IEEE Transactions on Nuclear Science, Vol. NS-26, No. 2, April 1979

THE ^{7}Li(P,N)^7 BE REACTION AS A SOURCE OF FAST NEUTRONS FOR SMALLER COMPACT CYCLOTRONS *

M. Anwar Chaudhri[1,2], J. Templer[2] and J.L. Rouse[2]

Abstract

The usefulness of the ^{7}Li(p,n)^{7}Be reaction as a fast neutron source for applications, such as neutron therapy etc., using smaller compact cyclotrons (proton energies of up to 15-18 MeV) has been investigated by measuring thin and thick target neutron spectra, absolute cross sections and angular distributions of various neutron groups produced in this reaction at 10.45 MeV. Our results indicate that the forward direction is still the preferred one for obtaining the most suitable fast neutron beam for biomedical application, and that moderately thick, rather than infinitely thick, target would provide higher mean energy. Moreover, it has also been shown that the ^{7}Li(p,n)^{7}Be reaction is more suited for producing neutron beams for therapy than proton and deuteron induced reactions on Be at corresponding energies, and that a therapeutically useful neutron beam can be produced even with smaller compact cyclotrons.

Introduction

It has been suggested by Chaudhri et al[1] that the ^{7}Li(p,n) reaction would be more suitable for cyclotron production of therapy neutrons than the commonly used ^{9}Be(d,n) reaction, especially for smaller cyclotrons which cannot product medically useful beams from a Be-target. They also pointed out that a "moderately-thick" target would produce higher mean neutron energies than an "infinitely-thick" target (stopping the incident beam completely). A number of measurements have since been carried out in various laboratories around the world on the neutron production from Li-targets, and comparing the output with other neutron producing reactions. However, these experiments are not fully conclusive regarding the possibility of using the ^{7}Li+p reaction for producing therapy neutrons, especially with smaller cyclotrons. Moreover, no systematic data is available on the possible effects of varying the target thickness and the angle of observation on the mean energy and intensity of neutrons from the ^{7}Li(p,n) reaction.

In order to investigate the usefulness of this reaction as a therapy neutron source, especially for smaller machines, and to examine the validity of empirical calculations of Chaudhri et al[1], we have carried out extensive studies of the ^{7}Li+p reactions at 10.5 MeV. For comparing Chaudhri et al's results with experimental data at higher energies we have made use of the published data, where available.

Experimental Details

These measurements have been carried out using the Melbourne University Cyclotron, whose easily accessible maximum proton energy was limited to around 10.5 MeV. A time-of-flight system[2] with a useful neutron energy range of 1-11MeV was used for neutron spectroscopy. Lithium targets of various thicknesses were prepared by cutting slides from 99% isotopically pure ^{7}Li metal, and pressing them to desired values. In this way thin, thick and moderately-thick targets of 20-90 mil thickness were obtained. The thickness of the targets was measured at several places over the surface with a micrometer and was uniform to ±0.2 mil in the central area hit by the beam. Neutron spectra were measured at different angles between 20-120°(lab.) from thin, thick and moderately-thick targets. From the thin target data, the absolute cross sections for various neutron groups were determined, while from thicker targets the neutron intensity and mean energies investigated.

Results and Discussion

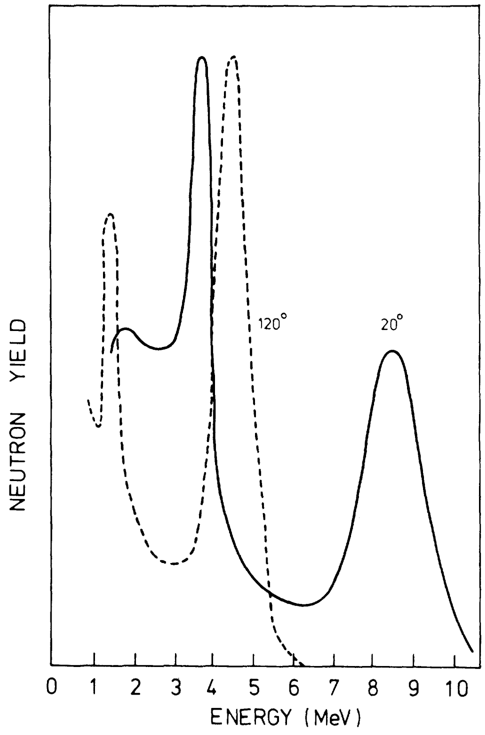

Fig. 1: Thin Target (3 mil) neutron spectra.

Thin target (3 mil) neutron spectra at 20° and 120° (lab.) are shown in Figure 1. The two main peaks in the spectra are due to neutrons going to the ground and first excited states (which being only 0.43 MeV apart, could not be separated), and to the second excited state at 4.55 MeV. The continuum of low energy neutrons is regarded to arise mainly from the multibody break-up reaction ^{7}Li(p, ^{3}He n)^{4}with a Q value of -3.23 MeV.

