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Excitation Function for Proton-Neutron Reaction in Lithium ($Li^7(p,n)$)*

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The excitation function of the (p,n) reaction in lithium ($Li^7(p,n)$) has been studied in the region from the threshold (1.85 Mev) to 3.20 Mev. Neutron groups have been found to be emitted at proton energies of 1.92, 2.28, and 3.06 Mev, suggesting the existence of energy levels in Be^8 at 19.8, 19.1, 18.8 Mev in addition to the other well-known states.

I. INTRODUCTION

REACTIONS of the (p,n) type in Li^7 were first observed by DuBridge, Barnes, and Buck[1] who showed that the excitation function possessed a definite threshold, and a rough measurement of it was made by using the radioactivity induced in silver foils by the neutrons. Since then the threshold was measured more accurately by detecting the neutron emission with a BF_3 ionization chamber.[2] The neutrons are copiously emitted from this source, and the apparent sharpness and easy reproducibility of the threshold has since been used in many laboratories as a convenient voltage calibration point. Furthermore the $Li^7(p,n)Be^7$ reaction provides a convenient source of fast neutrons, the maximum energy of which may be varied in a determinable manner by controlling the energy of the incident protons. The presence of resonance levels demonstrated here requires that this technique be used with some caution. These neutrons have been used to investigate the energy threshold of certain neutron-induced endoenergetic nuclear reactions.[3–5] In the work reported here, the yield of neutrons from thin films of lithium was measured as a function of energy of the bombarding protons. This investigation resulted in the discovery of two rather sharp maxima and possibly a third.

II. EXPERIMENTAL PROCEDURE

The Westinghouse pressure electrostatic generator[6] was used as a source of high energy protons. The magnetically deflected mass one (H^+) spot was used to avoid any possible deuterium contamination. A boron tri-fluoride ionization chamber surrounded by 12 cm of paraffin and placed in the direct line of the proton beam beyond the lithium target was used as the neutron detector[2] (Fig. 1). The output pulses from the ionization chamber were amplified and fed into a scale of 16 circuit that was

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* This work was completed in 1940 and was voluntarily withheld from publication.

[1] DuBridge, Barnes, and Buck, Phys. Rev. 51, 995 (1937).

[2] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. 58, 1035 (1940).

[3] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. 57, 1088(A) (1940).

[4] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. 58, 199(A) (1940).

[5] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. 59, 57 (1940).

[6] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. 58, 162 (1940).

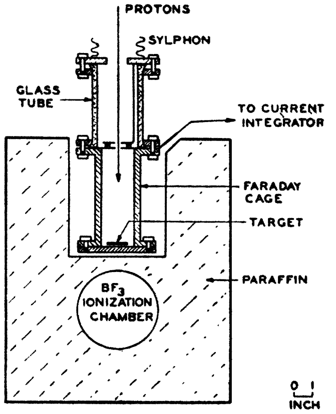

FIG. 1. Target arrangement.

used to drive a mechanical recorder. The neutron yield from a lithium target of about 140-kilovolts equivalent half-width was measured as a function of proton energy. The thin lithium targets were evaporated in vacuum onto a tantalum sheet which could be turned from evaporating position to a position under the proton beam. As a final cleaning measure, the tantalum sheet was bombarded by protons prior to the evaporation. Without the lithium film in the bombarding position no neutron background was observed. The equivalent thickness of the lithium films was observed by measuring the half-width of the $Li^7(p,\gamma)$ resonance which occurs for 440-kilovolt protons. The neutron excitation function obtained when the same lithium films were bombarded by protons of varying energy is plotted in Fig. 2.

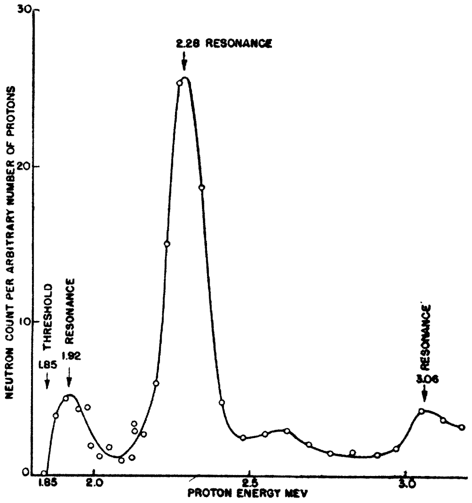

FIG. 2.

III. RESULTS

It is apparent from (Fig. 2) that the neutron emission from the $Li^7(p,n)$ reaction possesses definite maxima at proton energies of 1.92, 2.28 Mev and possibly another at 3.06 Mev. The calculated statistical deviation is not indicated, but at all points taken it is less than the diameters of the circles used in the drawings.

Using a thick LiH crystal as a target, it was found that the γ-ray intensity also started to increase at the (p,n) threshold and increases further with increasing proton energy. This agrees with the observations of Hudson, Herb, and Plain,[7] who also observed the increase in the hard component of γ-rays at the bombarding proton energy of 1.83 Mev. The intensity of γ-rays seems to flatten out and give a maximum at about 1.9 Mev.

