THE REACTIONS ^{6}Li(γ, d) AND ^{7}Li(γ, t) BELOW 4 MeV*†

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In the present experiment the reactions ^{6}Li(γ, d) and ^{7}Li(γ, t) were investigated with bremsstrahlung from a linear accelerator by detecting the charged reaction products in coincidence with solid-state surface barrier detectors.||

Earlier experiments with monochromatic γ-rays (Glenn 1952; Titterton and Brinkley 1952; Jensen and Gis 1953; Däublin, Bertholt, and Jensen 1959) have shown the reaction ^{6}Li(γ, d) below 4 MeV to be extremely weak. The reaction ^{7}Li(γ, t) below 4 MeV has not been investigated previously. It is likely to be extremely weak too, as there are no known levels in ^{7}Li between 4 MeV and the reaction threshold (Ajzenberg-Selove and Lauritsen 1959). Assuming an "alpha+triton" model of the ^{7}Li nucleus, Czyż (1955) predicted on theoretical grounds a resonance peak of order $3 \cdot 5 \times 10^{-27}$ cm^2 near the reaction threshold. However, in a more complete report of his investigation (Czyż 1956), the applicability of this model for the energy region below 4 MeV was questioned. Using a Breit–Wigner formula (Peaslee 1952) we have calculated the cross section of ^{7}Li(γ, t) below 4 MeV. We have assumed that this reaction takes place via the known states at $0 \cdot 478$ and $4 \cdot 63$ MeV. The partial radiative width of the $4 \cdot 63$ MeV level was estimated from known ^{7}Li(γ, t) cross-section data of Erdös *et al.* (1954). Other parameters were taken from the compilation of Ajzenberg-Selove and Lauritsen (1959). We estimate on the basis of this calculation that the cross section of ^{7}Li(γ, t) below 4 MeV is $\sim 5 \times 10^{-31}$ cm^2.

The purpose of the present experiments was to confirm with bremsstrahlung the extreme weakness of the ^{6}Li(γ, d) and ^{7}Li(γ, t) reactions below 4 MeV. The investigation of ^{7}Li(γ, t) is of particular interest also for the following reason. E_Q, the energy at which photodisintegration becomes possible energetically, is usually slightly less, by an amount ΔE, than E_1, the energy of the first virtual state, i.e. the energy of the first level above E_Q. In general ΔE is some tens of keV or less. It is of interest to know whether photodisintegration cross sections occur at E_Q, E_1, or some intermediate value. Such knowledge is required, for example, for the precision calibration of the energy scale of accelerators by measurement of empirical photonuclear thresholds.¶ ^{7}Li is unique inasmuch as here ΔE has the anomalously large value of $2 \cdot 1$ MeV. The photodisintegration becomes possible via ^{7}Li(γ, t) at $E_Q = 2 \cdot 47$ MeV, whereas the first virtual state occurs at $E_1 = 4 \cdot 63$ MeV (Ajzenberg-Selove and Lauritsen 1959). Thus the investigation of ^{7}Li(γ, t) below $4 \cdot 1$ MeV can decide unambiguously whether a photonuclear reaction can occur below the first virtual state.

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|| A detailed account of these experiments is given by Lam (1964).

¶ Such calibrations naturally presume that, within experimental accuracy, cross sections have a reasonably sharp "cut-off" point.

The same experimental arrangement was used for the investigation of ^{6}Li(γ, d) and ^{7}Li(γ, t), and it is shown diagrammatically in Figure 1. A linear accelerator (Linac) produced 4 MeV bremsstrahlung. The output of this machine is about 120 r/min at 1 m, and its beam is pulsed, giving 500 two-microsecond pulses per second. The γ-beam first passed through a 3·5 cm aluminium absorber to relatively enhance the high energy end of the bremsstrahlung spectrum. It then passed through two calibrated transmission ionization chambers, one to measure the instantaneous dose rate and one to measure the integrated dose, and, via an aligned $0\cdot8\times0\cdot3$ cm aperture in a 20 cm lead collimator, entered the brass target chamber, which had

