstract:

Hellum production cross sections for Al and Si at neutron energies near 14 MeV have been measured by using a helium accumulation method. Hellum production cross sections are required in design of fusion reactors, because of embrittlement of structural materials caused by helium produced in fast neutron irradiation.

Al and Si samples were irradiated with an intense D-T neutron source of Japan Atomic Energy Research Institute (JAERI). The neutron fluence was about $4 \times 10^{14}\left(\mathrm{n} / \mathrm{cm}^{2}\right)$ at each sample. The number of He atoms produced in a sample was measured by the Helium Atoms Measurement System (HAMS) at Kyushu University. Each sample contained about $1 \times 10^{11} \mathrm{He}$ atoms.

The results of this work are in good agreement with early experimental data.

## B. Department of Nuclear Engineering

V-B-1 Double differential cross section data and analysis of ( $\mathbf{p}, \mathrm{d}$ ) reaction cross section ( ${ }^{64} \mathrm{Ni}(p, d)$ reaction at $\mathrm{E}_{\mathrm{p}}=\mathbf{6 5} \mathrm{MeV}$ )

K.Yamaguchi', K.Kuroumaru ${ }^{1}$, H.Murohka ${ }^{1}$, A.Nohtomi ${ }^{1}$, Y.Uozumi ${ }^{1}$, T.Sakae ${ }^{1}$, and M.Matoba ${ }^{1}$, N.Koori ${ }^{2}$, T.Maki ${ }^{3}$

Nucleon induced reaction data for nuclear spectroscopy were tried to convert to double differential cross section data, and the data were analyzed theoretically. To discuss the problem quantitatively, the data from the ${ }^{64} \mathrm{Ni}(\mathrm{p}, \mathrm{d})$ reaction with polarized proton beam at 65 MeV are reported.

Recently, needs for nuclear data have been diversified in view points of energy, sort of particle and also target nuclei, and various studies have been widely started. In nuclear data, data from neutron related reactions, such as neutron scattering cross section, are mostly important, and they were studied widely in many years. But now, charged particle related data, such as protons, deuter-
(a)


Fig . 1 Flow chart of nuclear data filing and analysis ons, alpha particles and so on,

[^6]become considerably important. In charged particle data, recently, ( $p, p$ ') data are analyzed extensively [1]. So we will try to consider some deuteron emitted reactions. For ( $\mathrm{p}, \mathrm{d}$ ) reactions, a large amount of data for nuclear spectroscopy have been stored.


Fig . 2 Double diffrential cross section of dueterons from ${ }^{64} \mathrm{Ni}(\overrightarrow{\mathrm{p}}, \mathrm{d}){ }^{62} \mathrm{Ni}$ reaction at $65 \mathrm{MeV} ; \theta_{L}=11^{\circ}$


Fig . 3 Double diffrential cross section of dueterons from ${ }^{64} \mathrm{Ni}(\overrightarrow{\mathrm{p}}, \mathrm{d}){ }^{63} \mathrm{Ni}$ reaction at $65 \mathrm{MeV} ; \theta_{L}=41^{\circ}$

Because these data were analyzed with a flow chart as shown in Fig . 1 (a), all cross section in continuum region and between discrete peaks had been abandoned. We tried to covert this analysis flow to that shown in Fig .1 (b), such as neutron reaction data analysis.

The analyzed data are the data from ${ }^{64} \mathrm{Ni}(\mathrm{p}, \mathrm{d})$ reaction experiments with polarized 65 MeV proton beams carried out at the AVF cyclotron facility of the Research Center for Nuclear Physics, Osaka University. Emitted deuterons were analyzed with a magnetic spectrograph. Angular distributions were measured at $5^{\circ}$ to $41^{0}$ laboratory angles in $3^{0}$ steps.

Firstly, double differential cross section spectra were produced from the experimental raw data. Examples of the result are shown in Fig .2 and 3 with histograms.

Nextly, we tried to analyze strength distributions of the hole states in the continuum by using these data. Assuming that the obtained spectra originate to pick-up direct process, analyses were performed as follows. The theoretical double differential cross section ( $\mathrm{mb} / \mathrm{sr} \mathrm{MeV}$ ) spectrum was obtained by using the result of DWBA calculations and the strength function with a shell model calculation for the energy, the spectroscopic factor and the spreading width [2].

The transferred neutron wave function has been calculated by using the effective binding energy method, because usual separation energy method is known to be somewhat questionable for analysis of states in a wide excitation-energy region. Resultant theoretical spectra were compared with experimental ones. Comparisons of spectra at $11^{\circ}$ and at $41^{\circ}$ are presented in Fig . 2 and 3, respectively. Furthermore each spectrum was divided to low excitation energy region and high, and the cross section in each region was summed. A ratio of experimental to theoretical sums was calculated at each angle. The results are presented in Fig. 4.

As understood from Fig .2, the theoretical spectrum is reproduced well, but is
estimated a little largely. From Fig .3, difference between two spectra in the continuum region is larger than that shown in Fig .2. And Fig .4 shows that the ratio in the continuum region becomes larger as the angle varying to backward. The increase of the ratio at backward angle may be due to the multi-step reaction process.

In summary, double differential cross section spectra are obtained from data of ${ }^{64} \mathrm{Ni}(p, d)$ reaction at 65 MeV . A method of theoretical analysis to reproduce data of double differential cross section


Fig. 4 Ratio of exprimental to theoretical sums at each angle is proposed.

## References:

1) For example, Y.Watanabe et al., Proceedings of Int. Conf. on Nuclear Data for Science and Technology, May 9-13, 1994.
2) M.Matoba et al., Nucl.Phys. A581(1995) 21-41

## V-B-2

Parameterization of the Fragmentation Cross Section for Proton-Induced Spallation Reaction
(Journal of Nuclear Science and Technology, Vol.32(1). pp. 1-7, 1995)

N. SHIGYO, S. SAKAGUCHI*, K. ISHIBASHI and Y. WAKUTA


#### Abstract

We study the systematics of the fragmentation reaction for incident proton energies up to 3 GeV . The mass yields of the reaction are successfully described by the liquid-gas phase transition model assuming reasonable values of the nuclear temperature. For representing the kinetic energy spectra, a double integral formula considering the effects of the Coulomb barrier and the fragment excitation energy is confirmed to be usable. A nother formula with a simpler form is introduced for reproducing the energy spectra. A formula utilizes five adjustable parameters, and we construct empirical expressions to determine them. The nuclear temperature common to both kinetic energy spectra and mass yields of the fragments is found to be useful for describing the fragmentation phenomena. The present systematics are suited for being incorporated as a subroutine set into the High Energy Transport Code.


