BRIEF REPORTS

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(γ,d) and (γ,t) reactions on ^{6}Li at intermediate photon energies

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The (γ,d) and (γ,t) reactions on ^{6}Li were studied at average (tagged) photon energies of 59 and 75 MeV. Differential cross sections were obtained at five different angles ($30° \leqslant \theta_{\mathrm{lab}} \leqslant 150°$), from which the integrated-over-angle cross sections for the d_0 and t_0 channels were determined. The experimental results are discussed in terms of a cluster model calculation. [S0556-2813(97)02602-2]

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The ground state of ^{6}Li is well known for its pronounced cluster structure, mainly composed of an α core and a deuteron. Several cluster models using an $\alpha+d$ or α-NN basis provide excellent descriptions of various properties of ^{6}Li. However, other cluster configurations such as ^{3}He t are, in principle, also present in this nucleus. Cluster knockout reactions are obviously very sensitive to details of this cluster structure and accordingly several types have been performed, among them real-photon induced ones. Already some time ago the ^{6}Li(γ,t) reaction was used to investigate the importance of the ^{3}He-t configuration in ^{6}Li [1–4]. In more modern work state-of-the-art cluster model calculations have been compared to recently obtained data, some of it with polarized beams [5–7]. None of these experiments has been performed with tagged photons, and there are large discrepancies between the different data sets, even from the same experiment. The ^{6}Li(γ,d) reaction has seen much less experimental effort, mainly because the transition to the ground state in ^{4}He is strongly inhibited by isospin selection rules. The usually dominant isovector transitions are here forbidden to all $T=0$ states in ^{4}He. Therefore, it is expected that strength will show up only above 21 MeV missing energy where the multiparticle breakup channels are open. In the only work with tagged photons up until now, the ^{6}Li(γ,d) reaction was studied by this collaboration [8] at photon energies around 60 MeV with deuterons detected at one single angle ($\theta_{\mathrm{lab}}=90°$). At this angle, the estimated upper limit for the cross section of the ^{6}Li(γ,d_0) reaction was 10 nb/sr [8].

In this paper we report on the results of the ^{6}Li$(\gamma$,d) and ^{6}Li(γ,t) reactions carried out at average tagged photon energies of 59 and 75 MeV. The experiments were carried out at the MAX-lab (Lund, Sweden) where a near-continuous electron beam for nuclear physics purposes is available. More details about this facility can be found in Refs. [9,10]. The energy settings of accelerator and tagging spectrometer correspond to two ranges of tagged photon energies as given in Table I. The energy bite covered by each individual focal plane counter is about 300 keV. The photon beam hit the ^{6}Li target at the center of the evacuated Gent Lund Universities Experiment (GLUE) reaction vessel [8,18]. Charged particles were detected in an array consisting of five telescopes placed at 30°, 60°, 90°, 120°, and 150° with respect to the photon beam. Each telescope consisted of a thin ($\approx$ 500 – 600 μm) passivated implanted planar silicon (PIPS) detector and a thicker ($\approx$ 10–20 mm) high purity germanium (HPGe) detector.[1] Typical values for the solid angle and the full width at half maximum angular acceptance covered by these telescopes are $\approx$ 55 msr and $\approx$16°, respectively. The detection thresholds for deuterons and tritons were about 15 and 17 MeV, respectively, mainly determined by the thickness of the ΔE counters. The ^{6}Li targets were obtained by rolling out Li metal (enriched to 94.9% in ^{6}Li) and sealing it by 8 μm aluminum foils. During different data

TABLE I. Relevant parameters of the Lund tagged photon facility.

Electron energy (Mev)	Current (nA)	Duty factor	Tagging efficiency	Tagged photon energies (MeV)	$\langle E_\gamma \rangle$ (MeV)
nom. 75	$\approx$20	$\approx$75%	20–26%	55.8–62.6	59
nom. 95	$\approx$20	$\approx$50%	20–30%	70.4–79.9	75

