Preequilibrium (n,n′) cross sections on nuclei around atomic number 50 at $E_n = 14.1$ MeV

Y. Watanabe, I. Kumabe, and M. Hyakutake*
Department of Nuclear Engineering, Kyushu University, Fukuoka, 812 Japan

A. Takahashi, H. Sugimoto, E. Ichimura, and Y. Sasaki
Department of Nuclear Engineering, Osaka University, Osaka, 565 Japan

(Received 14 September 1987)

The energy spectra of neutrons emitted from 14.1-MeV-neutron-induced reactions on Ag, Cd, In, Sn, Sb, and Te were measured at 70° in order to investigate the shell and odd-even effects in the preequilibrium (n,n′) process. The cross sections integrated over the outgoing energies of 7–10 MeV, where the preequilibrium process is dominant, increased monotonically with increasing atomic numbers of all scatterers except Te. The results of calculations based on the exciton model showed an underestimation in 7–10 MeV only for Te. This underestimation could be explained by taking into account the contribution from the collective excitations of the low energy octupole resonance by the direct process. As a result, it was found that there were no appreciable shell and odd-even effects in the preequilibrium (n,n′) process that leaves the residual nucleus into the continuum region.

I. INTRODUCTION

Recently, we have measured 18 MeV (p,p′) spectra for nuclei around neutron number 50, with special attention focused on the shell and odd-even effects in the preequilibrium (p,p′) process.[1] There were no appreciable shell and odd-even effects in the preequilibrium components derived from the experimental (p,p′) spectra corresponding to excitations above 4 MeV. To see whether such experimental results from the (p,p′) scattering are applicable to the case of the (n,n′) scattering or not, is of interest for not only enhancing our understanding of the reaction mechanism but also fusion energy applications.

In the present work, we measured systematically the energy spectra of neutrons emitted from the reactions induced by 14.1-MeV neutrons. Six elements around the atomic number 50 (Ag, Cd, In, Sn, Sb, and Te) were chosen as the target nuclei to investigate the shell and odd-even effects. The energy spectra of inelastically scattered neutrons have been measured by several groups.[2–7] However, there are scarcely enough data to allow detailed and systematic arguments on the preequilibrium (n,n′) process.

We will summarize the experimental results in Sec. III after describing experimental procedures in Sec. II. In Sec. IV, the results will be discussed by taking into account the contribution from the direct process. Finally, our conclusion will be summarized in Sec. V.

II. EXPERIMENTAL PROCEDURES AND DATA REDUCTION

The experiment was performed with an 85° time-of-flight (TOF) spectrometer using a 14.1-MeV pulsed neutron beam at the OKTAVIAN facility at Osaka University. The experimental equipment used in the present measurement has been described in detail elsewhere.[4,5] Only the experimental procedure, therefore, is briefly summarized here.

The scatterers used in the experiment were the cylindrical solid samples (3 cm diam × 3.7 cm for Ag, 2.6 cm diam × 5 cm for Cd, and 3 cm diam × 5 cm for In, Sn, Sb, and Te). The scattered neutrons were detected with a 25.4 cm diam × 10 cm NE213 scintillator, optically connected with an RCA 1250 photomultiplier tube. The neutron detector was set inside a 5 cm thick lead shell with 10 cm inner polyethylene layer, and was heavily shielded by ordinary concrete. The distance between the scatterer and the detector changed slightly around 8.25 m with the change of the sample position.

Conventional electronics were employed in the neutron TOF measuring system.[4] For the suppression of γ-ray backgrounds in a wide dynamic range, two parallel pulse shape discrimination circuits were adopted with two delay line amplifiers that allow a "low" and "high" gain setting, respectively. Sufficient n-γ separability was achieved over a dynamic range of 0.3–14 MeV neutron energy.

The efficiency of the neutron detector was determined by two methods: TOF experiments using both a ^{252}Cf neutron source for the energy range of 0.3–9 MeV and a cylindrical polyethylene sample (1 cm diam × 5 cm) for 5–14 MeV.