* Present address: Science and Technology Agency


## V-B-3

Development of High Energy Transport Code HETC-3STEP Applicable to the Nuclear Reaction with Incident Energies above 20 MeV (Journal of Nuclear Science and Technology, Vol. 32(7), pp.601-607, 1995)

N. YOSHIZAWA*1, K. ISHIBASHI and H. TAKADA*2


#### Abstract

Spallation reaction calculation based on the intranuclear-cascade-evaporation model is modified to take into account the pre-equilibrium process by using a closed from exciton model. For the double differential ( $\mathrm{p}, \mathrm{xn}$ ) reaction cross section, the calculation of the exciton model is devised to produce smooth connection that the cascade process. The result of the exciton model calculation is compared with the neutron energy spectra decomposed from the experimental data by the moving source model analysis. Two parameters for the transition probability of the excitons and the termination conditions of the pre-equilibrium process are adjusted to reproduce the experimental data. The addition of pre-equilibrium process into the intranuclear-cascade-evaporation model improves the accuracy of the calculation code. The improvement is significant in the backward emission at incident energy between 20 and 100 MeV for target nuclei more massive than aluminum.

^[ ${ }^{* 1}$ Mitsubishi Research Institute Inc. (Collaboration Researcher of Kyushu University) *2 Japan Atomic Energy Research Institute ]


#### Abstract

The experimental method of measuring neutron production double-differential cross sections was tested at incident proton energies of 0.8 and 1.5 GeV with C and Pb targets. Neutrons were measured with liquid scintillators by the time-of-flight method. The use of very weak secondary beam forced us to take atypical flight path length as short as 1 m . Preliminary experimental consideration led to the results that the amount of back ground neutrons were made low by the short flight path measurement, and a two-gate integration method was suited for the pulse shape discrimination between high energy neutrons and gamma-rays. The cross sections were obtained in the neutron energy range up to 100 MeV with acceptable energy resolution. The experimental results obtained at the incident proton energy of 0.8 GeV were consistent with the data taken with much longer flight paths. It was confirmed that the time-offlight method with bare detectors at the short flight path was reliably applicable to the spallation neutron measurement. *1 Japan Atomic Energy Research Institute *2 National Laboratory for High Energy Physics *3 Cyclotron Radioisotope Center, Tohoku University *4 Energy Conversion Engineering, Kyushu University


## VI. Nagoya University

## A. Department of Nuclear Engineering

## VI-A-1 Measurement of Thermal Neutron Cross Section and Resonance Integral of the Reaction ${ }^{99} \mathrm{Tc}(\mathrm{n}, \gamma)^{100} \mathrm{Tc}$

Hideo Harada*, Shoji Nakamura*, Toshio Katoh ${ }^{\dagger}$, Yoshimune Ogata

A paper on this subject was published in Journ. Nuclear Science and Technology vol.32, no.5, pp395 ~ 403(1995) with a following abstract.

To obtain fundamental data for research on the transmutation of nuclear waste, the thermal neutron cross section and the resonance integral of the reaction ${ }^{99} \mathrm{Tc}(\mathrm{n}, \gamma)^{100} \mathrm{Tc}$ have been measured using an activation method.

Four ammonium pertechnetate targets containing $371 \sim 375 \mathrm{kBq}$ of ${ }^{99} \mathrm{Tc}$ were irradiated for 2 min with reactor neutrons. Activation detectors of $\mathrm{Co} / \mathrm{Al}$ and $\mathrm{Au} / \mathrm{Al}$ alloy wires were irradiated for 10 min to monitor the neutron flux and the fraction of the epithermal part(Westcott's epithermal index). The Tc samples and flux monitors were irradiated with and without a Cd capsule.

The $\gamma$-ray spectra from the irradiated samples were measured using a high purity Ge detector.

The thermal neutron cross section $(2,200 \mathrm{~m} / \mathrm{s}$ neutron cross section) and the resonance integral of the ${ }^{99} \mathrm{Tc}(\mathrm{n}, \gamma) 100 \mathrm{Tc}$ reaction were found to be $22.9 \pm$ 1.3 b and $398 \pm 38 \mathrm{~b}$, respectively. The thermal neutron cross section obtained agrees with the previously reported values $(20 \pm 2 \mathrm{~b}$ by Lucas, 24.8 b by Pattenden, $24 \pm 4 \mathrm{~b}$ by Ovechkin) within the limits of error. On the other hand, the resonance integral is twice the value reported by Lucas(186 $\pm 16 \mathrm{~b})$.

[^8]
## B. Department of Energy Engineering and Science

## VI-B-1

$\mathrm{O}_{\beta}$ measurements of neutron-rich isotopes in the mass region $147 \leq \underline{A} \leq 152$

T. Ikuta, A. Taniguchi, H. Yamamoto, K. Kawade and Kawase*

A paper on this subject was published in J. Phys. Soc. Japan ,vol. 64, pp. 3244-3254, 1995.

The systematic $Q_{\beta}$ measurements of14 neutron-rich nuclei in the mass region from $\mathrm{A}=147$ to $\mathrm{A}=152$ have been performed with an HPGe detector. Neutron-rich nuclei were mass separated from the thermal neutron induced fission of ${ }^{235} \mathrm{U}$ using a He-jet type on-line isotope separator which has been developed at the Kyoto University Reactor (KUR). From $\beta$-ray singles and $\beta$ - $\gamma$ coincidence measurements the $Q_{\beta}$ values of ${ }^{147} \mathrm{La},{ }^{147-150} \mathrm{Ce},{ }^{147-152} \mathrm{Pr}$, ${ }^{152} \mathrm{Nd}$ and ${ }^{152} \mathrm{Pm}$ have been determined. The $\mathrm{Q}_{\beta}$ values of ${ }^{152} \mathrm{Nd}$ and ${ }^{152} \mathrm{Pm}$ have been measured for the first time. The atomic masses derived from the $Q_{\beta}$ values are compared with the predictions of theoretical mass calculations.

[^9]
## VI-B-2

Systematics of activation cross sections for 13.4-15.0 MeV neutrons
Y. Kasugai, Y. Ikeda*, H. Yamamoto and K. Kawade

A paper on this subject was presented at the 1994 symposium on nuclear data and published in JAERI-Conf 95-008, pp. 181-184, 1995, with the following abstract:

The cross sections at 14.0 MeV and the relative slopes for the ( $\mathrm{n}, \mathrm{p}$ ) and ( $\mathrm{n}, \mathrm{a}$ ) reactions were expressed by simple formulae. We could reproduce the excitation functions for the ( $\mathrm{n}, \mathrm{p}$ ) and ( $\mathrm{n}, \mathrm{a}$ ) reactions in the energy range 13.4 to 15.0 MeV within the accuracy of $25 \%$ and 30 $\%$ respectively. The present formulae are also useful for check of the decay data.