[1]Kindly made available by the VU Amsterdam (The Netherlands), Dr. W. Hesselink

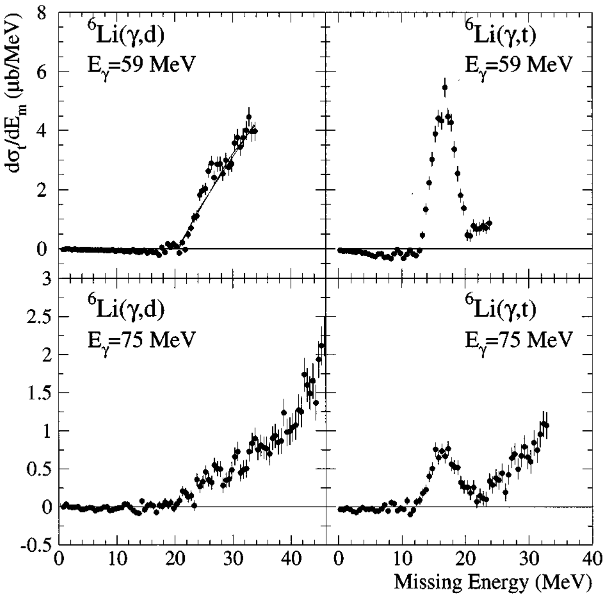

FIG. 1. Total energy differential cross section for the $^{6}\mathrm{Li}(\gamma,d)$ and $^{6}\mathrm{Li}(\gamma,t)$ reactions at $\langle E_{\gamma}\rangle$ = 59 and 75 MeV. The ground-state transitions correspond to a missing energy value of 1.475 and 15.769 MeV, respectively. The high-energy cutoff is determined by the detection threshold in the telescopes. The curve in the left top part of the figure corresponds to the estimate for the multiparticle breakup background as used in the analysis.

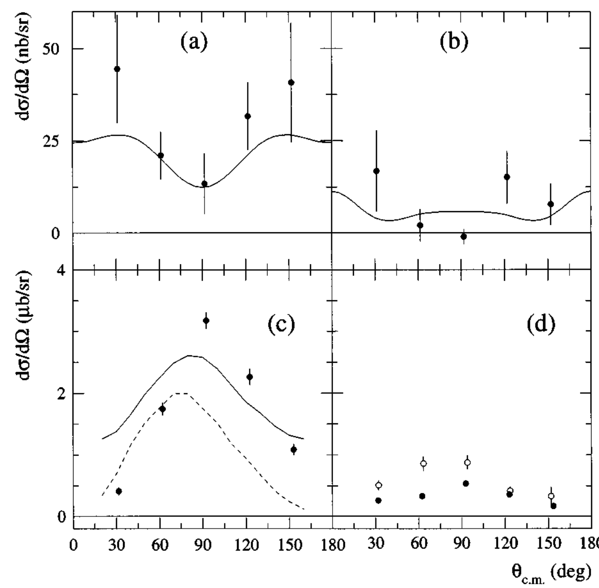

FIG. 2. Angular distributions for (a) the $^{6}\mathrm{Li}(\gamma,d_{0})$ reaction at $\langle E_{\gamma}\rangle$ = 59 MeV, (b) $^{6}\mathrm{Li}(\gamma,d_{0})$ at $\langle E_{\gamma}\rangle$ = 75 MeV, (c) $^{6}\mathrm{Li}(\gamma,t_{0})^{3}\mathrm{He}$ at $\langle E_{\gamma}\rangle$ = 59 MeV, (d) closed circles: $^{6}\mathrm{Li}(\gamma,t_{0})^{3}\mathrm{He}$ at $\langle E_{\gamma}\rangle = 75$ MeV; open circles: $^{6}\mathrm{Li}(\gamma,d_{T=1})$ at $\langle E_{\gamma}\rangle$ = 59 MeV. The lines in (a) and (b) are the predictions of a cluster model calculation [16]. These calculations were multiplied by a factor of 3 for a better comparison with data (see text). Full line in (c): α-d model (multiplied by 3); dashed line in (c): ^{3}He-t model (divided by 3) [7].

taking periods different target foils were used with thicknesses varying between 31.0 and 35.1 mg/cm^{2}. The final energy resolution in the missing energy spectra was predominantly determined by this energy loss. The missing energy spectra were obtained using our standard analysis procedure, details of which are described in [11,12]. The experimental cross sections were corrected for the dead time of the acquisition system and of the focal plane counters. The systematic uncertainty affecting these cross sections was evaluated to be approximately 13%. Moreover, the missing energy spectra were corrected for the energy loss in the target. Finally, total cross sections were obtained by fitting a Legendre polynomial expansion to the angular distributions.