By taking the integrated area of the spectra obtained, and subtracting the n(0+1) and n(2) peak areas, it has been possible to estimate the multibody breakup cross section in the ^{7}Li+p reaction with an uncertainty of about ±15%.

---

[1] School of Physical Sciences, The Flinders University of South Australia, Bedford Park 5042, South Australia.

[2] School of Physics, University of Melbourne, Parkville 3052, Victoria, Australia.

* This work has been supported by a grant from the Colgate-Palmolive Pty. Ltd.

0018-9499/79/0400-2287$00.75©1979 IEEE

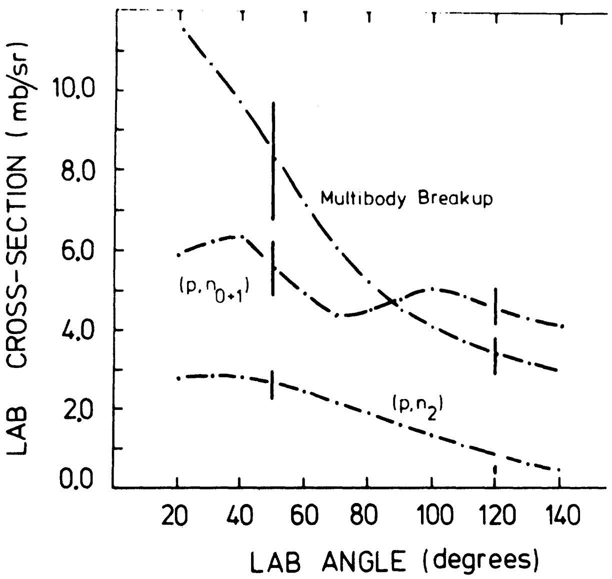

Fig. 2: Angular distributions for the ^{7}Li(p,n)^{7}Be and ^{7}Li(p, ^{3}He n)^{4}He reactions. Target thickness = 3 mil.

The angular distributions of various neutron groups are shown in Figure 2. The Legendre Polynomial fits to these distributions have been obtained, and total as well as 0° cross section values calculated and given in Table 1.

TABLE 1

Neutron Group	Integrated Cross Section (mb)	0° Cross Section mb/sr
n(0+1)	62.70	4.23
n(2)	17.03	2.48
Break-up	71	

Thick target neutron spectra at 20° and 120° are shown in Figure 3, and compared with the spectrum measured by Scott[3] using a magnesium bath. The agreement is good, especially when the fact that Scott's spectrum is averaged over all the angles is taken into account.

Forward direction (20°) neutron spectra from lithium targets of 40-90 mil thicknesses are shown in Figure 4. The average neutron energy of various spectra is indicated with the arrow and listed in Table II along with respective dose rates. Also given in the Table are the mean energy and dose rate from a thick Be target at corresponding deuteron energy of 5.25 MeV.

The improvement in the mean energy of neutrons ($\bar{E}n$) is clearly noticeable as the target thickness is varied from "infinitely" thick to moderately thick, though accompanied by a loss of total neutron intensity. Moreover, it can also be noticed that even from a thick Li-target the $\bar{E}n$ is almost twice that of neutrons produced by the ^{9}Be(d,n) reaction at the corresponding deuteron energy of 5.25 MeV (generally the modern compact cyclotrons produce protons of about twice the deuteron energy) calculated using the relation $\bar{E}n = 0.33$ Ed.[5] This effect on the improvement of $\bar{E}n$ would be even more pronounced at higher proton energies as pointed out by Chaudhri et al[1].

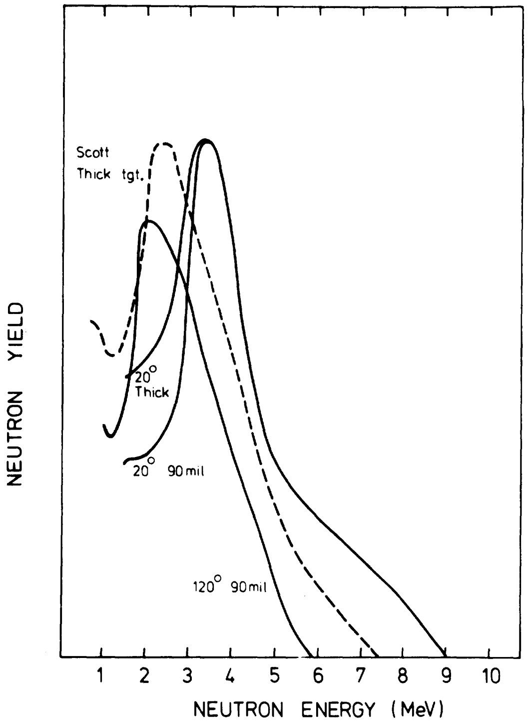

Fig. 3: Thick target neutron spectra at 20° and 120° from the present measurements, and Scott's spectra averaged over all the angles.