[^10]
## VI-B-3

Measurement of formation cross sections producing short-lived nuclei by 14 MeV neutrons $-\mathrm{Na}, \mathrm{Si}, \mathrm{Te}, \mathrm{Ba}, \mathrm{Ce}, \mathrm{Sm}, \mathrm{W}, \mathrm{Os}-$
Y. Satoh, T. Matsumoto, Y. Kasugai, H. Yamamoto, T. Iida*,
A. Takahashi* and K. Kawade

A paper on this subject was presented at the 1994 symposium on nuclear data and published in JAERI-Conf 95-008, pp. 189-192, 1995, with the following abstract:

13 activation cross sections for ( $\mathrm{n}, 2 \mathrm{n}$ ), ( $\mathrm{n}, \mathrm{p}$ ), ( $\mathrm{n}, \mathrm{np}$ ) and ( $\mathrm{n}, \mathrm{a}$ ) reactions producing short-lived nuclei with half-lives between 4 s and 19 min were measured in the energy range of 13.7 and 14.9 MeV for $\mathrm{Na}, \mathrm{Si}, \mathrm{Te}, \mathrm{Ba}, \mathrm{Ce}, \mathrm{Sm}, \mathrm{W}$ and Os . The cross sections of ${ }^{123} \mathrm{Te}(\mathrm{n}$, $\mathrm{np})^{122 \mathrm{~m}} \mathrm{Sb},{ }^{188} \mathrm{Os}(\mathrm{n}, \mathrm{p})^{188 \mathrm{~m}} \mathrm{Re}$ and ${ }^{189} \mathrm{Os}(\mathrm{n}, \mathrm{np})^{188 \mathrm{~m}} \mathrm{Re}$ were measured for the first time. Measured ( $\mathrm{n}, \mathrm{p}$ ) cross sections were compared with the excitation functions estimated by our systematics. Estimated excitation functions agreed well with experimental data.

[^11]
## VI-B-4

Measurement of beta-decay half-lives of short-lived nuclei by using high-rate spectroscopy amplifier

S. Itoh, M. Yasuda, H. Yamamoto, T. Iida*, A. Takahashi*<br>and K. Kawade

A paper on this subject was presented at the 1994 symposium on nuclear data and published in JAERI-Conf 95-008, pp. 185-188, 1995, with the following abstract:

The half-lives of short-lived nuclei produced by 14 MeV or thermal neutron bombardments were measured with Ge detectors and a high-rate spectroscopy amplifier (EG \& G ORTEC model 973) in the multi-scaling mode. The corrections for pile-up and dead-time losses were performed by applying source and pulser methods. The half-lives of ${ }^{16} \mathrm{~N},{ }^{19} \mathrm{O}$, ${ }^{20} \mathrm{~F},{ }^{63} \mathrm{Co},{ }^{89 \mathrm{~m}} \mathrm{Y},{ }^{139 \mathrm{~m}} \mathrm{Ce},{ }^{161} \mathrm{Gd},{ }^{173} \mathrm{Er},{ }^{176} \mathrm{Tm},{ }^{185 \mathrm{~mW}}$ and ${ }^{186} \mathrm{Ta}$ were determined with accuracy of $0.08 \sim 1.2 \%$ and the accuracy has been much improved.

[^12]
# Uncertainties in fission product decay heat summation calculations 

K. Oyamatsu, H. Ohta and K.Tasaka*<br>Department of Energy Engineering and Science, Nagoya University<br>Furo-cho , Chikusa-ku , Nagoya , 464-01 JAPAN

The present precision of the aggregate decay heat calculations is studied quantitatively for 50 fissioning systems. In the practical calculation, a simple approximate method is proposed to avoid complications of the calculations so that we can point out easily the main causal nuclear data for the uncertainties in decay heat calculations. In this evaluation, nuclear data and their uncertainty data are taken from ENDF/B-VI nuclear data library and uncertainty data that are not available in this library are supplemented with a theoretical consideration.

## 1. Introduction

The precise determination of the production and decay of fission product nuclei is necessary from the viewpoints of not only their decay heat release but also their activities emitted for a long time. The knowledge of fission product properties serves as a basis in designing a heat removal system of a reactor, a spent fuel reprocessing plant and a final processing plant for radioactive wastes.

Thanks to the accumulation of the measured and properly estimated decay data for about two decades, the decay heat summation calculations for major fissioning systems, such as ${ }^{235} \mathrm{U}$ and ${ }^{239} \mathrm{Pu}$, have come to give good agreement with the measured values within a typical error of $5 \%$. However, this agreement does not guarantee the precision of the whole nuclear data or the prediction power for other fissioning systems. A higher burnup fuel in light water reactors, and transmutations of actinides and long-lived fission products require more precise knowledge of the properties of fission products from minor actinides, such as Cm and Am, which have not been considered well so far. In spite of their increasing importance, the nuclear data for these minor actinides seem to be still less accurate compared with those for major actinides.

The purpose of this study is to evaluate the uncertainties in the decay heat summation calculations for these minor actinide fissioning systems and to point out fission product nuclides whose yields, decay constants or decay energies need to have better precision. This work is also intended to be our first step for the precise determination of properties of fission product nuclei.
2. The exact method to obtain the uncertainty in the decay heat power calculation

The total decay heat power $P(\mathrm{t})$ at a cooling time $t$ after fission is obtained by summing up the decay power released from all fission product nuclei

$$
\begin{equation*}
P(t)=\sum_{i} E_{i} \lambda_{i} N_{i}(t), \tag{1}
\end{equation*}
$$

where $\lambda_{i}$ and $E_{i}$ are the decay constant and the average decay energy of nuclide $i$, respectively. In the case of instantaneous irradiation, the number of atoms of nuclide $i, N_{i}(t)$ is obtained as the solution of the simultaneous differential equations

$$
\begin{equation*}
\frac{d N_{i}(t)}{d t}=-\lambda_{i} N_{i}(t)+\sum_{j} a_{j \rightarrow i} \lambda_{j} N_{j}(t), \tag{2}
\end{equation*}
$$

with initial conditions

$$
\begin{equation*}
N_{i}(0)=y_{i} . \tag{3}
\end{equation*}
$$

Here, $a_{j \rightarrow i}$ and $y_{i}$ are the production rate of nuclide $i$ from a decay of nuclide $j$ and the independent fission yield of nuclide $i$, respectively.

The uncertainty in the calculated decay heat power (Eq. (1)) is given by

$$
\begin{equation*}
(\delta P(t))^{2}=\sum_{i}\left\{\left(\frac{\partial P}{\partial E_{i}}\right)^{2}\left(\delta E_{i}\right)^{2}+\left(\frac{\partial P}{\partial \lambda_{i}}\right)^{2}\left(\delta \lambda_{i}\right)^{2}+\left(\frac{\partial P}{\partial y_{i}}\right)^{2}\left(\delta y_{i}\right)^{2}\right\} \tag{4}
\end{equation*}
$$

where we denote the uncertainty of a parameter $X$ as $\delta X$ and neglect the uncertainties in the branching ratio $a_{j \rightarrow i}$ as in the previous uncertainty evaluation by Katakura and IIjima [1]. Unfortunately, we are forced to deal with complicated dependence on the decay constants of about 1000 nuclides as long as we use the exact solution of the decay heat power. Consequently, the uncertainty in the aggregate decay heat power has been evaluated in some approximate methods [1-3].

