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Photoreaction mechanism of ^{6}Li

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Photoreaction mechanisms of ^{6}Li were studied using bremsstrahlung below the $(\gamma,{}^{3}\mathrm{H})$ threshold. It was confirmed by the present work that only the $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}$ and $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}$ reactions actually occur in the energy range of incident γ ray lower than the $(\gamma,{}^{3}\mathrm{H})$ threshold, and the $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$ reaction in various types does not occur in practice although this reaction is energetically possible. The assignment of the reactions $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}$ and $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}$ to the measured photoproton spectrum for 15.4 MeV irradiation is presented.

NUCLEAR REACTIONS ^{6}Li, checked photoreaction mechanisms, bremsstrahlung E = 15.4 and 10.2 MeV, measured proton spectra, peak energies and widths, $\sigma(\theta)$, confirmed only $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}$ and $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}$ actually occur below the $^{6}\mathrm{Li}(\gamma,{}^{3}\mathrm{H})^{3}\mathrm{He}$ threshold.

In the photoreactions of the ^{6}Li nucleus by γ rays of energies lower than the $(\gamma,{}^{3}\mathrm{H})$ threshold, the following four types are allowed energetically: $^{6}\mathrm{Li}(\gamma,{}^{2}\mathrm{H})^{4}\mathrm{He}$, $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}$, $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}$, and $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$. These reaction types have been studied experimentally by many authors.[1-7] The $^{6}\mathrm{Li}(\gamma,{}^{2}\mathrm{H})^{4}\mathrm{He}$ type and a special type of the $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$ reaction,[3] among the four types mentioned above, seem to be eliminated experimentally.[1,3] However, the information about the remaining models seems yet to be not satisfactory, and therefore the detailed description of the reaction mechanisms toward the really acquired photoproton or photoneutron energy spectrum have not been fulfilled. This work was intended to clarify these situations experimentally. In the following, the remaining reaction mechanisms are related minutely. On the basis of the characteristic features of protons produced with each reaction mechanism in the measured energy spectrum, the analytical method is summarized and is described in the experimental frame in this work.

(1) $^{6}Li(\gamma,p)^{5}He(n)^{4}He$ *reaction*. In this reaction type, one proton outside the α core is first emitted from an excited state of the ^{6}Li nucleus and then the residual nucleus ^{5}He is resolved into an α particle and a neutron as shown in Fig. 1(a).

(2) $^{6}Li(\gamma,np)^{4}He$ *reaction*. This reaction mechanism is noticed as the free direct three body breakup that the proton, the neutron, and the α particle are emitted simultaneously without passing through any excited state of ^{6}Li as shown in Fig. 1(b).

(3) $^{6}Li(\gamma,np)^{4}He$ *reaction*[6]. In this reaction type the proton and neutron outside the α core are simultaneously emitted from the excited state 8.37 MeV of ^{6}Li, having equal energy and nearly the same direction as shown in Fig. 1(c).

(4) $^{6}Li(\gamma,n)^{5}Li(p)^{4}He$ *reaction*. In this reaction mechanism, one neutron outside the α core is first emitted from an excited state of the ^{6}Li nucleus and then the residual nucleus ^{5}Li decays into an α particle and a proton as shown in Fig. 1(d). From now on the reactions $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}(n)^{4}\mathrm{He}$, $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$, $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$,[6] and $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}(p)^{4}\mathrm{He}$ are designated as reactions (1), (2), (3), and (4), respectively. According to the considerations of energy-momentum conservation and the kinematic calculation in each reaction model, we can roughly divide into two points at issue in the analytical method as follows: (i) The reactions (1) and (2) mainly contribute to the range of proton energy $K \gtrsim 3$ MeV in the proton spectrum. One can distinguish experimentally between reactions (1) and (2) by measuring the energy and angular distributions of the protons for the following reasons: With reaction (1) the resonance peaks for the energy levels of the ^{6}Li nucleus must appear in the range of proton energy $0 \leq K \leq (\frac{5}{6})\ (K'_{j\,\max} - 4.655)$ MeV, where $K'_{j\,\max}$ is the maximum energy of bremsstrahlung. Further, for each peak the angu-