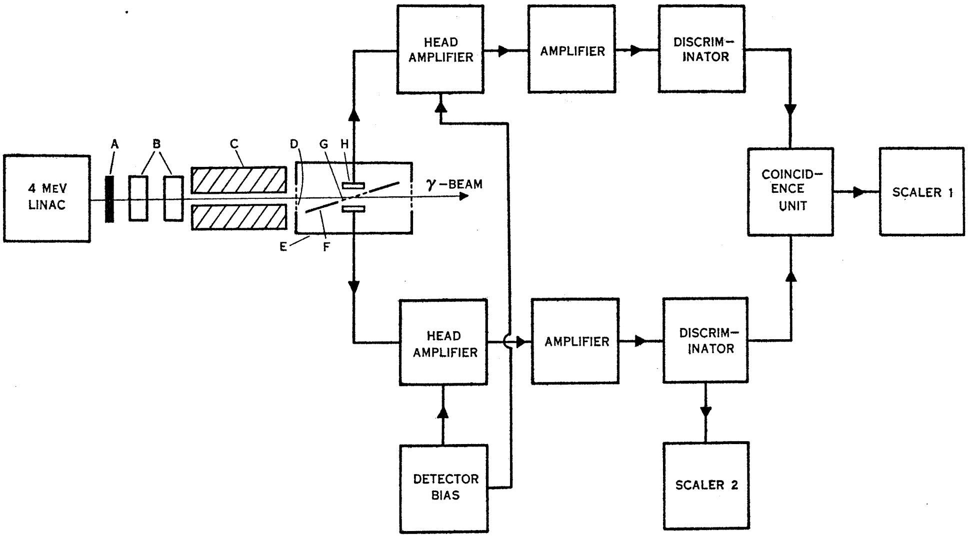

Fig. 1.—Diagrammatic experimental arrangement for the investigation of ^{6}Li(γ, d) and ^{7}Li(γ, t). A, aluminium absorber; B, transmission ionization chambers; C, lead collimator; D, Perspex window; E, target chamber (evacuated to 0·1 torr); F, target support; G, target film; H, solid-state detector.

0·16 cm Perspex entrance and exit windows. The target consisted of lithium hydroxide films supported by thin carbon backings; for ^{6}Li(γ, d), 190 μg/cm^2 of lithium enriched to 95·6% in ^{6}Li on 20 μg/cm^2 of carbon; for ^{7}Li(γ, t), 370 μg/cm^2 of natural lithium supported by 40 μg/cm^2 of carbon. Target films were held at 15° to the beam axis by stainless steel frames with 1·9 cm central openings. This method of support ensured that the direct γ-beam traversed the lithium hydroxide–carbon film without striking the supporting frame or the detectors, which were mounted as close as possible to the γ-irradiated part of the targets. Great care was taken in the design of the chamber target geometry to prevent photo electrons and Compton electrons from hitting the detector surfaces. The two detectors were conventional solid-state surface barrier detectors made from 1000 ohm-cm silicon with 100 μg/cm^2 gold "windows" of 0·52 and 0·40 cm diameter respectively, possessing a resolution of better than 100 keV to 5 MeV α-particles. The detector bias was kept so low that the thickness of the sensitive depletion layer was only slightly greater than the range of the most energetic deuterons to be detected. As the charged reaction products from $^6Li(\gamma, d)$ and $^7Li(\gamma, t)$, i.e. α-particles, deuterons, and tritons, have much smaller ranges than electrons at corresponding energies, "electron pile-up" pulses were only relatively small. By severely differentiating in the head amplifiers it was possible to reduce the rate of pile-up pulses entering the main amplifier to a tolerable non-coincident count rate. The electronic arrangement used was conventional (see Fig. 1). Coincident signals were to be recorded by scaler 1, and non-coincident signals by scaler 2. The count rate of scaler 2 thus permitted calculation of the random coincidence rate to be expected.

Each target was irradiated with 50 000 r during continuous 9 hr runs. No coincidences were recorded.* The random coincidence count rate to be expected was $0 \cdot 05$ counts per 9 hr. Before and after each run the complete counting system was tested by applying appropriate coincident test pulses from a pulse generator to the head amplifiers and, in its non-coincident mode, by bringing an α-source close to the detectors. Upper limits for the weighted average reaction cross section between E_Q and $4 \cdot 1$ MeV were calculated. In this calculation, account was taken of the exact