The composite nucleus ${}_4Be^{8*}$ may be assumed to form first when a proton enters a ${}_3Li^7$ nucleus. This nucleus is highly excited since 17.5-Mev γ-ray is emitted for a bombarding proton energy of only 0.440 Mev. The excited ${}_4Be^{8*}$ nucleus, assuming it was formed with zero proton energy, may decompose in several ways as follows:

$$ {}_4Be^{8*} \rightarrow {}_2He^4 + {}_2He^4 + 17.28 \text{ Mev.} \tag{1} $$

$$ {}_4Be^{8*} \rightarrow {}_4Be^8 + \gamma + 17.5 \text{ Mev.} \tag{2} $$

$$ {}_4Be^{8*} \rightarrow {}_4Be^7 + {}_0n^1 - 1.62 \text{ Mev.} \tag{3} $$

$$ {}_4Be^{8*} \rightarrow {}_3Li^7 + {}_1H^1 + 0 \text{ Mev.} \tag{4} $$

$$ {}_4Be^{8*} \rightarrow {}_3Li^6 + {}_1H^2 - 4.96 \text{ Mev.} \tag{5} $$

Reactions (3) and (5) will not proceed unless the bombarding proton beam possesses enough kinetic energy to supply the necessary reaction energy. In this particular case $(Li^7(p,n))$, the proton energy should be about 8/7 of the reaction energy. In the range of proton energy used in this experiment, 1.85 to 3.2 Mev, all the reactions with the exception of reaction (5) have a probability of occurring. However, it is unlikely that the variation of neutron yield, as indicated in Fig. 2, is due to the result of competition of these various processes because the natural

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[7] Hudson, Herb, and Plain, Phys. Rev. 57, 587 (1940).

energy spread of the maxima is very small, as indicated by their half-widths, which are about the same order as the target thickness. It is possible that these maxima actually indicate resonance levels of certain nuclear mechanism. The neutrons are probably due to the excited energy levels in the composite ${}_4\mathrm{Be}^{8*}$ nucleus from which decomposition by emission of a neutron is highly possible. If this is the case, the energy levels of the ${}_4\mathrm{Be}^{8*}$ will have a value given by $17.5-(7/8)\times 0.440+(7/8)E$, where E is the bombarding proton energy at the neutron maxima. For the three maxima observed, these levels correspond to 18.8, 19.1, and 19.8 Mev, respectively. It should be noted that decomposition in other fashions is not impossible, since our quantitative detection only covered the emitted neutrons. Since the reaction energy Q of ${}_3\mathrm{Li}^7(p,n){}_4\mathrm{Be}^7$ is -1.62 Mev, the excess energies possessed by the Be^{8*} composite nucleus at the resonances are 0.06, 0.38, and 1.06 Mev, and will be distributed between the neutron and the residual nucleus ${}_3\mathrm{Be}^7$, as kinetic energy. Since the Be^7 nucleus has a much greater mass than the neutron, most of the energy will be carried away by the neutrons. In the forward direction of the laboratory coordinate system, the neutrons also carry a part of bombarding proton energy lost through the kinetic energy transfer during collision. The maximum energy of the neutrons in the forward direction in the laboratory system at these resonance levels is then 0.16, 0.58, and 1.4 Mev, respectively. It is probable that the excited nucleus ${}_4\mathrm{Be}^{8*}$ may at the same time also emit hard γ-rays which accounts for the experimental indication of Hudson, Herb, and Plain[7] (as well as ours), even though the (p,γ) process is, in general, not as significant as the (p,n) process.[8] It is interesting to note that, in the study of proton bombardment of thin beryllium targets, Hushley[9] also found a sharp resonance maximum after the threshold both for neutrons and γ-rays.

An alternative explanation may be made by assuming the existence of several excited states of the product nucleus ${}_4\mathrm{Be}^7$ from which it decays to the ground state by emitting γ-rays. The excess energy supplied by the proton above the threshold will be distributed among the neutrons and ${}_4\mathrm{Be}^7$ until the optimum energy is reached which corresponds to the excited levels of ${}_4\mathrm{Be}^{7*}$. At this point all the neutrons will assume zero energy (in the center of gravity system). According to the $1/v$ law, the BF_3 chamber should respond much more efficiently to these slow neutrons. The maxima, then, would not represent a real increase in neutrons, but would be characteristic of the method of detection. If this hypothesis were true, one would expect to be able to observe γ-rays associated with the excited states of Be^{7*}, and definite energy groups would be observable. Observations have not been made on this point. A careful study of the thin target (p,γ) excitation function and the neutron and γ-ray energy above the (p,n) threshold would be most interesting.

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[8] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947), p. 115.

[9] W. J. Hushley, Phys. Rev. **67**, 34 (1945).