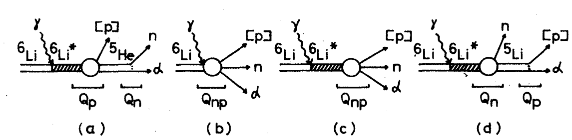

FIG. 1. Feynman diagram of each reaction type. The symbol p in the brackets in each diagram indicates a proton being measured if such a reaction mechanism exists. (a) $^{6}\mathrm{Li}(\gamma,p)^{5}\mathrm{He}(n)^{4}\mathrm{He}$, $Q_p = -4.655$ MeV, $Q_n = 0.958$ MeV. (b) $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}$, $Q_{np} = -3.697$ MeV. (c) $^{6}\mathrm{Li}(\gamma,np)^{4}\mathrm{He}^{6}$, $Q_{np} = -3.697$ MeV. (d) $^{6}\mathrm{Li}(\gamma,n)^{5}\mathrm{Li}(p)^{4}\mathrm{He}$, $Q_n = -5.662$ MeV, $Q_p = 1.965$ MeV.

lar distribution is expressed by the Legendre polynomial expansion as $A(\theta)=\sum_n a_n P_n(\cos\theta)$, and the values of peak energy and its half-width are independent of the maximum bremsstrahlung energies used. On the other hand, with reaction (2) no structure ought to be observed in the proton or neutron spectrum and the angular distribution of the protons should have an isotropic form for statistical reasons. Further, the range of proton energy distribution is given by $0 \leq K \leq (\frac{5}{6})\ (K'_{j\,\max} - 3.697)$ MeV and it is clear that only reaction (2) can contribute to the energy range $(\frac{5}{6})\ (K'_{j\,\max} - 4.655) \leq K \leq (\frac{5}{6})\ (K'_{j\,\max} - 3.697)$ MeV in the proton spectrum for $K'_{j\,\max}$ MeV irradiation. (ii) The reactions which contribute mainly to the range $K \lesssim 3$ MeV of the proton spectrum are the reactions (1), (3), and (4). Since the width of the energy distribution of the proton group produced by reaction (4) depends on the bremsstrahlung maximum energy because of the recoil velocities of ^{5}Li, we have investigated this fact quantitatively. The spectrum of decay protons from the ground state of recoiling residual ^{5}Li is represented by

$$S(K)=\sum_j N_j(K'_j)A_j f_j(K,K'_j)dK\,,$$

with the normalization factor

$$A_j=\left(\int_{K_{j\,\min}}^{K_{j\,\max}} f_j(K,K'_j)dK\right)^{-1}$$

and the weight function $N_j(K'_j) \propto \sigma_{\gamma n}(K'_j)$, where K'_j, $f_j(K,K'_j)$, and $\sigma_{\gamma n}(K'_j)$ are the available incident γ-ray energies corresponding to each rank j, the energy distribution function of decay protons (unknown) in L system, and the cross section for this reaction as a function of γ-ray energy, respectively. The upper and lower limits of the energy distribution width are given by the kinematic calculation assuming $0° \leq \theta_{\text{c.m.}} \leq 180°$, where $\theta_{\text{c.m.}}$ is the angle, in C system, of the emitted proton with respect to the recoiling direction of ^{5}Li,

$$K_{j\,\substack{\max\\ \min}}=(\tfrac{1}{2})m_p\left\{\left[\frac{2m_\alpha}{m_p(m_p+m_\alpha)}[Q_p\pm(\tfrac{1}{2})\Gamma]\right]^{1/2} \pm\left[\frac{2m_n}{m_l(m_l+m_n)}(K'_j+Q_n)\right]^{1/2}\right\}^2$$
$$=0.503\,91(1.764\,97\pm 0.258\,53\sqrt{K'_j-5.662})^2\,\text{MeV},$$

where using $m_n=1.008\,665\,2$, $m_l=5.012\,538\,1$, $m_p=1.007\,825\,2$, $m_\alpha=4.002\,603\,1$ (u), $Q_n=-5.662$, and $Q_p=1.965$ (MeV), and the ground state width of ^{5}Li $\Gamma=0$ was assumed. The numerical calculations of $S(K)$ were performed in the following typical three cases about $N_j(K'_j)$, assuming that all the photoneutron production cross-sections cited here, below the $(\gamma,{}^3\text{H})$ threshold, depend only on the neutrons arising from this reaction type [see Fig. 4(b) as an example]:

