peratures. We have also noted that in the superconducting state deviations from the AR theory appear as the ultrasonic frequency is increased. Finally, it must be emphasized that, as yet, the agreement between the AR theory and the ultrasonic results, at low frequencies, in the superconducting state is purely empirical.

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PHOTONEUTRON CROSS SECTIONS OF Li^6†

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(Received 24 September 1965)

The photoneutron cross sections of Li^6 were measured as a function of photon energy from 5.7 to 32 MeV, using the monoenergetic photon beam achieved by the annihilation in flight of fast positrons from the Livermore electron linear accelerator.[1]

The photon beam was allowed to strike the Li^6 sample in the center of a 4π neutron detector, which consists of a two-foot cube of paraffin in which are embedded 48 BF_3 tubes arranged in four concentric rings of 12 tubes each. Each ring is monitored independently, and the detector is gated on for 300 μsec by the beam burst. The neutron multiplicities are counted during each gate interval as well, enabling one to measure the (γ,n) and $(\gamma,2n)$ cross sections simultaneously. The total neutron-detection efficiency is well known in the energy region of interest and averages 0.39. Also, since the relative counting efficiencies of the four rings vary with neutron energy, a rough value for the average neutron energy can be determined for each photon energy.[2]

Several 95% pure Li^6 samples ranging in size from 8 to 64 moles were used during the course of the experiment. The absorption of neutrons by the Li^6 samples themselves was measured in two different ways. First, a $\frac{1}{4}$-in.-thick lead sample was sandwiched between two Li^6 samples, and the absorption of photoneutrons from the (γ,n) process on lead was measured at several photon energies. Second, a PuBe neutron calibration source was employed as the source of neutrons instead of the lead sample. Both measurements gave the same answer, either one resulting in a 6.2% correction to the data in the case of the 32-mole sample. The effect of the length of this Li^6 sample (8 in.) was accounted for by measuring the variation of detector efficiency with sample position, necessitating a 2% correction to the data. The attenuation of the photon beam in passing through this sample necessitated a 6.9% correction to the data, and varied negligibly with photon energy in the region of interest. Runs were performed on the empty thin-walled Lucite con-

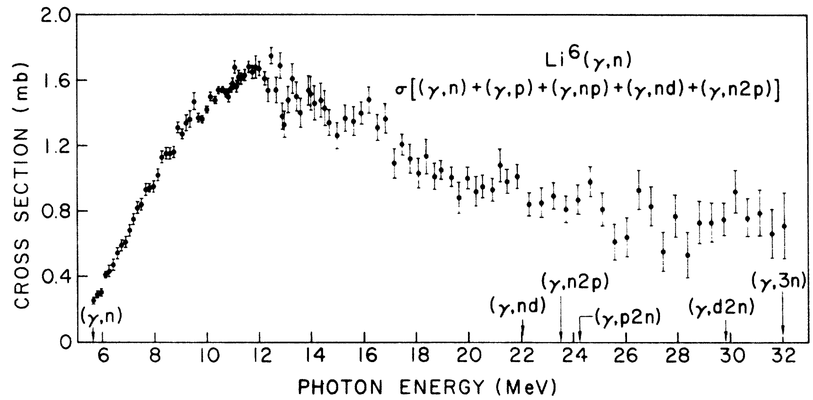

FIG. 1. Li^6 single-neutron-production cross section. This contains all partial cross sections except (a) those where all the emitted particles are charged, and (b) those where two or more neutrons are emitted. The errors given are statistical only.

tainers at all photon energies. The resulting background subtraction was negligible for photon energies below 12 MeV, rose to $\simeq 10\%$ by 19 MeV, and was $\simeq 20\%$ in the carbon giant-resonance region and above.

The Li^6 single-neutron-production cross section is shown in Fig. 1. This consists of the sum of the (γ,n), (γ,np), (γ,nd), $(\gamma,n2p)$, and also (γ,p) cross sections, since He^5 is unstable with respect to neutron emission. The thresholds for these processes are indicated in the figure. The $(\gamma,2n)$ contribution is not included, since it is very small (<0.1 mb) and uncertain [owing to the 5% contamination of Li^7 in the sample, which has a much larger $(\gamma,2n)$ cross section with a much lower threshold]. The photon energy resolution is less than 4% below 12 MeV; less than 3% from 12 to 19 MeV; and equal to about 460 keV above 19 MeV; these differences arise chiefly from the fact that positron-annihilation targets of different thicknesses were used for these regions. The absolute cross-section determination was made for the region from 11.7 to 21.4 MeV; the rest of the data were normalized to the cross section in this region (the region of overlap was 1 MeV for the low- and 2.5 MeV for the high-energy data).