A typical TOF spectrum of emitted neutrons from In is shown in Fig. 1, together with a background spectrum which was taken without the scatterer. The TOF spectra of neutrons emitted from In were measured at nine angle points between 20° and 160°. However, the TOF spectra for the remaining scatterers were taken only at 70°. The data accumulation time was about 3 h for all the measurements at 70°, and about 2 h for the measurements at the other angles. An additional 3 h were spent on background runs for sample-out.

After subtraction of backgrounds, the TOF spectra were converted into energy spectra using the detector

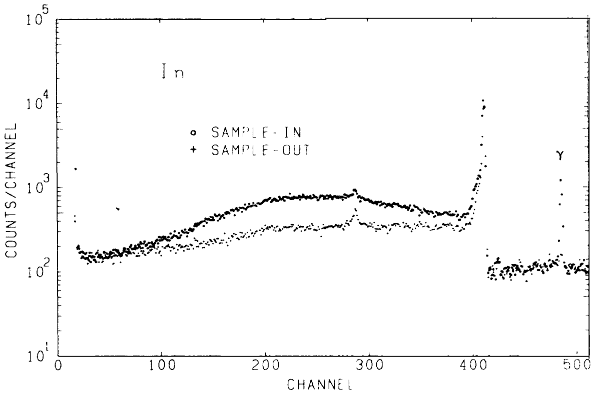

FIG. 1. Time-of-flight spectrum of 70° for the In(n,xn) reaction at 14.1 MeV and the associated background spectrum.

efficiency, monitor counts, and $^{1}H(n,n)$ cross sections as standard. The details of the data-reduction procedures are provided elsewhere[4]. Finally, the differential cross sections were averaged over 0.2 MeV energy bins corresponding to the energy resolution of the TOF spectrometer used. The correction for neutron attenuation and multiple scattering was performed using a computer program MUSCC3.[8]

The main systematic uncertainties arise from the neutron detector efficiency ($\sim 5\%$), the intensity of source neutrons ($\sim 3\%$), the subtraction of backgrounds ($\sim 3\%$), and the multiple scattering correction ($\sim 10\%$). After addition of the statistical errors, the overall uncertainties were estimated to be 8–17% for the double differential cross sections at 70°; the energy spectra at the other angles for the In sample have rather large uncertainties because of poorer counting statistics.

III. EXPERIMENTAL RESULTS

Figure 2 shows double differential neutron emission cross sections measured at 70° for Ag, Cd, In, Sn, Sb, and Te, together with the calculated results. Each peak around 14 MeV corresponds to elastic scattering. Broad peaks, which may be due mainly to collective excitations by the direct process, are observed in the outgoing neutron energies of 10–13 MeV for all the measured spectra. Their shape and magnitude change obviously with atomic number. On the other hand, continuum spectra below 10 MeV have almost similar shape, regardless of variation of the atomic number and the mass number. In the energy spectrum for Te, however, structures with overlapping of small peaks are observed in the energy region of 6–10 MeV, and the magnitude is somewhat larger than those of the other spectra.

In Fig. 3, the experimental cross sections integrated over 7–10 MeV are plotted with respect to the atomic weight of the scatterer by solid circles. While the cross sections increase monotonically with increasing atomic number from Ag to Sb, the cross section for Te shows a discontinuous increase. In a similar way, we also compared the cross sections of 14 MeV (n,n') scattering measured by Hermsdorf *et al.*[2] for the same elements as chosen in the present work, except for Ag and Te for which the cross sections were not measured by them. It was found that the cross sections changed smoothly with variation of the atomic and mass numbers as well as the present experimental results.