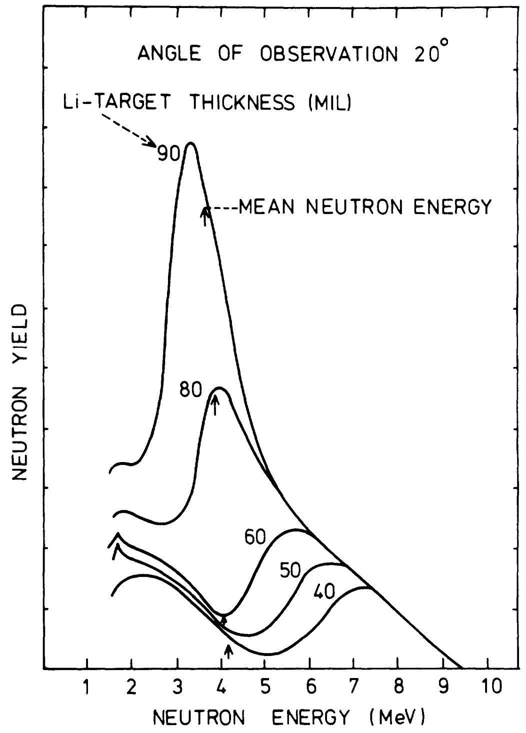

Fig. 4: Neutron spectra from moderately thick targets at 20°. The thickness of various targets and the corresponding mean energy is indicated on the curves.

TABLE II

Target Thickness mil	g/cm^2	Mean Neutron energy (MeV) Li	Be	Dose Rads min^{-1} 100 μA^{-1} at 100 cm Li	Be
40	5.43×10^{-2}	4.26	-	1.65	-
60	8.14×10^{-2}	4.11	-	2.56	-
80	1.09×10^{-1}	3.94	-	3.90	-
90	1.22×10^{-1}	3.69	-	5.50	-
Thick		3.14	1.73	6.20	1.54

In the present measurements the neutron intensity from a thick target is just over one-half of that calculated by Chaudhri et al[1]. This discrepancy may be mainly due to the exclusion of neutrons with less than 1 MeV energy in the present measurements and the fact that these measurements are carried out at 20° and not at 0°. This non-detection of lower energy neutrons may also account for a factor of 2 between the measurements of Lone et al[5] at 15 MeV and Chaudhri's calculations. However, in spite of this difference in the absolute values of thick target neutron yields, the neutron intensity from moderately-thick targets, which are of main interest, appear to be similar. For example, from a moderately-thick target (1.17g/cm^2) which reduces a proton beam from 18 to 15 MeV, neutron fluxes of 4.5×10^{11} and 3.5×10^{11} (n sec^{-1} sr^{-1} 100 μA^{-1}) would be produced according to Chaudhri's calculations and Lone's measurements respectively. This sort of neutron flux would correspond to dose rates of between 10-14 rads/min, at a distance of 100 cm from the target, depending upon the value of $\bar{E}n$ used. Moreover, the average neutron energies in this case would be significantly higher than at incident proton energy of 10.5 MeV. As the maximum proton energies from most smaller compact cyclotrons are around 15-18 MeV, it seems that therapeutically useful neutrons, though by no means ideal, can be obtained by using moderately-thick ^{7}Li target.

We also investigated in the present measurements the effect of the angle of observation on the neutron beam quality. As can be seen from Figure 2, the cross sections of the neutrons to higher-excited states in ^{7}Be and from the ^{7}Li(p, ^{3}He n)^{4}He reaction decrease more rapidly than those of the higher energy neutrons going to the ground and first excited state (.43 MeV) as the angle of observation is varied from forward to backward direction. Therefore, one would expect more high energy neutrons at backward angles than in the forward direction, and hence achieve higher average neutron energies. However, the kinematic decrease in the energy of the primary neutrons (ground and 0.43 MeV states) at backward angles more than cancels out this advantage. It is concluded, therefore, that the forward direction is still the most suitable one for obtaining the best neutron quality from the ^{7}Li(p,n) reaction.

References

1. M. A. Chaudhri, S. Zuberi, A. J. Chaudhri and Q. J. Chaudhri. The ^{7}Li (p,n)^{7}Be reaction as a useful source of fast neutrons for therapy. Eur. J. Cancer 10, 260-61. (1974)
2. J. Templer. Ph.D. Thesis, University of Melbourne 1978 (unpublished), Page 219.
3. M. C. Scott. The rate of energy loss and neutron yield for protons on thick lithium targets at energies from 3-10 MeV. J. Nucl. Energy 25, 405-416. (1971)
4. M. A. Chaudhri. The potential and application of cyclotrons in biomedical fields. Proc. 7th Int. Conf. on Cyclotrons and their Application (Birkhaeuser, Basel, 1975) P. 447-456.
5. M. A. Lone, C. B. Bigham, J. S. Fraser, H. R. Schnieder, T. K. Alexander, A. J. Ferguson and A. B. McDonald. Thick target neutron yields and spectral distributions from the Li (d,n), Li (p,n), Be(d,n) and Be(p,n) reactions. Nucl. Inst. and Meth. 143, 331-344 (1977).