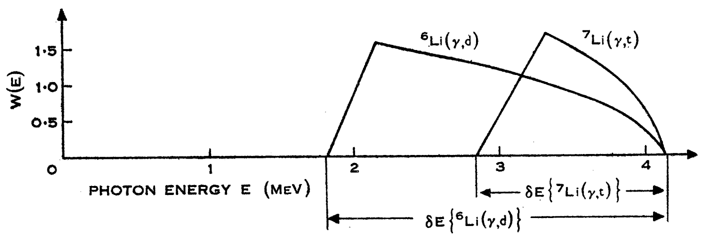

Fig. 2.—Weighting functions employed in the calculation of upper limits of the average reaction cross sections $\bar{\sigma}$, where

$$\bar{\sigma} = \frac{1}{\delta E} \int_{4\cdot 1\ \mathrm{MeV}-\delta E}^{4\cdot 1\ \mathrm{MeV}} W(E)\sigma(E)\,\mathrm{d}E.$$

detector–target geometry. Allowance was made for energy losses of the charged particles in the target films and in the solid-state detectors. The bremsstrahlung spectrum used was calculated with a Schiff formula modified at the high energy end to the corrected Sauter–Fano value (Fano, Koch, and Motz 1958). Attenuation in the ionization chambers and the aluminium filter was allowed for.

The weighting functions that were used in calculating an upper limit for the weighted average cross sections are shown in Figure 2. They take account of the spectral distribution of the photons at the target and the losses in the finite-size targets and detectors, and may be interpreted as hypothetical photon spectra in ideal equivalent experiments with infinitesimal targets and ideal detectors. The calculated weighted average cross-section values are: for $^6Li(\gamma, d)$

$$\bar{\sigma}\{^6\mathrm{Li}(\gamma, \mathrm{d})\} < (6 \cdot 70 \pm 1 \cdot 00) \times 10^{-31}\ \mathrm{cm}^2,$$

* This does not preclude that the only reaction competing below $4 \cdot 1$ MeV, namely $^6Li(\gamma, np)\alpha$, has an appreciable cross section in this region. E_Q for this reaction occurs at $3 \cdot 70$ MeV, but even for $4 \cdot 1$ MeV photons corresponding p–α pairs have insufficient energies to be recorded in coincidence in the present experiment.

and for ^{7}Li(γ, t)

$$\bar{\sigma}\{^7\text{Li}(\gamma, \text{t})\} < (1\cdot 55 \pm 0\cdot 20) \times 10^{-30}\ \text{cm}^2.$$

Errors indicated are estimated systematic errors. The $<$ sign implies here that there was a 65% probability that actual weighted average cross sections are smaller than the stated values.

The result for ^{6}Li(γ, d) confirms the extreme weakness of this reaction below 4·1 MeV, as was found previously with some monochromatic γ-rays by Glenn (1952), Titterton and Brinkley (1952), Jensen and Gis (1953), and Däublin, Bertholt, and Jensen (1959). It is in agreement with the theoretical calculation of Vashakidze and Chilashvili (1954).

The result for ^{7}Li(γ, t) shows that an empirical photonuclear threshold need not coincide with the energy at which the corresponding reaction becomes energetically possible. The observed extreme weakness of the reaction ^{7}Li(γ, t) below 4·1 MeV is in agreement with a theoretical estimate reported in the present paper. It does not confirm the existence of a resonance peak near E_Q, as was predicted, with reservations, by a calculation of Czyż (1955, 1956).

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References

Ajzenberg-Selove, F., and Lauritsen, T. (1959).—*Nucl. Phys.* **11**: 1.
Czyż, W. (1955).—*Nuovo Cim.* **2**: 320.
Czyż, W. (1956).—*Acta Phys. Pol.* **15**: 129.
Däublin, F., Bertholt, F., and Jensen, P. (1959).—*Z. Naturf.* **14a**: 208.
Erdös, P., Stoll, P., Wächter, W., and Wataghin, V. (1954).—*Nuovo Cim.* **12**: 639.
Fano, U., Koch, H. W., and Motz, J. W. (1958).—*Phys. Rev.* **112**: 1679.
Glenn, H. B. (1952).—*Phys. Rev.* **88**: 418.
Jensen, P., and Gis, K. (1953).—*Z. Naturf.* **8a**: 137.
Lam, K. S. (1964).—M.Sc. Thesis, University of Western Australia.
Peaslee, D. C. (1952).—*Phys. Rev.* **88**: 812.
Titterton, E. W., and Brinkley, T. A. (1952).—*Proc. Phys. Soc.* A **65**: 1052.
Vashakidze, I. Sh., and Chilashvili, G. A. (1954).—*Zh. Eksper. Teor. Fiz.* **26**: 254.