IV. ANALYSES AND DISCUSSION

First we compared the angle-integrated energy spectrum and 4π times the energy spectrum at 70° for $In(n,n')$ in Fig. 4. The integration with respect to angles was carried out by fitting the angular distributions for each 0.2 MeV bin with a series of Legendre polynomials up to $l=4$. Both spectra are identical in the whole energy region except for the elastic peak around 14 MeV. Moreover, it has been reported that the angular distributions do not depend strongly on target mass in the outgoing energy region where the preequilibrium emission is dominant.[9] In Fig. 2, therefore, the experimental spectra were compared with $1/4\pi$ of the angle-integrated spectra calculated for all target nuclei.

The calculated energy spectra were obtained on the basis of the evaporation[10] and the exciton models.[11] In the present calculation, the isotope with the mass number almost equal to the atomic weight was assumed to be the target nucleus (i.e., ^{107}Ag, ^{112}Cd, ^{115}In, ^{118}Sn, ^{121}Sb, and ^{128}Te), although measurements were performed with natural elements. A formulation of the exciton model is the same as that used in the previous (p,p') calculation[1]. The only difference is that it is not necessary to take into account the decay from states with higher isospin $T_{>}$ in the composite nucleus, because such states are not excited by neutron induced reactions. The parameter K value in the exciton model calculation was chosen to be 550 MeV^3. The single particle level density g was equal to $A/13$, where A is the mass number. The standard pairing shift proposed by Blann and Vonach[12] was employed as the pairing correction for the exciton model calculation. On the other hand, the level density expression by Gilbert and Cameron[13] was used in the evaporation model calculation. The reaction cross sections and the inverse cross sections were obtained using the optical potential parameters by Wilmore and Hodgson,[14] Mani *et al.*,[15] and Huizenga and Igo[16] for neutrons, protons, and alpha particles, respectively.

As shown in Fig. 2, the calculated spectra except for Te were in good agreement with the experimental ones in the continuum region of 1–10 MeV, while the result for Te showed underestimation in the region of 7–10 MeV. This underestimation could not be explained well by the difference of contribution from the compound process, because the calculated compound cross sections were very small in the 7–10 MeV region.

Here we pay attention to spectral structures with overlapping of small peaks observed in the 7–10 MeV region for Te, and explore the possibility of the strong excitation of the low energy octupole resonance (LEOR) by the direct reaction process. Results of systematic investigations show the following features for $E3$ transitions and the LEOR.[17–20] (i) The strength of the $1\hbar\omega$ transition exhausts about 30% of the energy weighted sum rule