(i) $N_j(K'_j) \propto \sigma_{\gamma n}(K'_j)$ in Ref. 2, $f_j(K,K'_j)=f_{xj}, f_{yj}, f_{zj}$,
(ii) $N_j(K'_j) \propto \sigma_{\gamma n}(K'_j)$ in Ref. 4, $f_j(K,K'_j)=f_{xj}, f_{yj}, f_{zj}$,
(iii) $N_j(K'_j) \propto \sigma_{\gamma n}(K'_j)$ in Ref. 8, $f_j(K,K'_j)=f_{xj}, f_{yj}, f_{zj}$,

where

$$f_{xj}=(K_{j\,\max}-K)(K-K_{j\,\min})\exp\{-(K_{j\,\max}-K)\times(K-K_{j\,\min})\},$$
$$f_{yj}=-(K-K_{j\,\max})(K-K_{j\,\min})\exp\{-(K-K_{j\,\max})\times(K-K_{j\,\min})\},$$
$$f_{zj}=(K-K_{j\,\max})^2\exp\{-(K-K_{j\,\max})^2/(K_{j\,\max}-M)^2\},$$
$$M=1.60\ \text{MeV}.$$

When $f_j(K,K'_j)$ is unknown, the rate of change of the spectral width can be used as a good tool to check the decay proton group. The rate of change of the spectral width is defined here by

$$av(W_{K'_{j\,\max 2}}/W_{K'_{j\,\max 1}})=(1/n)\sum_{i=1}^{n}(W_{K'_{j\,\max 2}}/W_{K'_{j\,\max 1}})_i\,,$$

where $(W_{K'_{j\,\max 2}}/W_{K'_{j\,\max 1}})_i$ is the value of the ratio for $(i/10)$-width between two interested spectra corresponding to two different maximum energies of bremsstrahlung: $K'_{j\,\max 1}$ and $K'_{j\,\max 2}$. In the above-mentioned three cases about $N_j(K'_j)$, the values of $av(W_{10.2}/W_{15.4})$ are represented in Table I. The observable value of ratio $av(W_{10.2}/W_{15.4})$ is noticed as the most striking feature of this reaction type. In this way, in regard to the important group in the range $K \lesssim 3$ MeV one can distinguish reaction (4) from reactions (1) and (3) by measuring the rate of change of the spectral width. Even if there is no change of spectral width one can distinguish reaction (3) from reaction (1) by

TABLE I. The calculated values of $av(W_{10.2}/W_{15.4})=(\frac{1}{9})\ \Sigma_{i=1}^{9}(W_{10.2}/W_{15.4})_i$. These were obtained from the calculated spectra in the cases of (i) $N_j \propto \sigma_{\gamma n}(K'_j)$ in Ref. 2, (ii) $N_j \propto \sigma_{\gamma n}(K'_j)$ in Ref. 4, and (iii) $N_j \propto \sigma_{\gamma n}(K'_j)$ in Ref. 8.

$S(K)$ \ $av(W_{10.2}/W_{15.4})$	(i)	(ii)	(iii)
$S_x(K)$ (f_{xj}: isotropic)	0.71	0.80	0.86
$S_y(K)$ (f_{yj}: Gaussian)	0.79	0.81	0.88
$S_z(K)$ (f_{zj}: Poisson)	0.80	0.80	0.87

comparing the proton and neutron spectra, because by reaction (3) the important peak corresponding to the interested proton group must appear in the lower energy fraction (8.37 MeV) of the neutron excitation spectrum, while reaction (1) is entirely independent of neutron spectral form. On the basis of the above-described circumstances, it was concluded that the following two experiments were necessary and sufficient for the purposes of this work, i.e., (i) bremsstrahlung: $K'_{j\,\max} = 15.4$ MeV; particle to be detected: proton; proton detector: nuclear emulsion; measurement: energy spectrum and angular distribution (from 0° to 180°), and (ii) bremsstrahlung: $K'_{j\,\max} = 10.2$ MeV; particle to be detected: proton; proton detector: nuclear emulsion; measurement: energy spectrum.