## 3. An approximate method

In this paper we also use an alternative approximate method based on the observation that the value of decay constant decreases rapidly in the successive decays in a decay chain. Suppose a linear decay chain

$$
\begin{equation*}
X_{1} \xrightarrow{\lambda_{1}} X_{2} \xrightarrow{\lambda_{2}} X_{3} \xrightarrow{\lambda_{3}} \cdots \rightarrow X_{i-2} \xrightarrow{\lambda_{i-2}} X_{i-1} \xrightarrow{\lambda_{i-1}} X_{i} \xrightarrow{\lambda_{i}} \cdots . \tag{5}
\end{equation*}
$$

We assume

$$
\begin{equation*}
\frac{\lambda_{3}}{\lambda_{1}} \ll 1, \frac{\lambda_{7}}{\lambda_{2}} \ll 1, \cdots \cdots \frac{\lambda_{i-1}}{\lambda_{i-3}} \ll 1, \frac{\lambda_{i}}{\lambda_{i-2}} \ll 1, \cdots \cdots, \tag{6}
\end{equation*}
$$

taking the even-odd effects into account. Then, the number of atoms of nuclide $\mathrm{i}, N_{i}^{a}$, is approximately determined only by its parent nuclide i-1 (mother of i) and her parent i-2 (grandmother of i). Namely, $N_{i}^{a}$ is given by the solution of the following set of equations

$$
\begin{align*}
& \frac{d M_{i 2}^{i}}{d!}=-\lambda_{i-2} M_{i-2}^{i},  \tag{7}\\
& \frac{d M_{i,}^{i}}{d!}=-\lambda_{i-1} M_{i-1}^{i}+\lambda_{i-2} M_{i-2}^{i},  \tag{8}\\
& \frac{d N_{i}^{a}}{d t}=-\lambda_{i} N_{i}^{a}+\lambda_{i}, M_{i,}^{i}, \tag{9}
\end{align*}
$$

with initial conditions

$$
\begin{align*}
& M_{i-2}^{i}(0)=\sum_{k=1}^{i} y_{k}^{2}\left(=Y_{i-2}\right),  \tag{10}\\
& M_{1-1}^{i}(0)=y_{1-1}  \tag{11}\\
& N_{i}^{a}(0)=y_{1} . \tag{12}
\end{align*}
$$

Here, we introduce the fictitious number of atoms of nuclide i-2 (i-1), $M_{i-2}^{i}\left(M_{i-1}^{i}\right)$ in order to obtain $N_{i}^{a}(1)$. The initial number of the grandmother nuclide i-2 in Eq. (10) is taken to be its cumulative yield so as to conserve the total number of atoms. The difference between $N_{i}^{a}(1)$ and the exact value $N_{i}(t)$ is propotional to $\lambda_{i-1} / \lambda_{i-3}$ and expected to be sufficiently small even if one of the two quantities $\lambda_{i-1} / \lambda_{i-2}$ or $\lambda_{i-2} / \lambda_{i-3}$ happens to be larger than unity. Furthermore, the above solution is not affected much by even-odd effects which are relatively significant in the neighborhood of the stable nuclide. Actually, the decay heat power calculated in this approximation is found to be in excellent agreement with the exact value at cooling times less than $10^{10}$ (s) as shown in Fig. 1. The breakdown of the approximation later than $10^{10}$ (s) is caused by the fact that an extremely long half life of $10^{5}$ years of ${ }^{126} \mathrm{Sn}$ substantially affects
the number of atoms of the major $\gamma$ emitter ${ }^{126} \mathrm{Sb}$. However, except for this case, our approximate method is found to give the sufficiently accurate decay heat power and the number of atoms of each fission product nuclide. Therefore, we perform the uncertainty evaluation in the decay heat summation calculation in the approximate method at cooling times less than $10^{10}$ (s) in the case of instantaneous irradiation.

The uncertainty in the decay heat power in our approximation is written as

$$
(\delta P(t))^{2}=\sum_{i=1}^{a l l F P}\left\{\left(\frac{\partial P}{\partial E_{i}}\right)^{2}\left(\delta E_{i}\right)^{2}+\left(\frac{\partial P}{\partial \lambda_{i}}\right)^{2}\left(\delta \hat{\lambda}_{i}\right)^{2}+\left(\frac{\partial P}{\partial y_{i}}\right)^{2}\left(\delta y_{i}\right)^{2}+\left(\frac{\partial P}{\partial Y_{i}}\right)^{2}\left(\delta Y_{i}\right)^{2}\right\} .
$$

With the analytic solution of $N_{1}^{a}(t)$, we obtain the explicit dependence of the total decay heat power (1) on decay constants, average energies and fission yields so that we can calculate analytically the right hand side of Eq. (13).

It should be noted that Eq. (13) includes terms with the cumulative yields because we solve different sets of equations (Eqs.(7)-(12)) from the exact ones (Eqs. (1) and (2)). The uncertainty value calculated in our approximate method is considered to be close to the exact one because the decay heat and the number of atoms of each nuclide are sufficiently in good agreement with the exact ones. Furthermore, although the introduction of the cumulative yields makes it impossible to point out which decay constant or independent yield values to be reviewed, our approximate method is still useful for finding out key nuclides whose numbers of atoms have substantial sensitivities to the total decay heat power.

The correlation effects among uncertainty values of independent yields are also taken into account the present uncertainty evaluation as in Refs. [2,3]. Therefore, the final formula for the uncertainty is more complicated than Eq. (13).

## 3. Nuclear data and their uncertainty values

Values of fission yields, decay constants, average decay energies and their uncertainties are taken from ENDF/B-VI. Unfortunately, this nuclear data library does not provide us with uncertainty values for decay constants and/or decay energies that were theoretically (or empirically) estimated. Therefore we supplement uncertainty values of these decay energies in a similar way to the one in Ref. [1]. As for the uncertainties in the estimated decay constants, we assume $\delta \lambda_{i}=\lambda_{i}$ because the estimated decay constants often differ from the measured ones by an order of magnitude.

Table 1. Uncertainties in decay heat summation calculations in \%.


Fig. 1. The comparison between of the approximate and exact decay heat power in the case of thermal fission of ${ }^{235} \mathrm{U}$.

| fissile | $\beta$ | $\gamma$ | $\beta+\gamma$ |
| :---: | :---: | :---: | :---: |
| ${ }^{235} \mathrm{U}(\mathrm{T})$ | $1 \sim 6$ | $1 \sim 6$ | $1 \sim 6$ |
| ${ }^{238} \mathrm{U}(\mathrm{F})$ | $1 \sim 5$ | $2 \sim 5$ | $2 \sim 4$ |
| ${ }^{239} \mathrm{Pu}(\mathrm{T})$ | $2 \sim 12$ | $2 \sim 13$ | $2 \sim 7$ |
| ${ }^{237} \mathrm{~Np}(\mathrm{~F})$ | $3 \sim 12$ | $3 \sim 9$ | $3 \sim 9$ |
| ${ }^{241} \mathrm{Am}(\mathrm{F})$ | $4 \sim 13$ | $4 \sim 20$ | $4 \sim 13$ |
| ${ }^{243} \mathrm{Am}(\mathrm{F})$ | $5-13$ | $5-16$ | $4 \sim 12$ |
| ${ }^{244} \mathrm{Cm}(\mathrm{F})$ | $4 \sim 13$ | $5 \sim 20$ | $5 \sim 13$ |
| ${ }^{246} \mathrm{Cm}(\mathrm{F})$ | $5 \sim 14$ | $6 \sim 17$ | $5 \sim 12$ |
| ${ }^{248} \mathrm{Cm}(\mathrm{F})$ | $5 \sim 15$ | $6 \sim 15$ | $5 \sim 12$ |



Fig. 2. Uncertainties in the $\gamma$ decay heat calculation for thermal fission of ${ }^{235} \mathrm{U}$. Also shown with arrows are the main causal nuclides for the large uncertainty values.

