Energies and Angular Distributions of Neutrons from $Be^9(d,n)B^{10}$†

J. S. PRUITT,* C. D. SWARTZ, AND S. S. HANNA
Department of Physics, Johns Hopkins University, Baltimore, Maryland
(Received September 11, 1953)

The angular distributions of neutrons from $Be^9(d,n)B^{10}$, leading to the five lowest states of B^{10}, have been measured at a bombarding energy $E_d=0.945$ Mev. These distributions are compared with previous data for $Be^9(d,p)Be^{10}$. In both cases there is evidence for the deuteron stripping process. Interpretation of the distributions is discussed. Excitation energies are obtained for the B^{10} states.

I. INTRODUCTION

THE bombardment of Be^9 by deuterons, followed by emission of a neutron or proton, leads to the formation of nuclei containing ten nucleons: B^{10} states may have isotopic spin 0 or 1, Be^{10} states only isotopic spin 1. Up to an excitation energy $E_x=4$ Mev (the region studied in the present investigation) there are five states in B^{10} but only two states in Be^{10}.[1] The second excited state of B^{10} ($E_x=1.74$ Mev) and the ground state of Be^{10} have been identified as the $T_3=0$ and -1 components of a $T=1$ state. The other four states of B^{10} have $T=0$.[2]

With bombarding energies of several Mev these reactions proceed chiefly by deuteron stripping, as shown by investigations of the angular distributions.[1] The general shape of the angular distributions in stripping depends only on the orbital angular momentum l for the captured particle. It is found that $l=1$ for all the states discussed here, hence the angular distributions for stripping are all very similar.

At low bombarding energies, on the other hand, the $Be^9(d,p)Be^{10}$ reaction appears to proceed chiefly by compound nucleus formation.[3] In this case one would expect that the distributions should depend to some extent on the detailed properties of the final states.

At intermediate bombarding energies (in the neighborhood of 1 Mev) the $Be^9(d,p)Be^{10}$ distributions[3,4] appear to contain contributions from both processes.[5] Evidence for stripping can also be seen in the distributions for other (d,p) and (d,n) reactions in this energy

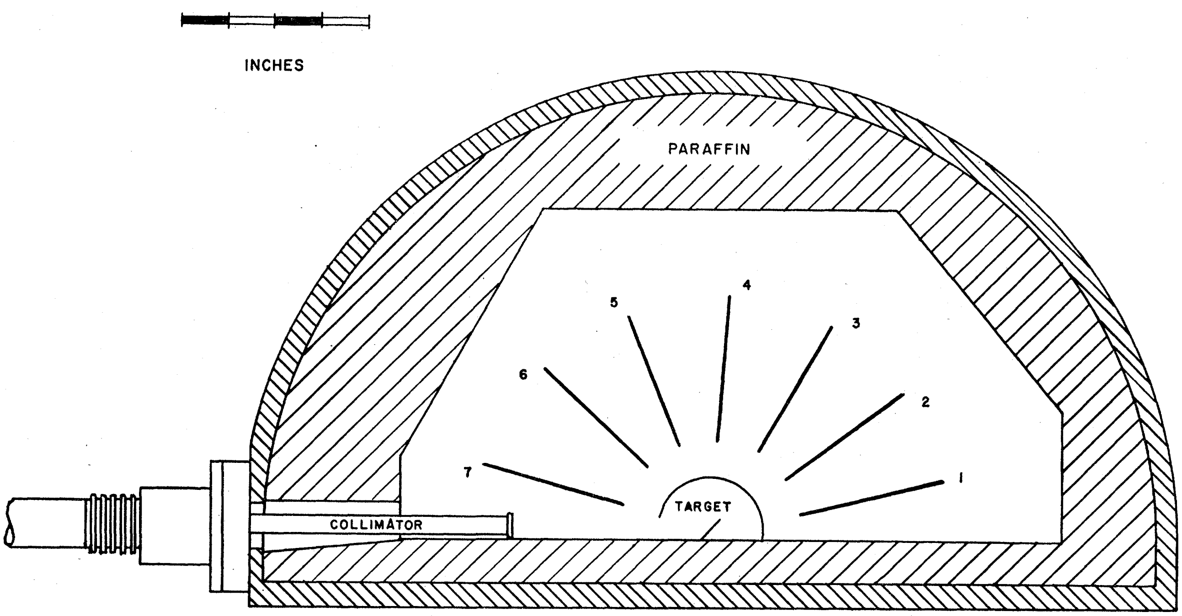

FIG. 1. Plan view of target chamber showing positions of plates 1 to 7. Deuteron beam enters through collimator from left.