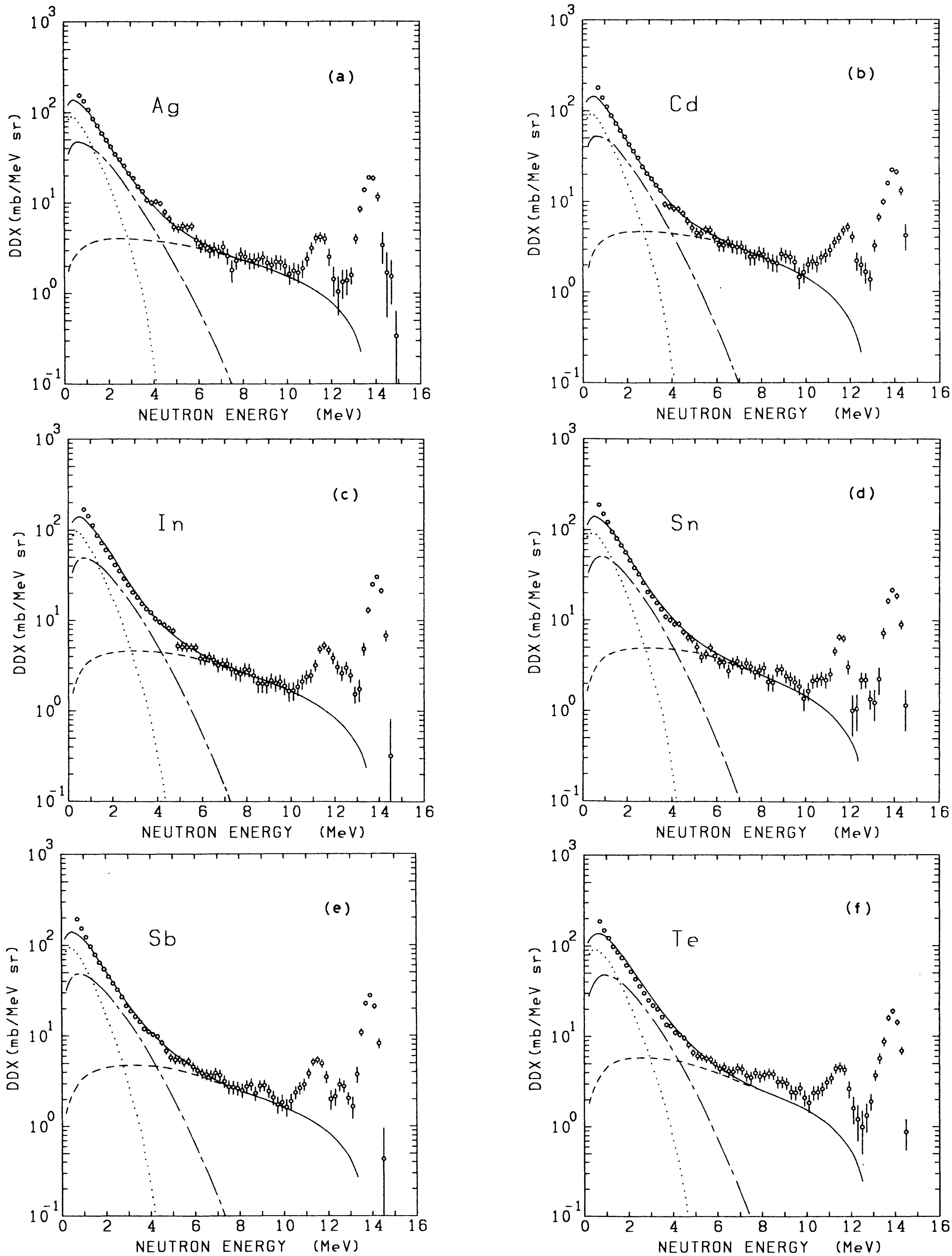

FIG. 2. Comparisons of the experimental and calculated double differential neutron emission cross sections for Ag, Cd, In, Sn, Sb, and Te at 70°. Dashed curves are the calculated preequilibrium spectra using the exciton model. Dot-dashed curves and dotted curves show the calculated evaporation spectra for emissions of one neutron and two neutrons, respectively. Solid curves are the sum of them.

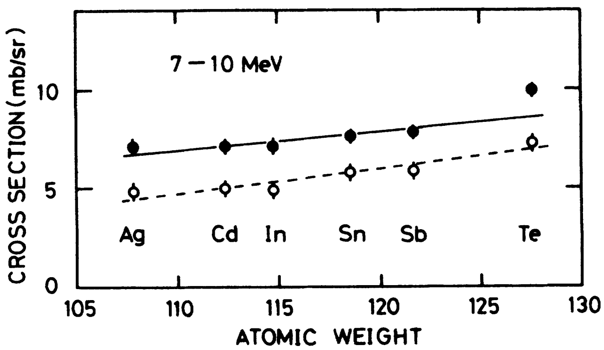

FIG. 3. Dependence of integrated cross sections over 7–10 MeV on the atomic weight of scatterers. Solid circles represent the measured cross sections at 70°. Open circles are the results after subtraction of the predicted LEOR cross sections. Error bars represent only the statistical errors.