## 4. Results and discussion

We have calculated uncertainties in summation calculations of the $\beta, \gamma$ and total decay heat for 50 fissioning systems. As an example, Fig. 2 depicts the cooling time dependence of the uncertainty in the $\gamma$ decay heat power for thermal fission of ${ }^{235} \mathrm{U}$. We also find similar cooling time dependence of the $\beta$ and total decay heat power for all fissioning systems. Namely, the uncertainty is relatively small in the range of cooling times between $10^{4}$ and $10^{8}$ (s) but large at shorter and longer cooling times. The large uncertainty at short cooling times reflects large uncertainties in nuclear data of nuclides with short half lives. The large uncertainty at long cooling times may imply the need for more precise knowledge of nuclear level structures. On the other hand, we see from Table 1 that the magnitude of the uncertainty value does depend on the fissioning system. The uncertainties for minor actinides are larger by a factor of $3-5$ than those for major actinides. Typical examples of the uncertainty values are 1$6 \%$ for ${ }^{235} \mathrm{U}(\mathrm{T}), 2-7 \%$ for ${ }^{239} \mathrm{Pu}(\mathrm{T}), 4-12 \%$ for ${ }^{241} \mathrm{Am}(\mathrm{F})$ and $5-3 \%$ for ${ }^{244} \mathrm{Cm}(\mathrm{F})$ where the letter F stands for the fission-neutron induced fission. As for ${ }^{235} \mathrm{U}(\mathrm{T}),{ }^{239} \mathrm{Pu}(\mathrm{T})$ and ${ }^{238} \mathrm{U}(\mathrm{F})$ studied in Ref. [1], the present results are consistent with Ref. [1] in spite of differences in the nuclear libraries and approximations. Furthermore, we find that each peak in Fig. 2 is caused by nuclear data of a few nuclides, and point out the main causal nuclides, some of which are shown with arrows. The more precise determination of these nuclear data will substantially reduce the uncertainties in the decay heat summation calculations. We are now preparing to publish the complete list of these causal nuclides together with tables and figures of the uncertainty values in the decay heat calculations for all fissioning systems in order to serve as a guidance for tuning up the present nuclear data library.

References:

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[^13]
## VII. Osaka University

# A. Department of Nuclear Engineering 

## VII-A-1 Double Differential Charged Particle Emission Cross Sections

 of ${ }^{59} \mathrm{Co}$, Mo and Nb by 14.1 MeV Incident NeutronAkito Takahashi, Takehiro Kondoh and Isao Murata

Double differential charged particle emission cross sections induced by 14 MeV neutrons play an important role in radiation damage analysis, nuclear heating calculation and biological effect evaluation for a fusion reactor. However, available experimental data are scarce because direct charged particle measurement is very difficult. We, therefore, introduced the two dimensional E-TOF method, and, since 1991, the double differential cross sections(DDXs) of various nuclides in the candidate materials in a fusion reactor have been measured at OKTAVIAN facility of Osaka university, Japan ${ }^{11}$. In 1995, DDX data of ${ }^{59} \mathrm{Co}$, natural- $\mathrm{Mo}\left({ }^{n \pi 1} \mathrm{Mo}\right)$ and natural $-\mathrm{Nb}\left({ }^{31} \mathrm{Nb}\right)$ with 14 MeV neutrons were measured. The obtained data were compared with other experimental data, calculated results and evaluated nuclear data.

DDX data for ${ }^{59} \mathrm{Co}(\mathrm{n}, \mathrm{x} \alpha)$ reaction were measured at the scattering angles of $30,45,60,90$ and 120 deg. in the LAB. system as shown in Fig. 1. The larger contribution is observed in the energy region over 10 MeV with decrease of the scattering angle, as expected by considering the preequibrium process. The DDX data around 7 MeV mostly agree with each other, which means that the angular distribution is mostly uniform, because the compound process is strongly contributed in this energy region. Figure 2 shows the energy differential cross section (EDX) for the ${ }^{59} \mathrm{Co}(\mathrm{n}, \mathrm{x} \alpha)$ reaction compared with the calculation and the evaluation. It was found that, in the energy region over 11 MeV where the preequibrium process was dominant, the experimental value was reproduced by the calculations with SINCROS-II and $\mathrm{UNF}^{2)}$ codes. However, in the low energy region, the calculations underestimate the experimental EDX. The evaluated nuclear data of JENDL-Fusion File fairly agree with the measurement. Figure 3 shows our EDX data for the ${ }^{n 11} \mathrm{Mo}(\mathrm{n}, \mathrm{xp})$ reaction compared with the experimental result by Haight ${ }^{3}$ and the calculation with SINCROS-II. The SINCROS-II calculation gives slightly underestimate result. While the experimental results are in good agreement with each other except in the energy region below 2.25 MeV . The EDX for the ${ }^{\text {nat }} \mathrm{Nb}(\mathrm{n}, \mathrm{xp})$ reaction is shown in Fig. 4 in comparison with other experimental values of Grimes ${ }^{4}$, Koori ${ }^{5}$, Traxler ${ }^{6}$ and Fischer ${ }^{7}$ and SINCROS-II calculation. Although the statistical error of the measurement is too large to perform the comparison precisely because the cross section of ${ }^{n 21} \mathrm{Nb}$ is relatively small, it was confirmed that our data mostly agreed with other experimental data and the calculation.

## References:

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2) J. Zhang, Nucl. Sci. Eng., 114, 53 (1993).
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Fig. 1 DDX for ${ }^{59} \mathrm{Co}(\mathrm{n}, \mathrm{x} \alpha)$


Fig. 3 EDX for ${ }^{\text {nat }} \mathrm{Mo}(\mathrm{n}, \mathrm{xp})$


Fig. 2 EDX for ${ }^{59} \mathrm{Co}(\mathrm{n}, \mathrm{x} \alpha)$


Fig. 4 EDX for ${ }^{\text {nat }} \mathrm{Nb}(\mathrm{n}, \mathrm{xp})$

## VII-A-2

Benchmark of FENDL-1, JENDL-3.2 and JENDL-Fusion File Using Neutron Leakage Spectra from Spherical Beryllium Assemblies

Akito Takahashi, Yo Makita, and Isao Murata

Integral experiments of beryllium spheres were carried out in 1991 at OKTAVIAN facility of Osaka University, Japan. By using the data of neutron leakage spectra, the benchmark analyses were performed using MCNP with three kinds of continuous energy cross section libraries based on FENDL-1, JENDL-3.2, and JENDL-Fusion File. The summary on this subjective was presented at the nuclear data conference at Del Mar ${ }^{1)}$. From the comparison of calculated and experimental results of four spherical assemblies having the equal outer radius of 173.5 mm and different thicknesses of $45.5,76.5,104.5$ and 116.5 mm . it was confirmed that each calculated spectrum showed underestimation in the $1-8 \mathrm{MeV}$ region and slight overestimation in the energy region lower than 0.1 MeV as shown in Fig. 1, for example. It was also confirmed that, for JENDL-3.2, better agreement was obtained in the $1-8 \mathrm{MeV}$ region, while for the energy integrated C/E ratios, FENDL-1 gave the best result among three data as shown in Table 1, for example.