† Assisted by a contract with the U. S. Atomic Energy Commission.
* Now at the National Bureau of Standards, Washington, D. C

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952). The experimental work on these reactions is summarized in this review article.
[2] Bockelman, Browne, Sperduto, and Buechner, Phys. Rev. **90**, 340 (1953).
[3] I. Resnick and S. S. Hanna, Phys. Rev. **82**, 463 (1951).
[4] F. L. Canavan, Phys. Rev. **87**, 136 (1952).
[5] W. W. True and L. Diesendruck, Phys. Rev. **87**, 381 (1952).

range.[6] It was of interest therefore to examine the angular distributions for $Be^9(d,n)B^{10}$ at a deuteron energy ~1 Mev to determine the extent to which these two processes contribute to this reaction, to investigate the dependence of the distributions on the properties of the various final states in B^{10}, and to obtain a comparison of the distributions for all seven states of Be^{10} and B^{10}.

II. EXPERIMENTAL ARRANGEMENT

A 0.1-mg/cm^2 beryllium target (approximately 30 kev thick for 1-Mev deuterons) evaporated on 1/64-in. copper backing was mounted in the cast-aluminum target chamber shown in Fig. 1. The target was bombarded with a 1/8-in. diameter beam of 0.96-Mev deuterons from the Van de Graaff accelerator in this department. The total exposure for this experiment was approximately 2 microampere-hours.

Neutrons from the target were detected by recoil proton tracks in Ilford C-2 nuclear plates (emulsion thickness 100 microns) placed inside the target chamber at several angles as shown in Fig. 1. The near edge of each plate was approximately 5 cm from the target.

TABLE I. Calculated Q values (Mev) for $Be^9(d,n)B^{10}$ and excitation energies E_x (Mev) for B^{10} states.

θ_{lab}	Q_1	Q_2	Q_3	Q_4	Q_5
12.4°	4.45	3.73	2.65	2.25	0.76
35.8°	4.44	3.71	2.70	2.21	0.75
60.4°	4.42	3.71	2.66	2.23	0.76
85.5°	4.43	3.70	2.64	2.24	0.80
110.8°	4.39	3.67	2.65	2.20	0.75
137.1°	4.44	3.64	2.65	2.23	0.75
Average Q	$=4.43\pm0.08$	3.69 ± 0.07	2.66 ± 0.06	2.23 ± 0.06	0.76 ± 0.05
E_x	$=0.00$	0.74 ± 0.11	1.77 ± 0.10	2.20 ± 0.10	3.67 ± 0.09

Charged particles from several competing reactions were stopped by a 0.008-in. brass shield surrounding the target. Back-scattering of neutrons from the chamber walls was minimized by a lining of paraffin, as shown.

Seven plates were exposed and then developed simultaneously to be sure that they received identical treatment. Approximately identical areas on plates 1 through 6 were scanned[7] for recoil proton tracks with a Zeiss-Winkel GF-375 binocular microscope, using a Bausch and Lomb 40× fluorite oil immersion objective, N.A. 1.00, and Bausch and Lomb 15× Hyperplane eyepieces. This equipment was very satisfactory for the present work. The field of view is about 270 microns in diameter, and depth measurements made with the fine focus adjustment (after correction for curvature of field) are reproducible to within 1/2 micron.

[6] W. Whaling and T. W. Bonner, Phys. Rev. **79**, 258 (1950); Krone, Hanna, and Inglis, Phys. Rev. **80**, 603 (1950); D. N. F. Dunbar and F. Hirst, Phys. Rev. **83**, 164 (1951); Australian J. Sci. Research 4, 268 (1951); J. R. Risser and W. H. Burke, Phys. Rev. **85**, 742 (1952).

[7] Plate 7 was accidentally fogged and could not be scanned.

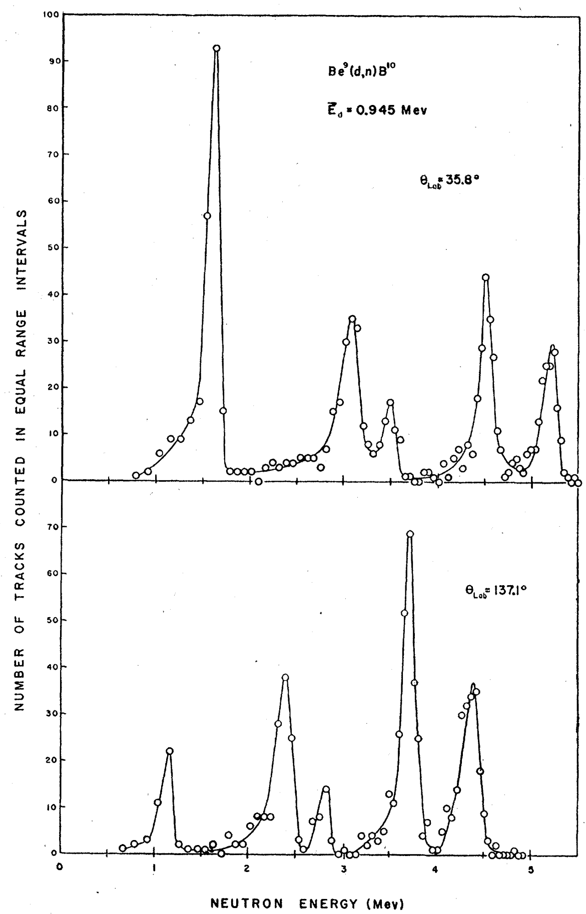

FIG. 2. Recoil proton spectra. Ordinate is the number of acceptable proton tracks counted in equal intervals of proton range. For the abscissa, proton range has been converted to neutron energy.