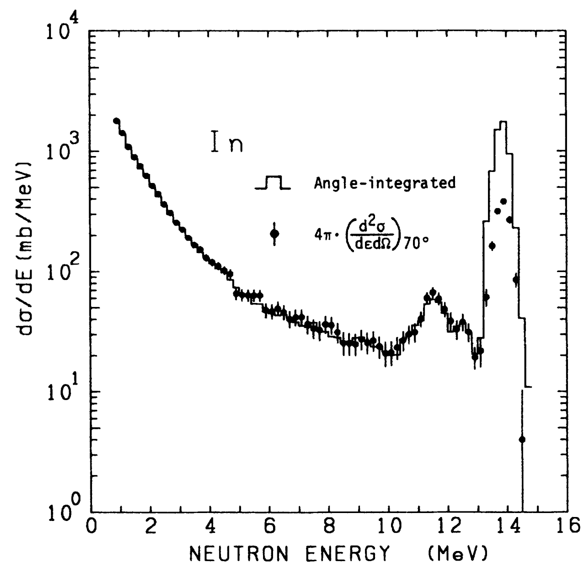

FIG. 4. Comparison of the angle-integrated energy spectrum (histogram) and 4π times the energy spectrum at 70° (solid circles) measured for the In(n,xn) reaction.

(EWSR) for the nuclei in a wide range of a Periodic Table. (ii) This strength is divided mainly into two groups: one is the first 3^-, and the other is the LEOR. (iii) The excitation of the LEOR is not appreciably observed if the first 3^- transition occurs strongly (e.g., ^{40}Ca and ^{208}Pb in Ref. 18).

Table I provides comparisons of the experimental values of the deformation parameter β_3 for the first 3^- states;[21,22] the square of β_3 is proportional to the $E3$ transition rate $B(E3)$. In the case of an odd-A nucleus, coupling of an unpaired nucleon and vibrational mode ($L=3$) gives rise to multiplet states. Since the sum of the $E3$ transition probabilities to the multiplet states is equal to $B(E3)$ for the neighboring even-even nucleus under the weak coupling assumption,[24] the excitation energies and the values β_3 for odd-A nuclei (^{107}Ag, ^{115}In, and ^{121}Sb) were compared using those for the neighboring even-even nuclei (^{106}Pd, ^{114}Cd, and ^{120}Sn, respectively). It should be noted that the values β_3 for ^{128,130}Te are considerably smaller than those for the others. This fact suggests the possibility of strong excitation of the LEOR for Te, considering the features of the LEOR mentioned above.

Next we estimated the deformation parameters $\beta_{\rm LEOR}$ for the LEOR under the assumption that the sum of the EWSR fraction of the first 3^- and that of the LEOR is 30% and the excitation energy of the LEOR is $31A^{-1/3}$, where A is the mass number. The results are listed in Table I.

TABLE I. Comparisons of experimental values of the deformation parameters β_3 for the first 3^- state, estimated $\beta_{\rm LEOR}$, and cross sections for the excitation of the LEOR by the direct process.

	First 3^{-a}			LEOR			
Nuclei	Energy (MeV)	β_3 (expt.)	EWSR (%)[b]	β_3	EWSR (%)	$\sigma_{\rm DW}$ (mb/sr)	$\sigma_{\rm LEOR}$ (mb/sr)
^{107}Ag	2.07	0.15	8.7	0.124	21.3	147.1	2.3
^{112}Cd	1.97	0.164	10.9	0.114	19.1	166.7	2.2
^{115}In	1.95	0.160	10.6	0.113	19.4	177.8	2.3
^{118}Sn	2.32	0.168	14.7	0.098	15.3	187.8	1.8
^{121}Sb	2.39	0.159	14.0	0.099	16.0	196.4	1.9
^{128}Te	2.50	0.110	7.8	0.111	22.2	213.9	2.7
^{130}Te	2.77	0.10	7.3	0.112	22.7	218.9	2.7

[a]The excitation energies and β_3 for odd nuclei (^{107}Ag, ^{115}In, and ^{121}Sb) were those for the neighboring even-even nuclei (^{106}Pd, ^{114}Cd, and ^{120}Sn, respectively). Experimental data for excitation energies and β_3 were taken from Ref. 21 for ^{106}Pd and Ref. 22 for the other isotopes.