There exist several benchmarks in other facilities. We compared our benchmark results with theirs. As a result, our analyses show the same tendency to the KANT's for the Karlsruhe Neutron Transmission Experiments on beryllium spheres, that is giving underestimations. On the other hand, two results from FNS, the beryllium slab TOF experiments, and IPPE, the TOF measurements of neutron leakage spectra from beryllium spheres, indicate overestimation. Though it is thought from the results that verification for the methods of experiment and measurement is necessary, we can propose that, at first, further analyses, such as sensitivity analysis, re-calculation and so on, are to be done, then, if possible, remeasurements using similar beryllium assemblies and re-analyses should be done to solve the abovementioned troublesome inconsistencies.

## References:

1) Proc. IAEA AGM on Completion of FENDL-1 and Start of FENDL-2, Del Mar, Dec. 5-9, 1995, to be published.

Table I C/E ratios of $\mathrm{Be}(45.5 \mathrm{~mm})$ Sphere

| Upper_Energy | Lower_Enery | JENDL-3.2 | JENDL-FF | FENDL-1.0 |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $16.4(\mathrm{MeV})$ | 10 | $1.08+-0.01$ | $1.09+-0.01$ | $1.08+-0.01$ |  |
| 10 | 5 | $1.00+0.01$ | $0.99+0.01$ | $0.95+0.01$ |  |
| 5 | 1 | $1.08+0.01$ | $0.97+0.01$ | $0.94+-0.01$ |  |
| 1 |  | 0.1 | $0.99+-0.01$ | $0.91+-0.01$ | $0.95+-0.01$ |
|  |  | Over_All | $1.06+-0.01$ | $1.03+-0.01$ | $1.02+-0.01$ |



Figure 1 Measured and caleulated spectra of Be sphere ( 45.5 mm )

Isao Murata, Daisuke Nakano and Akito Takahashi

The ${ }^{129}$, which is one of the most famous fission products (FPs), was very important from the standpoint of waste transmutation due to its extremely long half life. The accurate reaction cross section data of ${ }^{12 s}$ induced by 14 MeV neutrons are indispensable when evaluating the performance to transmute it in a fusion reactor. However, there was no available experimental data reported until now. We measured the 14 MeV neutron induced reaction cross sections of ${ }^{129} \mathrm{I}$ to give the reference cross section data for evaluation of transmutation performance and nuclear data at OKTAVIAN facility of Osaka university, Japan. Since the available amount of ${ }^{129} \mathrm{I}$ as a sample is quite small, probably less than 1 mg , the foil activation method was adopted in the measurement. The sample was a sealed source of ${ }^{129} I$ and the gammarays from the irradiated sample were measured with a $\mathrm{Hp}-\mathrm{Ge}$ detector. In the experiment, irradiating for about 70 minutes and 20 hours in order to eliminate backgrounds due to the production of long half life radioisotopes, then cooling for an appropriate period to exclude some short half life ones. The several measurements were done separately at various intervals to count the target gamma-rays.

Figures 1 and 2 show the examples of pulse height spectra of gamma-rays from ${ }^{128} \mathrm{I}$ and ${ }^{130} \mathrm{I}$ which were produced by the ${ }^{129} \mathrm{I}(\mathrm{n}, 2 \mathrm{n})$ and ${ }^{129} \mathrm{I}(\mathrm{n}, \gamma)$ reactions, respectively. Their irradiation, cooling and counting periods are determined separately considering different half lives of 25 min for the former and 12 hours for the latter, respectively. As shown in the figures, several gamma-rays which are expected to be due to abovementioned two nuclear reactions are observed. We confirmed that these peaks corresponded to those of ${ }^{128} \mathrm{I}$ and ${ }^{130} \mathrm{I}$ through ascertaining each energy and half life. From the measurement, the cross section of ${ }^{129} \mathrm{I}(\mathrm{n}, 2 \mathrm{n})$ and the effective production cross section of ${ }^{130} \mathrm{I}$ by the ${ }^{129} \mathrm{I}(\mathrm{n}, \gamma){ }^{130} \mathrm{I}$ reaction including the contribution of ${ }^{129} \mathrm{I}(\mathrm{n}, \gamma){ }^{130 \mathrm{~m}} \mathrm{I}$ reaction, that were estimated to be $1.1 \pm 0.1 \mathrm{~b}$ and $0.032 \pm$ 0.003 b , respectively at 14.8 MeV neutrons, were obtained with an acceptable accuracy of about $10 \%$, though the errors caused by the uncertainty of gamma decay scheme data still existed.


Fig. 1 Puise height spectrum of gamparays from ${ }^{123}$ I irradiated by 14 MeV neutrons (Peaks associated with 1 are observed)


Fig. 2 Pulse height spectrum of gammp-rays from ${ }^{199}$ I irradiated by 14 MeV neutrons (Peaks associated with ${ }^{10} 1$ are observed)

# VIII. Tohoku University 

# A. Department of Nuclear Engineering 

# VIII-A-1 Correction of Double-differential Neutron Emission Data for Sample-dependent Effects 

M.Baba, S.Matsuyama, M.Ishikawa ${ }^{1)}$, S.Chiba ${ }^{2}$, T.Sakase ${ }^{3)}$, N.Hirakawa

A paper of this subject has been published in Nuclear Instruments and Methods in Physics Research A366 (1995) 354-365 with the following abstract.

A data correction method was developed to correct the double-differential neutron emission data for sample-size effects and the sample-dependent background due to contaminant source neutrons. The latter correction proved to be very important to obtain consistent results. The correction is based on the following: 1)Monte Carlo simulation of neutron scattering considering the kinematics and finite experimental geometry, 2)derivation of the energy-angular neutron emission data that provide simulation results consistent with the experimental data, and 3)correction for sample-size effects and the sample-dependent background by, in a unified manner, using the correction factor deduced by the simulation. The present method was applied successfully for a wide range of target masses. The correction procedure, examples of the correction and the effect of the input data on the correction are presented.

[^14]
# VIII-A-2 Development of Long Liquid Scintillation Detector for Fast Neutron Time-of-Flight Experiments <br> S.Matsuyama, T.Ohokubo, M.Baba, S.Iwasaki, D.Soda, M.Ibaraki, N.Hirakawa 

A paper of this subject has been accepted for publication in Nuclear Instruments and Methods in Physics Research with the following abstract.

We have developed a long liquid scintillation detector (LLSD, $80 \mathrm{~cm} \times 6.5 \mathrm{~cm} \times 9.5 \mathrm{~cm}$ ) which is useful as a position sensitive detector and a high-efficiency neutron detector for measurements of neutron emission cross sections. LLSD is a long rectangular shaped NE213 scintillator coupled with two photomultiplier at both ends of the scintillator cell. Position information along the cell axis is obtained by the time difference method. The time compensated signal needed for time-of-flight (TOF) experiments is provided by a mean timer. Data are acquired for TOF, position and pulse-height signals gated by $\mathrm{n}-\gamma$ discriminator signals using a three parameter data acquisition system. The updated data acquisition system and a position-dependent biasing analysis could achieve a remarkably lower bias level down to $\sim 1 \mathrm{MeV}$ neutrons with good $n-\gamma$ discrimination compared to the similar type NE123 detectors and remove position dependence of detection efficiency.