In Fig. 1 the total energy differential cross section as a function of missing energy is presented for the $^{6}\mathrm{Li}(\gamma,d)$ reaction at $\langle E_{\gamma}\rangle$ = 59 and 75 MeV. From this picture it appears that the ground state of ^{4}He (at 1.475 MeV) is hardly or not populated while this state is strongly populated in, e.g., the $^{6}\mathrm{Li}(e,e'd)$ [13] reaction. This lack of strength in the $^{6}\mathrm{Li}(\gamma,d_{0})^{4}\mathrm{He}$ reaction is in accordance with the isospin selection rule, which forbids isovector transitions to the $T=0$ states in ^{4}He. However, closer examination of the spectra obtained at several angles revealed some strength located between 0 and 3 MeV missing energy, corresponding to the population of the ground state in ^{4}He. Figures 2(a) and 2(b) show the results for the angular distributions (where the error bars refer to the statistical uncertainty only). The distribution at $\langle E_{\gamma}\rangle$ = 59 MeV has a local minimum around $\theta_{\mathrm{c.m.}}$ = 90° and reaches a maximum at both forward and backward angles, resulting in a shape which is typical of predominantly $E2$ absorption. These features are less pronounced at $\langle E_{\gamma}\rangle$ = 75 MeV, perhaps due to the larger error bars on this very small cross section. A strictly similar pattern is observed in the $^{4}\mathrm{He}(d,\gamma)^{6}\mathrm{Li}$ capture reaction at center-of-mass energies of about 1.5 MeV [15], where cluster model calculations show a good overall agreement with the experiment. The angle-integrated cross sections are represented in Fig. 3. In Figs. 2 and 3 we also show the results of calculations by Burkova *et al.* [16], based on three-body α-np wave functions for the ^{6}Li ground state. The same model gave excellent agreement with experiment at lower energies [16]. Figure 3 shows that, as expected, the dominant contribution in this reaction stems from (isoscalar) $E2$ absorption. However, it is also clear that the model fails here in predicting the absolute cross section. The theoretical $E2$-absorption curve lies about a factor of 3 lower than the experimental results. Nonetheless the shape of the angular distribution is reasonably well described, certainly at $E_{\gamma}\approx 59$ MeV where the relative error bars are smaller. While this supports the picture of dominant $E2$ absorption, it gives little hints as to why the absolute values are predicted wrongly. The reason for this failure of the theory is unclear, since exactly the same model works well at low energies. Possibly, components in the wave function such as those due to tensor interactions, which were neglected here, play a larger role at intermediate energies than at lower energies. There the inclusion of a D-state component in the calculations enhanced the total cross section by only 5% [16]. In the missing energy region between 21 and 32 MeV (Fig. 1), there are another 11 $T=0$ states [17]. These states are not likely to be strongly populated either because of the isospin selection rule. Most of the strength observed above 21 MeV missing energy is thus due to the three-particle and multiparticle breakup of ^{6}Li [18]. However, a bump is observed in

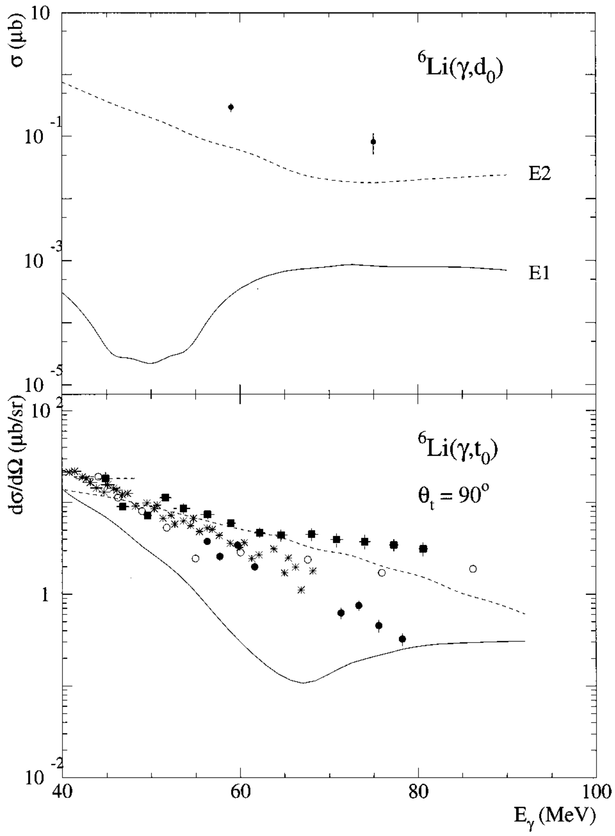

FIG. 3. Upper part: total cross section for the ^{6}Li(γ,d_0) reaction as a function of the photon energy. Data points: this work; full and dashed lines: predictions of a cluster model calculation for the $E1$ and $E2$ multipoles, respectively [16]. Lower part: differential cross section as a function of the photon energy for the ^{6}Li(γ,t_0) reaction at $\theta_{\rm lab}$ = 90°. Closed circles: this work; asterisks: Ref. [3]; full squares: Ref. [7] (electron data); open circles: Ref. [7] (photon data). Full line: α-NN model; dashed line: ^{3}He-t model [7].