[b]The EWSR fractions were obtained from the formula in Ref. 23,

$$\Delta S_L=\frac{3}{2\pi}\frac{Mc^2}{(\hbar c)^2}A\frac{(\beta_L R)^2}{L(2L+1)}E_x ,$$

under the assumption of the uniform mass distribution, where M is the nucleon mass, c the velocity of the light, A the mass number, R the nuclear radius ($R=1.27A^{1/3}$), L the multipolarity ($L=3$), and E_x the excitation energy.

On the basis of the direct reaction theory for inelastic scattering, the cross section for excitations of LEOR is predicted from the following expression:

$$\sigma_{\rm LEOR} = \beta^2{}_{\rm LEOR}\sigma_{\rm DW} , \qquad (1)$$

where $\sigma_{\rm DW}$ is the distorted-wave Born approximation (DWBA) cross section for the (n,n′) scattering with the transferred angular momentum $L=3$. In the present analysis, it was calculated with the code DWUCK[25] using the optical potential parameter by Wilmore and Hodgson[14] and the conventional collective form factor. The calculated $\sigma_{\rm DW}$ at 70° are also listed in Table I. The predicted LEOR cross section for Te is 17–50 % larger than those for the other nuclei.

In the excitation region under consideration, the transitions to the other multipolarities by the direct process are expected to have smaller contributions than the transitions of $L=3$ for the following reasons. Since the giant monopole resonance (GMR) and the giant dipole resonance (GDR) are located at $\sim 80A^{-1/3}$ and $\sim 78A^{-1/3}$, respectively[26] (i.e., 15.9 and 15.5 MeV for ^{128}Te), there would be negligible contribution in the region of 4–7 MeV. For the transitions of $L=2$, there must also be very small contribution, because their strengths concentrate strongly on the lowest 2^+ and the giant quadrupole resonance (GQR).[26] In the case of the transitions of $L \geq 4$, there has been no direct experimental evidence for giant resonances.[26] The strengths would fragment in the continuum region rather than concentrate as in the case of the LEOR. Moreover, the $\sigma_{\rm DW}$ for 14.1 MeV (n,n′) scattering decreases rapidly as the transferred angular momentum increases. Thus the predicted $\sigma_{\rm LEOR}$ is considered as a major component by the direct process in excitation energies of 4–7 MeV.

The direct inelastic process excites strongly collective states such as the first 2^+, 3^- and the giant resonances. On the other hand, such collective excitations cannot be treated in the framework of the preequilibrium model (e.g., the exciton model), in which the reaction is assumed to proceed through sequential two-body interactions after the formation of the composite system.[27] Application of the preequilibrium model, therefore, requires subtraction of components of the direct collective excitation in inelastic scattering. As mentioned above, the excitation of the LEOR is a major direct component in the excitation region of 4–7 MeV in 14.1 MeV (n,n′) scattering. Consequently, we subtracted the LEOR cross sections calculated from Eq. (1). The resultant cross sections are shown by open circles in Fig. 3; these will be referred to as the preequilibrium cross sections. Compared with experimental cross sections (solid circle), the preequilibrium cross sections increase monotonically over the whole mass region including Te, and show no appreciable shell and odd-even effects.

As discussed in Ref. 1, preequilibrium energy spectra are closely related to the state density of the residual nucleus. No appreciable shell and odd-even effects in the preequilibrium (p,p′) spectra were interpreted on the basis of the particle-hole state densities generated from the Nilsson model; it was shown that the influence of a shell gap on the calculated one-particle and one-hole state densities for the neutron shell was reduced significantly in the excitation energies above 4 MeV. A similar consideration for the proton shell can provide a qualitative explanation on A or Z dependence of the preequilibrium (n,n′) cross sections in Fig. 3.