The present experiments were performed with the betatron at the Tokyo Institute of Technology. The emulsions were 100 μm thick SAKURA NR-M1 photographic plates (Ilford C2 equivalent). The bremsstrahlung beam passed through a lead collimator and an evacuated aluminum reaction chamber 28 cm in diameter and then reached the Victoreen r meter. The target foil was fixed at 45° with respect to the incident γ ray. The photographic plates were arranged around the target radially. The distance from the center of the target to the centers of the plates was 10 cm. The glancing angle of the plates was 10°. For the 15.4 MeV irradiation, the proton spectrum from the 99% enriched ^{6}Li target of 5.60 mg/cm^2 was measured at 15°, 45°, 60°, 90°, 120°, 150°, and 165°. For the 10.2 MeV irradiation the spectrum was measured at 30°, 60°, and 90°. The overall background effect was found to be negligible on the runs without target and with a 1 mm thick polyethylene target in order to check the effects of carbon and hydrogen in the ^{6}Li target. The energy resolution of the emulsion used was found to be 200 keV in the range 2 MeV $\leq K \leq$ 8 MeV on the run of ^{27}Al$(p,p)^{27}$Al.

Taking into account the energy resolution of the emulsion used and the effect of neighboring energy intervals of incident γ rays, the proton yield at the energy interval i was smoothed out twice as $N_i = (\frac{1}{4})(N'_{i-1} + 2N'_i + N'_{i+1})$, where N'_{i-1}, N'_i, and N'_{i+1} were, respectively, the original proton yield at the $(i-1)$th, ith, and $(i+1)$th intervals, where the unit energy interval was 100 keV. The photoproton spectra of ^{6}Li thus obtained are represented in Figs. 2(a) and 2(b). The overlapped peaks were decomposed by the least squares method using the symmetric Gaussian curves and then the peak value and the half-width for each peak was determined in the usual way except for the cases concerning the important peak at 1.70 MeV. The in-

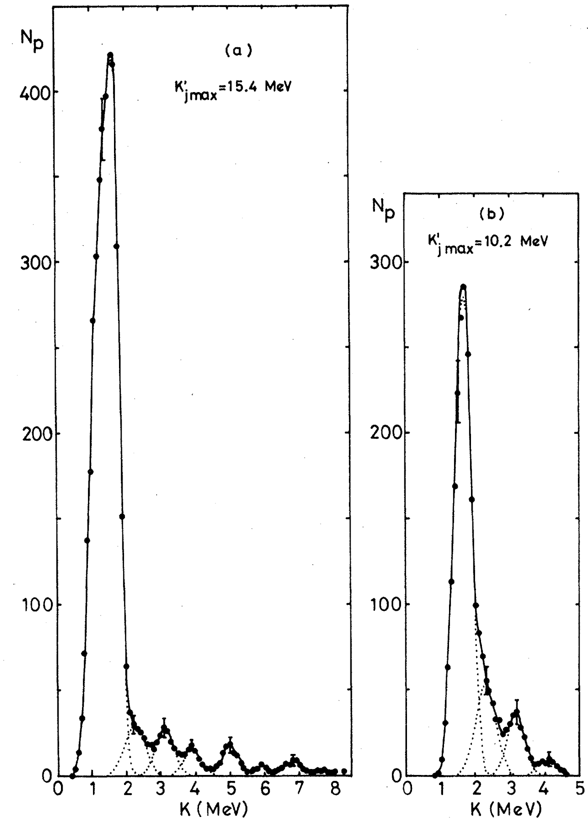

FIG. 2. Photoproton energy spectra of the ^{6}Li nucleus. The errors represent statistical errors.

dicated error of each peak value is the probable error and that of the half-width shows the uncertainty arising from the statistical error. In all cases concerning the 1.70± 0.10 MeV peak the spectral curves and their $(i/10)$-width $W_i = K_{\max i} - K_{\min i}$ were obtained within the uncertainty of ± 0.01 MeV by means of a graphical method since the forms of the spectral curves $S(K)$ are complicated. The peak energies of six peaks in the range of $K \gtrsim 2$ MeV for the 15.4 MeV irradiation were found to be 2.29± 0.19, 3.14± 0.18, 3.93± 0.18, 5.00± 0.17, 5.90± 0.13, and 6.80± 0.15 MeV. The angular distributions for all peaks are asymmetrical about 90°, as shown in Fig. 3. The half-width and peak energy for each of the first three peaks are independent of the bremsstrahlung maximum energy as shown in Table II. These facts are the characteristic features of reaction (1), but not that of reaction (2). Further, there exist no protons in the range 8.95 MeV $\leq K \leq$ 9.75 MeV of the proton spectrum for the 15.4 MeV irradiation and also no protons in the range 4.62 MeV $\leq K \leq$ 5.42 MeV for the 10.2 MeV irradiation. This is evidence for the nonexistence of reaction (2). The above-mentioned circumstances lead to the conclu-