the spectrum in the region around 25–29 MeV missing energy. This feature is clearly visible in Fig. 1 for the lower photon energy range and it also shows up in all the individual spectra for each detector angle. It appears superimposed on the continuum multiparticle breakup strength and possibly corresponds to the population of the four $T=1$ (2^-, 1^-, 0^-, 1^-) states in ^{4}He located between 24 and 28 MeV missing energy [17]. At higher photon energies it seems that this bump is less pronounced, although this may well be a consequence of the poorer statistics in this case. The population of these $T=1$ negative parity states implies the removal of two nucleons from different shells. Also in other reactions where the primary absorption occurs on two nucleons there are indications for such interactions with pairs of nucleons in different shells and their combination into the bound deuteron which is eventually detected, see, e.g., Ref. [14]. The angular distribution for the ^{6}Li(γ,d) reaction leading to these $T=1$ states is presented in Fig. 2(d) (open symbols) for $\langle E_\gamma \rangle$ = 59 MeV. The contribution from the multiparticle breakup modes was subtracted to obtain these cross sections. It was estimated as a smooth continuation of the high-energy part of the spectrum. It is clear that first, the magnitude of the cross section is much higher than that for the ground-state transition and second, that the angular distribution has a shape which is typical of $E1$ absorption. Both findings suggest that indeed the transitions to discrete (although unbound) $T=1$ states in ^{4}He may be responsible for this structure.

In Fig. 1 also missing energy cross sections for the ^{6}Li(γ,t) reaction at average photon energies of 59 and 75 MeV are presented. In this figure the ground-state transition, i.e., the two-body breakup $\gamma + {}^6\mathrm{Li} \rightarrow t + {}^3\mathrm{He}$, is clearly visible as a broad peak between 10 and 20 MeV missing energy. At $\langle E_\gamma \rangle$ = 75 MeV a rising trend is observed at missing energies above 21 MeV, due to the multiparticle breakup of ^{6}Li.

In Figs. 2(c) and 2(d) the angular distributions for the t_0 channel are shown. Both distributions are more or less symmetrically peaked around $\theta_{\rm c.m.}$ = 90°. Indeed, here there are no isospin selection rules at work which hinder isovector $E1$ absorption. The shape of the angular distribution is fairly well reproduced by cluster model calculations (full and dashed lines). In Fig. 3 the present results at $\theta_{\rm lab}$ = 90° are compared with those of Refs. [3,7]. As mentioned before the older data are not consistent among each other, even the two data sets of Ref. [7] are not compatible. Their (converted) electron data lie above all other data, particularly for photon energies higher than 60 MeV. On the other hand, their photon data appear to be more or less consistent with the results of this work and of Ref. [3] for photon energies up to 70 MeV. Above 70 MeV our results predict a much lower cross section than given by [7] but clearly represent a smooth continuation of our low-energy data and those of Ref. [3]. Again we can compare our data with the results of cluster model calculations. Just as in the case of the (γ,d) reaction we will make the comparison with the calculations of Burkova *et al.* [7]. For this reaction they used two different approaches to describe the ^{6}Li ground state, once in terms of the α-d model which was used before, and once with a ^{3}He-t model. In the case of the α-d model, the ^{3}He and the triton would appear as a result of a photoabsorption process on the α core with a rearrangement of particles in the final state. For photon energies lower than 50 MeV, both approaches describe quite well the triton strength at $\theta_{\rm lab}$ =90° and yield very similar results. At the higher photon energies covered in the present experiment the α-d and the ^{3}He-t models give very different results, neither of them being in good agreement with the data. The reason for the very different behavior of both models seems to be the fact that in the α-d model the usually dominant $E1$ multipole (at 90°) goes through a deep minimum between 60 and 70 MeV, while this is not so in the ^{3}He-t model. It is interesting to point out that the presence of this minimum was essential to describe the polarized photon data for the (γ,t) reaction [7]. The present data, however, indicate that the effect of this minimum in the 90° (γ,t) cross section is overestimated. As to the shape of the angular distributions, this is reasonably well described by both model approaches [Fig. 2(c)], although the experiment favors a somewhat sharper angular peaking than is predicted by the model.

In this work we reported on the first results for the ^{6}Li (γ,d) and ^{6}Li(γ,t) reactions at photon energies above 40 MeV obtained with tagged photons. The shape of the angular distributions is for both reactions more or less in agreement with the predictions of cluster model calculations, but the absolute values are typically a factor of three off. Interestingly, the same calculations are in good agreement [6,7,16] with other data at photon energies lower than the energy region covered in this work. The failure of such calculations when applied to the intermediate photon energy region may indicate that new ingredients like meson exchange currents and tensor forces should be included in the calculations. Especially in the case of the (γ,t) reaction it is clear that a calculation which includes both α-d and ^{3}He-t components in a consistent way is needed and might well give a good description of all data in this energy range.

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