In the previous (p,p′) study,[1] the experimental results were interpreted using the preequilibrium model without taking into account excitations of the LEOR. The components of direct process are probably included in the continuum region of the (p,p′) spectra as well as the (n,n′) spectra. If such components vary smoothly as the target mass does, they may not be as noticeably observed as in Te(n,n′) scattering. In the above-mentioned way, we calculated the $\sigma_{\rm LEOR}$ for the (p,p′) scattering on nuclei in the Mo region, and obtained the preequilibrium cross sections from subtraction of the calculated $\sigma_{\rm LEOR}$. The result also indicated that there were no appreciable shell and odd-even effects in the preequilibrium cross sections of (p,p′) scattering corresponding to excitations above 4 MeV of the residual nucleus as well as in those of (n,n′) scattering.

We mentioned in Ref. 1 that the shell and odd-even effects are not appreciably observed above 4 MeV in excitation energy in (p,n) spectra[28] as well as in (p,p′) spectra. On the other hand, Scobel *et al.*[29] have shown that the shell effect appears in a high outgoing energy portion of the 25 MeV (p,n) spectra for the near-closed shell nuclei. Mordhorst *et al.*[30] have reported that $^{92-100}$Mo(p,n) spectra show a pronounced odd-even effect. The difference between (p,p′) and (n,n′) scatterings and (p,n) reactions is that the (p,p′) and (n,n′) spectra have structures with several peaks due to strong collective excitations in the region below 4 MeV, but the (p,n) spectra have structureless continuum except for isobaric-analog-state (IAS) peaks and small peaks due to the transitions to low lying states. Thus, the present (n,n′) results do not contradict the (p,n) results,[29,30] but confirm the conclusion reached in Ref. 1 that the difference is due to the excitation energy region examined.

V. CONCLUSION

We measured the energy spectra of neutrons emitted from 14.1 MeV (n,n′) scattering by Ag, Cd, Sn, Sb, and Te at the emission angle of 70° and those by In at several angles including 70°. The cross sections integrated over the outgoing neutron energies of 7–10 MeV increased montonically as the atomic weight increased from Ag to Sb, while the cross sections for Te showed a discontinuous increase. The results of the exciton model calculations also showed an underestimation by 7–10 MeV only for Te.

To interpret these observations, we estimated the contribution of the collective excitation of the LEOR due to the direct process under the rather rough assumption using experimental values of deformation parameters β_3 for the first 3^- state and systematics for the $E3$ transitions. The predicted LEOR cross section was subtracted from the experimental cross section as a major component of the direct process in the continuum region of 7–10 MeV, because direct collective excitations cannot be explained by the preequilibrium model. The resulting preequilibrium cross sections showed a monotonic increase over the whole mass region including Te. Consequently, no appearance of the shell and odd-even effects was observed in the preequilibrium (n,n′) cross section.

Finally, from the present (n,n′) and the previous (p,p′) studies,[1] we can draw the conclusion that there were no appreciable shell and odd-even effects, as far as the preequilibrium component in continuum (n,n′) and (p,p′) spectra corresponding to excitations above 4 MeV is concerned.

ACKNOWLEDGMENT

The authors would like to thank the staffs of the OKTAVIAN facility, Osaka University, for their assistance in operating the accelerator.

---

*Present address: Sasebo Technical College, Sasebo, Japan.

[1]Y. Watanabe I. Kumabe, M. Hyakutake, N. Koori, K. Ogawa, K. Orito, K. Akagi, and N. Oda, Phys. Rev. C **36** 1325 (1987).

[2]D. Hermsdorf, A. Meister, S. Sassonoff, D. Seeliger, K. Seidel, and F. Shahin, Zentralinstitut für Kernforschung Report No. ZfK-277 (unpublished).