The cross section has a resonance shape, rises from 0.25 mb at 5.7 MeV to 1.7 mb at 11.9 MeV, and then gently tails off to 0.7 mb at 32 MeV, with perhaps a few ripples at intermediate energies. The integrated cross section $\sigma_{\text{int}} = \int\sigma(E_\gamma)dE_\gamma$ from 5.55 to 32.05 MeV is 27.4 ± 2.0 MeV mb, which exhausts only about a third of the sum-rule prediction of the minimum total dipole strength (90 MeV mb for Li^6). Since the $(\gamma,d)He^4$ and $(\gamma,2d)H^2$ breakup modes are strongly inhibited or forbidden by isospin selection rules, and in fact have been measured to be very small,[3] the only important cross sections not measured here are $(\gamma,t)He^3$ and $(\gamma,pd)H^3$. In fact, these cross sections, especially the former, appear to be quite large.[4,5] Also, $\sigma_{-1} = \int\sigma(E_\gamma)E_\gamma^{-1}dE$ is 1.85 ± 0.10 mb, and $\sigma_{-2} = \int\sigma(E_\gamma)E_\gamma^{-2}dE$ is 0.15 ± 0.01 mb MeV^{-1} for the processes measured in this energy range. This σ_{-2} value is 3.4 times the sum-rule prediction of 0.044 mb MeV^{-1}.

There is some evidence for structure in the cross section, particularly at 10.5, 11.9, and 16.2 MeV, but it is clear that a better resolution experiment must be performed to study these and perhaps other peaks.

The average neutron energy obtained from the ratio of counting rates in the outer and inner rings of BF_3 counters is shown in Fig. 2 for photon energies up to 12.5 MeV. Also shown in the figure are several straight lines corresponding to the neutron energy expected as a function of photon energy for various reaction mechanisms. The data are ambiguous, owing to the three-body breakup for the direct (γ,np) process, but if one assumes that the average neutron energy in this process is equal to half the maximum energy possible, then (a) at $E_\gamma = 5.7$ MeV, $\sigma(\gamma,p) = 0.18$ mb and $\sigma(\gamma,np) = 0.07$ mb; and (b) at $E = 6.3$ MeV, $\sigma(\gamma,n)+\sigma(\gamma,p) = 0.18$ mb and $\sigma(\gamma,np) = 0.26$ mb, showing that $\sigma(\gamma,np)$ rises sharply in this region.[6] Second, if one

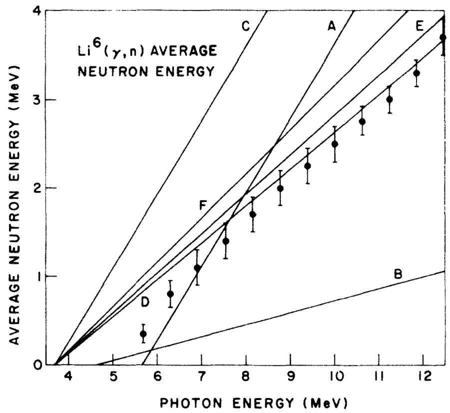

FIG. 2. Average neutron energy of photoneutrons from Li^6. The straight lines assume various reaction mechanisms, as follows: A, $Li^6(\gamma,n)Li^5 \rightarrow He^4+p$; B, $Li^6(\gamma,p)He^5 \rightarrow He^4+n$; C, $Li^6(\gamma,np)He^4$ and the neutron energy is the maximum possible; D, $Li^6(\gamma,np)He^4$ and the neutron energy is one-half the maximum possible; E, $Li^6(\gamma,np)He^4$ and the three omitted particles have equal center-of-mass momentum; F, $Li^6(\gamma,np)He^4$ and the neutron-proton pair are emitted back to back in the center-of-mass system (quasideuteron model).

assumes that $\sigma(\gamma,np)$ is negligible at $E_\gamma = 12$ MeV,[6] then the branching ratio at that energy is $\sigma(\gamma,n)/\sigma(\gamma,p) = 1.3$.[7]

Finally, it should be pointed out that the photoneutron cross sections reported here are markedly different in character from two previously published measurements,[6,8] both of which show a sharp valley at 19 MeV and then rise to one or more peaks comparable in magnitude with the 12-MeV peak before falling to small values. This has important theoretical implications, since it was thought that the high-energy peak corresponded to the photoexcitation of an α-particle core within the Li^6 nucleus, while the low-energy peak corresponded to photoemission of the "valence" neutron.

In view of this absence of a high-energy peak in the measured cross section and the large $(\gamma,t)He^3$ cross section, the authors would like to put forward the suggestion that there may be present in the ground state of Li^6 an appreciable mixing of a bound He^3-H^3 configuration. Other pieces of evidence consistent with this point of view follow.