LLSD with the sophisticated data taking and processing technique proved to be very effective for neutron emission cross section measurements for $10-18 \mathrm{MeV}$ incident neutrons as a wide-angle scattering detector and a high-efficiency single detector.

## VIII-A-3

Measurements of Double-differential Neutron Emission Cross Sections of Fe and Nb for 11.5 MeV Neutrons<br>S.Matsuyama, D.Soda, M.Baba, M.Ibaraki, Y.Nauchi, S.Iwasaki, N.Hirakawa

A paper of this subject has been published in Proc. 1994 Nuclear Data Symposium (JAERI-Conf $95-008$ ) p. 157 with the following abstract.

Double-differential neutron emission cross sections (DDXs) for 11.5 MeV neutrons have been measured using the ${ }^{15} \mathrm{~N}(\mathrm{~d}, \mathrm{n})^{16} \mathrm{O}$ neutron source at the Tohoku University 4.5 MV Dynamitron facility. In this study, DDX for Fe and Nb for $\mathrm{En}>6 \mathrm{MeV}$ were measured by the conventional single time-offlight method without distortion by background neutrons associated in the ${ }^{15} \mathrm{~N}(\mathrm{~d}, \mathrm{n})^{16} \mathrm{O}$ neutron source. Further, for Fe , secondary neutron energy range was extended down to 2 MeV adopting the double time-of-flight method.

## VIII-A-4

Measurements of Neutron-induced Charged-particle Emission Cross Sections
M.Baba, I.Matsuyama, T.Sanami, S.Matsuyama, T.Kiyosumi, Y.Nauchi, N.Hirakawa

A paper of this subject has been published in Proc. 1994 Nuclear Data Symposium (JAERI-Conf 95-008) p. 153 with the following abstract.

Experiments have been carried out on 1)double-differential ${ }^{50} \mathrm{Cr}(\mathrm{n}, \mathrm{x} \alpha)$ cross sections between 5.1 and 14.1 MeV , 2)high-resolution ${ }^{58} \mathrm{Ni}(\mathrm{n}, \boldsymbol{\alpha})$ emission spectrum between 4.8 and 5.8 MeV , and $3)^{14} \mathrm{~N}(\mathrm{n}, \mathrm{p})^{14} \mathrm{C}$ cross section for quasi-Maxwellian neutrons with $\mathrm{kT} \sim 25 \mathrm{keV}$, using a high efficiency gridded-ionization chamber.

# B. Laboratory of Nuclear Science 

## VIII-B-1

# ${ }^{7}$ Li(e, e $\left.\mathrm{e}^{\prime}\right)^{6}{ }^{6} \mathrm{Li}$ Reaction near the Giant Resonance 

T. Endo, T. Saito, M. Oikawa, K. Kino, T. Nakagawa*, K. Abe** and H. Ueno***

In the cross sections of the giant resonance region of ${ }^{7} \mathrm{Li}$ are pointed out contributions from excitation of a-t cluster and absorption by quasi a particles ${ }^{1)}$. Many experiments for the giant resonance have been done, but all of these are measurements for charged particles, few experiments for the neutron decay. Ferdinande et al. ${ }^{2}$ measured the ( $\mathrm{g}, \mathrm{n}$ ) cross sections for the ground state and first excited states transitions separately, but there are no measurements for angular distribution.

The angular distributions for decay neutrons feeding the ground state and first excited states in ${ }^{6} \mathrm{Li}$ in the ${ }^{7} \mathrm{Li}\left(\mathrm{e}, \mathrm{e}{ }^{\prime} \mathrm{n}\right)^{6} \mathrm{Li}$ reaction have been measured using 129 MeV continuous electron beam. Scattered electrons were measured at $30^{\circ}$ with a magnetic spectrometer which corresponds to a momentum transfer of $q=0.33 \mathrm{fm}^{-1}$. Neutrons were measured with ten NE213 liquid scintillators. The neutron energy was determined by the time-of-flight methods with flight path of 1 m .

Fig. 1 shows a missing energy spectrum at 90 degrees. The peaks at 7.3 and 9.6 MeV which correspond to the neutrons feeding the ground and first excited states in ${ }^{6} \mathrm{Li}$ respectively, are clearly separated. The angular distributions obtained for these peaks for the excitation energy range of 13 to 16 MeV are shown in Fig. 2. These angular distributions were fitted with Legendre polynomials and associated Legendre polynomials up to third order (solid lines). ${ }^{3)}$ The nonzero values of the Legendre parameters bl and b3 indicate interference between dipole and quadrupole excitation.

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1) R.A. Eramyhyan, B.S. Ishikhanov, V.G. Neudatchin: Phys. Rep. 136, Nos. 4-6, 229 (1986).
2) H. Ferdinansnde et al. : Can. J. Phys. 55, 428 (1977).
3) W.E. Kleppinger and J.D. Walecka: Ann. Phys. 146, 349 (1983).

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Fig. 1. Missing energy for the ${ }^{7} \mathrm{Li}\left(e, e^{\prime} \mathrm{n}\right)^{6} \mathrm{Li}$ reaction. The peaks at 7.3 and 9.6 MeV correspond to the neutrons feeding the ground and first excited states in ${ }^{6} \mathrm{Li}$, respectively.


Fig. 2. Angular distribution of neutrons measured in the reactions ${ }^{7} \mathrm{Li}\left(\mathrm{e}, \mathrm{e}^{7} \mathrm{n}_{0}\right)^{6} \mathrm{Li}$ (left) and ${ }^{7} \mathrm{Li}(\mathrm{e}$, $\left.\mathrm{e}^{\prime} \mathrm{n}_{1}\right)^{6} \mathrm{Li}$ (right). Solid lines represent Legendre polynomial fits.

# IX. Tokyo Institute of Technology 

## LX-1

# Measurements of keV -neutron capture $\gamma$-rays of fission products 

M. Igashira, K. Masuda, S. Mizuno, M. Mizumachi, T. Ohsaki, and H. Kitazawa

We are measuring $\gamma$-rays from $k e V$-neutron capture reactions by fission products in a neutron energy region of 10 to 100 keV in order to obtain capture cross sections and capture $\gamma$-ray spectra, using a large antiCompton NaI (TI) spectrometer and pulsed keV neutrons from the ${ }^{7} \mathrm{Li}(\mathrm{p}, \mathrm{n}){ }^{7} \mathrm{Be}$ reaction by a 1.5 ns -pulsed proton beam. Up to now, the measurements have been finished for ${ }^{140} \mathrm{Ce},{ }^{141} \mathrm{Pr},{ }^{143} \mathrm{Nd},{ }^{147,148,150,152,154} \mathrm{Sm},{ }^{153} \mathrm{Eu}$, and ${ }^{161,162,163} \mathrm{Dy}$, and the preliminary results are obtained. ${ }^{1,2)}$

## References:

1) M. Igashira, K. Masuda, S. Mizuno, M. Mizumachi, T. Ohsaki, T. S. Suzuki, Y. Nagai and H. Kitazawa: Proc. Specialists' Meeting on Measurement, Calculation and Evaluation of Photon Production Data, Bologna, Italy, November 9-11, 1994, NEA/NSC/DOC (95) 1, p. 269 (1995).
2) M. Igashira: Proc. the 1994 Symposium on Nuclear Data, Tokai, Japan, November 17-18, 1994, JAERI-Conf 95-008, p. 129 (1995).