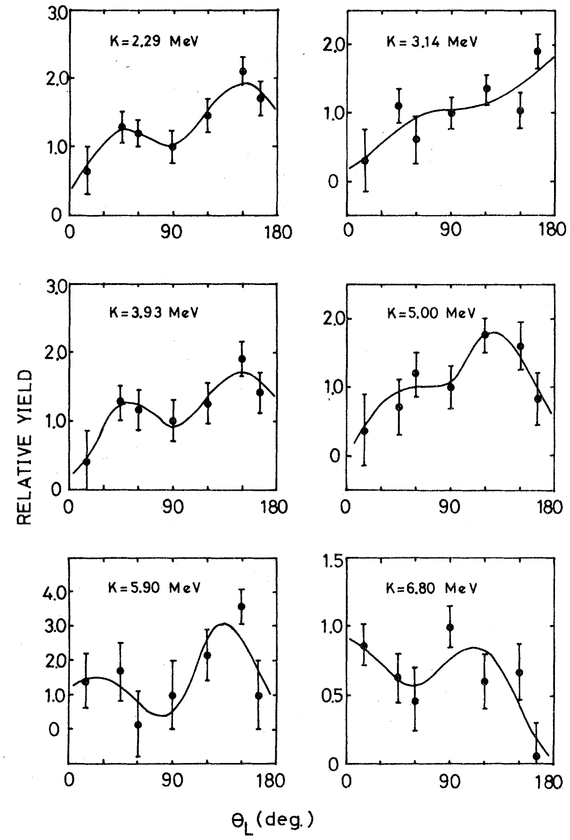

FIG. 3. Angular distributions for the proton groups in the 15.4 MeV irradiation. The errors represent $\pm[\sqrt{Y_p(\theta_L)}/Y_p(90°)]$ where $Y_p(\theta_L)$ is the proton yield for each group at θ_L. The solid curves are the least squares fit in terms of the Legendre polynomials up to order 4 for the groups of 2.29, 3.93, 5.00, and 5.90 MeV, and up to order 3 for the 3.14 and 6.80 MeV groups.

sion that reaction (2) did not occur in practice. Figure 4(a) shows the spectra of the 1.70± 0.10 MeV group corresponding to the 15.4 and 10.2 MeV irradiations normalized to 10 for the peak value. This important group did change in width between the 15.4 and 10.2 MeV irradiations, as $av(W_{10.2}/W_{15.4})=0.70\pm 0.02$. This value is in quantitative agreement with the calculated value of $S(K)=S_x(K)$, i.e., $f_j=f_{xj}$(isotropic form) : $N_j(K_j')\propto\sigma_{\gamma n}(K_j')$ in Ref. 2, in Table I. The comparison of Fig. 4(a) with Fig. 4(b) shows the measured spectrum is cut off above ~1.9 MeV. This suggests that the decay protons are emitted only in the backward hemisphere in the C system with respect to the recoiling direction of the ^{5}Li produced by reaction (4). If the decay protons from the broad first excited state[9] of recoiling residual ^{5}Li nucleus exist, a peak, which changes in width between the 15.4 and 10.2 MeV irradiations, should appear at $K\simeq 5.38$ MeV in both proton spectra. However, such a peak was not found in the present experiment. Further, the difference in shape between the present photoproton spectrum (Fig. 2) and the photoneutron spectrum of ^{6}Li of Ref. 2 is the characteristic feature of reaction (4), but not that of reaction (3). This difference, together with the angular distribution of the 1.70 group in Fig. 5, seems to be similar to that of the reaction $^{14}N(\gamma,n)^{13}N^*(p)^{12}C$ indicated in Figs. 9 and 11 of Ref. 10. The abovementioned facts mean that the important 1.70 MeV peak is produced only by reaction (4), and reaction (3) does not exist in practice. These circumstances lead to the idea that all the photoneutrons measured by Romanowski *et al.*[2] should be produced only by the reaction (4). This idea seems to be supported by the experimental results obtained by Green *et al.*[5] and Hayward *et al.*,[11] from the viewpoint that the photoneutron spectrum should have the resonance peaks corresponding to the levels of the ^{6}Li nucleus.