[3]Y. Irie, M. Hyakutake, M. Matoba, and M. Sonoda, J. Phys. Soc. Jpn. **39**, 537 (1975).

[4]A. Takahashi, J. Yamamoto, K. Oshima, M. Ueda, M. Fukazawa, J. Miyaguchi, and K. Sumita, J. Nucl. Sci. Technol. **21**, 577 (1984).

[5]A. Takahashi, E. Ichimura, H. Sugimoto, and K. Katoh, in *Proceedings of the JUDC 1985 Seminar on Nuclear Data, Tokai, 1985,* edited by T. Asami and M. Mizumoto (Japan Atomic Energy Research Institute, Ibaraki, Japan, 1986), p. 393.

[6]M. Drosg, P. W. Lisowski, R. A. Hardekopf, D. M. Drake, and K. Treitl, Radiat. Eff. **92**, 145 (1986).

[7]M. Baba, M. Ono, N. Yabuta, T. Kikuti, and N. Hirakawa, Radiat. Eff. **92**, 223 (1986).

[8]E. Ichimura and A. Takahashi, OKTAVIAN Report No. A-87-02 (unpublished).

[9]C. Kalbach and F. M. Mann, Phys. Rev. C **23**, 112 (1981).

[10]V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

[11]J. J. Griffin, Phys. Rev. Lett. **17**, 478 (1966).

[12]M. Blann and H. K. Vonach, Phys. Rev. C **28**, 1475 (1983).

[13]A. Gilbert and A. G. W. Cameron, Can. J. Phys. **43**, 1446 (1965).

[14]D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).

[15]G. S. Mani, M. A. Melkanoff, and I. Iori, Centre a l'Energie Atomique Report No. CEA 2379 (unpublished).

[16]J. R. Huizenga and G. Igo, Nucl. Phys. **29**, 462 (1962).

[17]C. J. Veje, K. Dansk. Vidensk. Selsk. Mat.-Fys. Medd. **35**, 1 (1966).

[18]J. M. Moss, D. R. Brown, D. H. Youngblood, C. M. Rozsa, and J. D. Bronson, Phys. Rev. C **18**, 741 (1978).

[19]T. Yamagata, S. Kishimoto, K. Yuasa, K. Iwamoto, B. Saeki, M. Tanake, T. Fukuda, I. Miura, M. Inoue, and H. Ogata, Phys. Rev. C **23**, 937 (1981).

[20]M. W. Kirson, Phys. Lett. **108B**, 237 (1982).

[21]R. L. Robinson, J. L. C. Ford, Jr., P. H. Stelson, and G. R. Satcher, Phys. Rev. **146**, 816 (1966).

[22]W. Makofske, W. Savin, H. Ogata, and T. H. Kruse, Phys. Rev. **174**, 1429 (1968).

[23]A. M. Berstein, *Advances in Nuclear Physics* (Plenum, New York, 1969), Vol. 3, Chap. 5.

[24]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Massachusetts, 1975), Vol. II, p. 649.

[25]P. D. Kunz (private communication).

[26]F. E. Bertrand, Nucl. Phys. **A354**, 129 (1981).

[27]P. E. Hodgson, G. M. Field, H. Gruppelaar, and P. Nagel, in *Proceedings of the International Conference on Nuclear Data for Basic and Applied Science, Santa Fe,* 1985, edited by P. G. Young *et al.* (Gordon and Breach Science, New York, 1986), Vol. 2, p. 1033.

[28]I. Kumabe and Y. Watanabe, Phys. Rev. C **36**, 543 (1987).

[29]W. Scobel, M. Blann, T. T. Komoto, M. Trabandt, S. M. Grimes, L. F. Hansen, C. Wong, and B. A. Pohl, Phys. Rev. C **30**, 1480 (1984).

[30]E. Mordhorst, M. Trabandt, A. Kaminsky, H. Krause, and W. Scobel, Phys. Rev. C **34**, 103 (1986).