Evidence from photonuclear processes. – (a) The general shape of the Li^6 cross section is very similar to that[9] for $He^3(\gamma,p)H^2$; it rises to its peak about 6 MeV above threshold, then tails off very gently, falling to one-half its peak value at $\simeq 12$ MeV above the peak. Since the $H^3(\gamma,n)H^2$ cross section should be similar to that for $He^3(\gamma,p)H^2$ (except for a threshold shift of 0.77 MeV),[10] one can say, on the basis of this model, that the Li^6 cross section should be the sum of the two; this agrees not only with the observed shape of the Li^6 cross section, but with its absolute magnitude as well [$\sigma_{max}(He^3(\gamma,p)H^2) = 0.9$ mb].

(b) If the He^4-H^2 model for Li^6 were correct, the peak in the cross section should be from 2 to 3 MeV above threshold and it is not, although there is evidence for some very weak structure at about 7.9 MeV. Moreover, one would expect to see an angular correlation of the neutron and proton from direct $Li^6(\gamma,np)He^4$ events at giant resonance energies, but no such correlation has been seen.[11]

(c) There is no enhancement of the neutron yield above the $Li^6(\gamma,nd)He^3$ threshold as one might expect if a deuteron already existed inside the nucleus; it would appear as a sharp rise above 22.04 MeV in the cross section measured here.

(d) The ratio $[\sigma_{int}(\gamma,nd)+\sigma_{int}(\gamma,pd)]/\sigma_{int}(\gamma,t)$ was measured to be 0.5 (from a deuteron-to-triton yield ratio of 0.25),[4] far lower than one would expect from a He^4-H^2 model.

(e) The large nuclear polarizability, as determined from the large value of σ_{-2}, could be accounted for by the highly polar nature of the He^3-H^3 system.

Other evidence. – (a) The rms charge radius of Li^6, from electron scattering, is about 2.80 F.[12] Using the recently measured charge radii for He^3 and H^3,[13] one can calculate the rms distance of either trinucleon cluster from the center of mass of the Li^6 nucleus to be equal to 2.13 F. Assuming a triplet S configuration for this deuteronlike two-fermion system, that the nucleon-nucleon force varies as the reciprocal of their distance apart, and that only forces between unlike nucleons are important (the like pairs, except in the trinucleon clusters themselves, are kept far apart by the Pauli principle), one can calculate the He^3-H^3 binding energy to be about 16.5 MeV, as compared with the experimental value of 15.78 MeV.

(b) The rms radius of Li^6 is larger than that of either Li^7 or C^{12}, a fact which is hard to explain if one assumes a He^4-n-p model for Li^6. In fact, this model gives a value for the Li^6 charge radius about 25% too low.[14]

(c) The magnetic dipole moment $\mu(Li^6)$ is $0.822\ \mu_N$.[15] This value is closer to $\mu(He^3)$

$+\mu(H^3)=0.851\ \mu_N$ than to $\mu(p)+\mu(n)=0.880\ \mu_N$. A calculation based on these values and analogous to that for the deuteron gives a small D-state admixture as expected (5.5%).

(d) The $Li^6(p,2p)He^5$ experiments yield a best fit to the data for an s-nucleon radius of[16] 1.93 F which is much larger than that of the α particle (1.61 F). Also, there is some evidence for protons with binding energy of about 10 to 14 MeV, between the s-nucleon and p-nucleon peaks (23 and 5 MeV, respectively),[17] compared with rough values of 11.8 and 12.1 MeV expected from the H^3 and He^3 clusters, respectively.

(e) The $Li^6(p,pd)He^4$ and $Li^6(p,p\alpha)H^2$ experiments at $E_p=155$ MeV give the probabilities for finding a deuteron and an alpha particle inside the Li^6 nucleus of only 31 and 20%, respectively, with an error of the order of 50%.[18] Moreover, a more recent $Li^6(p,pd)He^4$ experiment at lower energy ($E_p=30.5$ MeV) gives a deuteron-cluster probability of only 7.1%; and increasing this probability to 14.1% spoils the fit noticeably.[19] This latter evaluation, however, suffers from the possible breakdown of the impulse approximation at this lower energy.

Finally, it should be pointed out that it is difficult to reconcile either the results of this experiment or this interpretive suggestion with the structure seen in the inelastic electron scattering from Li^6.[20] It may be that some of this structure results from transitions of multipolarities other than $E1$ (particularly $E2$); and possibly the relatively larger cross section at higher energies results from a momentum-transfer-dependent effect.[21]

Thanks are due to Mr. R. J. Knox and Mr. M. A. Kelly for assistance in taking the data, and to the latter for discussions pertaining to all phases of the experiment. The authors also acknowledge the able assistance of the Linac operating staff.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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