It is concluded that only the $^6Li(\gamma,p)^5He(n)^4He$ and $^6Li(\gamma,n)^5Li(p)^4He$ reactions actually occur in the energy range lower than the $(\gamma,{}^3H)$ threshold, and the energetically possible $^6Li(\gamma,np)^4He$ reactions of various types do not exist in practice. In the proton spectrum for the 15.4 MeV irradiation, the 1.70± 0.10 MeV group consists of the decay protons emitted from the ground state of the recoiling residual ^{5}Li produced by the reaction $^6Li(\gamma,n)^5Li$. The peaks of 2.29± 0.19, 3.14± 0.18, 3.93± 0.18, 5.00± 0.17, 5.90± 0.13, and 6.80± 0.18 MeV induced by the reaction $^6Li(\gamma,p)^5He$ are the resonance peaks corresponding to the levels of the ^{6}Li nucleus.

The author wishes to express her wholehearted

TABLE II. The peak energy and half-width for each peak of the first three peaks in the range $K\gtrsim 2$ MeV of observed proton spectra of ^{6}Li.

15.4 MeV irradiation		10.2 MeV irradiation	
peak energy (MeV)	half-width (MeV)	peak energy (MeV)	half-width (MeV)
2.29 ± 0.19	0.691 ± 0.066	2.30 ± 0.20	0.693 ± 0.062
3.14 ± 0.18	0.606 ± 0.052	3.17 ± 0.17	0.601 ± 0.066
3.93 ± 0.18	0.605 ± 0.066	4.08 ± 0.16	0.600 ± 0.064

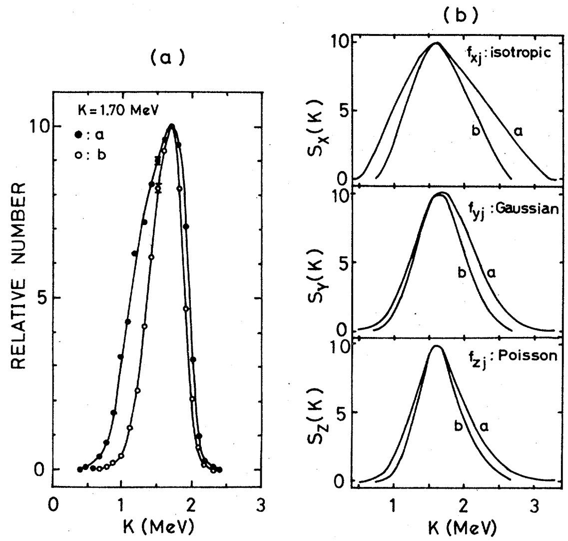

FIG. 4. The a and b correspond to the 15.4 and 10.2 MeV irradiations, respectively. (a) Normalized spectra of the 1.70 MeV group. The errors represent $\pm 10\sqrt{N_i}/N_{max}$, where N_i is the number of protons at the ith interval. (b) The calculated spectra $S(K)$ of decay protons from the ground state of the recoiling ^{5}Li produced by reaction (4), where $N_j(K_j') \propto \sigma_{\gamma n}(K_j')$ in Ref. 2 was used. The peak values of $S_x(K)$, $S_y(K)$, and $S_z(K)$ were normalized to 10.

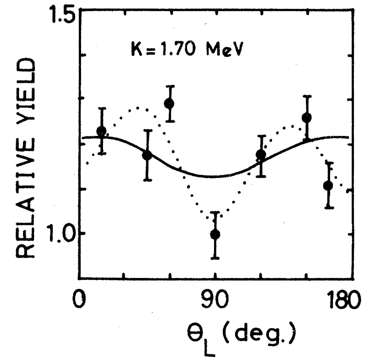

FIG. 5. Angular distribution for the 1.70 MeV proton group in the 15.4 MeV irradiation. The errors represent $\pm [\sqrt{Y_p(\theta_L)}/Y_p(90°)]$, where $Y_p(\theta_L)$ is the proton yield of this group at θ_L. The solid and dotted curves show the Legendre polynomial fits up to orders 2 and 4, respectively.

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