## IX-2

# Measurement of the ${ }^{16} 0(n, \gamma){ }^{17} 0$ reaction cross section at stellar energy and the critical role of nonresonant $p$-wave neutron capture 

M. Igashira, Y. Nagai, K. Masuda, T. Ohsaki, and H. Kitazawa

A paper on this subject was published as the Astrophysical Journal, 441, L89 (1995) with the following abstract:

The cross section of the ${ }^{16} 0(n, \gamma){ }^{17} 0$ reaction, important for nucleosynthesis theories of $s$ and $p$ processes and of inhomogeneous big bang models, has been measured at stellar neutron energy. The Maxwellian-averaged cross section at $\mathrm{kT}=30 \mathrm{keV}$ was derived as $34 \pm 4 \mu$ barn; 170 times larger than the value reported previously. The results could significantly alter the $s$ and p process efficiencies in metal-deficient stars due to a strong neutron poison of ${ }^{16} 0$ and increase the primordial nucleosynthesis yield in inhomogeneous models. The large cross section is attributed to a nonreso-
nant $p$-wave neutron-capture process. It is pointed out that this process plays an important role in the neutron-capture reaction of light nuclei at stellar energy. The cross section deviates considerably from the extrapolated value of the measured thermal-capture cross section by assuming a $1 / v$ law and therefore the process significantly influences both the stellar and above-mentioned primordial nucleosynthesis theories.

## IX-3

## First measurement of a $p(n, \gamma) d$ reaction cross section between 10 and 80 keV

T. S. Suzuki, Y. Nagai, T, Shima, T. Kikuchi, H. Sato, T. Kii, and M. Igashira

A paper on this subject was published as the Astrophysical Journal, 439, L59 (1995) with the following abstract:

For the first time we have successfully measured the important cross section of the $p(n, \gamma) d$ reaction at astrophysically relevant energies between 10 and 80 keV , where the difference in the cross section between old and new calculations is quite large. In the measurement we used a prompt $\gamma-$ ray detection method, combined with a pulsed neutron beam, which is crucial for determining the cross section accurately by discriminating small true signals from huge background signals; we also used a recently developed Monte Carlo code for correcting neutron multiple-scattering effects in a sample. The cross sections derived in the present experiment were 318(25) $\mu \mathrm{b}, 203(19) \mu \mathrm{b}$, and $151(7) \mu \mathrm{b}$ at neutron energies of 20,40 , and 64 keV , respectively. They do not follow a simple $1 / v$ law and are in good agreement with new calculations. Regarding the primordial adundances of light elements, the present result supports a recent calculation by Smith et al. However, the discrepancy in the deuteron photodisintegration cross sections between the experimental values and a newly calculated one by Ohtsubo et al. remains to be explained.

## IX-4

Non-statistical $\gamma$-ray emission from broad neutron resonances on $p$-shell and $s d$-shell nuclei

## H. Kitazawa and M. Igashira

A paper on this subject was published in the Proceedings of a Specialists' Meeting on Measurement, Calculation and Evaluation of Photon Production Data, Bologna, Italy, November 9-11, 1994, NEA/NSC/DOC(95) 1, p. 269 (1995) with the following abstract:

We have observed primary $\gamma$-rays from broad $s, p, d$-wave neutron resonances on $p$-shell and $s d$-shell nuclei. The results exhibit characteristic features of non-statistical $\gamma$-ray emission from those resonances: (1) strong $p \rightarrow s$ and $s \rightarrow p$ single-particle transitions, (2) considerable retardation of $p \rightarrow d$ and $d \rightarrow p$ single-particle transitions, resulting from the coupling between a neutron single-particle motion and the giant-dipole resonance mode of a target nucleus in a resonance state, and (3) vibrational, rotational and isovector spin-dipole core polarization of resonance states.

## IX-5

# Neutron effective charge for primary E1 transitions from broad neutron resonance on $p$-shell and $s d$-shell nuclei 

## H. Kitazawa

A paper on this subject was published in the Proceedings of the 1994 Symposium on Nuclear Data, Tokai, Japan, November 17-18, 1994, JAERI-Conf $95-008$, p. 233 (1995) with the following abstract:

Strong retardation of primary single-particle E1 transitions from broad neutron resonances on $p$-shell and $s d$-shell nuclei, previously observed in E1 transitions from the $d_{5 / 2}$-wave neutron resonance on ${ }^{9} \mathrm{Be}$ at 622 keV and from the $p_{3 / 2}$-wave neutron resonances on ${ }^{24} \mathrm{Mg}$ at 84 keV and 431 keV , is reasonably explained by coupling a single-particle motion with the giant electric-dipole resonance mode.


[^0]:    The content table in the CINDA format was compiled by the JNDC CINDA group:
    S.Chiba(JAERI), T.Fukahori(JAERI), M.Kawai(Toshiba), H.Kitazawa(Tokyo Inst. of

    Technol.), H.Matsunobu(Sumitomo At. Energy Industries), T.Nakagawa(JAERI), R.Nakasima(Hosei Univ.),

[^1]:    *Members are A. Hashizume, T. Ichimiya, H. Iimura, M. Kambe, K. Kitao, J. Katakura, K. Miyano, K. Ogawa, M. Ohshima, S. Ohya, T. Tamura, and Y. Tendoh

[^2]:    * Present Address: GE Yokogawa Medical System Inc., Asahigaoka, Hino-shi, 191

[^3]:    * Japan Atomic Energy Research Institute
    ** The University of Tokushima
    + Lawrence Livermore National Laboratory, U.S.A.
    ++ University of Oxford, U.K.

[^4]:    * Department of Physics, Kyushu University

[^5]:    * Japan Atomic Energy Research Institute

[^6]:    ${ }^{1}$ Kkyushu Univ.
    ${ }^{2}$ Tokusima Univ.
    ${ }^{3}$ Univ. of Occupational and Environmental Health

[^8]:    * Power Reactor and Nuclear Fuel Development Corp.
    $\dagger$ Present address: Gifu College of Medical Technology, and Power Reactor and Nuclear Fuel Development Corp.

[^9]:    * Research Reactor Institute, Kyoto University

[^10]:    *Department of reactor engineering, JAERI

[^11]:    * Osaka University

[^12]:    * Osaka University

[^13]:    * Deceased, Feb. 14, 1995.

[^14]:    1. Present Address; Tokyo Electric Power Inc., 100 Tokyo, Japan
    2. Present Address; Japan Atomic Energy Research Institute, 319-11 Tokai, Japan
    3. Present Address; Genus Inc. Massachusetts, USA
[^15]:    *Present Address: Department of Physics, Tohoku University
    ** Present Address: Department of Nuclear Engineering, Tohoku University
    *** Present Address: Department of Physics, Yamagata University