III. MEASUREMENT OF NEUTRON ENERGIES AND ANGULAR DISTRIBUTIONS

Neutron energies were calculated from the observed recoil proton track lengths and directions by methods similar to those described by others.[8,9] Proton tracks were accepted for measurement only if the horizontal recoil angle measured from the assumed neutron direction[10] was not more than 15° and if the dip angle in the processed emulsion was not more than 4.8°. A standard range-energy curve[11] was used to convert proton range to proton energy. Figure 2 shows two examples

[8] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).

[9] W. M. Gibson and D. L. Livesey, Proc. Phys. Soc. (London) **A60**, 523 (1948).

[10] Since the emulsion area scanned was only 6 cm from the target, it was not adequate to assume that all neutrons moved parallel to the center line of the plate. Instead, the plate was mapped in sectors each subtending $1\frac{1}{2}$° at the center of the target. In each sector, it was assumed that neutrons moved parallel to the midline of the sector and in the plane of the emulsion.

[11] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **A59**, 883 (1947); N. Nereson and F. Reines, Rev. Sci. Instr. **21**, 534 (1950).

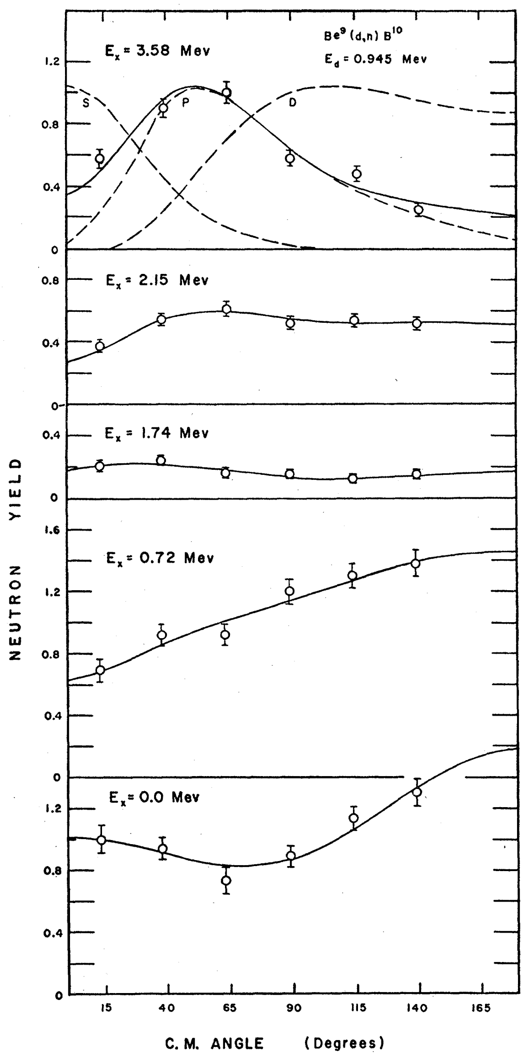

FIG. 3. Neutron angular distributions. For $E_x=3.58$ Mev, deuteron stripping curves for proton capture in s, p, and d orbits have been drawn with broken lines.

of the recoil proton spectra obtained. Five peaks are visible, corresponding to five states of the residual B^{10} nucleus.

A reaction energy Q was calculated for each peak on each plate. Table I shows these values, their averages on the six plates and estimated errors based on deviations from the average, uncertainties in the range-energy curve, and errors in measurement of the average deuteron energy ($E_d=0.945\pm0.02$ Mev) and the plate angles. Table I also shows the calculated excitation energies E_x of the B^{10} states. These measurements are in good agreement with the work of others.[2,12–14]

[12] F. Ajzenberg, Phys. Rev. **82**, 43 (1951); **88**, 298 (1952).
[13] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).
[14] In the following discussion the B^{10} states are labelled with the values of E_x adopted in reference 1.

To calculate the angular distribution of neutrons of a given energy group, the total number of proton tracks in the corresponding peak on each plate was counted. The usual corrections for variations of the neutron-proton scattering cross section[15] and for the varying probability that a proton stops in the emulsion[16] were applied to find the relative number of neutrons responsible for each peak. In addition, since neutron intensities on different plates were to be compared, these numbers were corrected for variations in the area scanned and in the effective solid angle subtended at the target by the emulsion which was scanned.[17]

The five angular distributions computed by this method are shown in Fig. 3. They have been normalized to unity for the most forward point in the ground-state ($E_x=0.0$ Mev) distribution. The errors indicated are only those due to counting statistics. For comparison the proton angular distributions obtained by Resnick and Hanna[3] are shown in Fig. 4, for a bombarding energy of 0.88 Mev. These two curves have the same normalization, but the relationship to the neutron curves is arbitrary.

IV. DISCUSSION

The neutron angular distribution for $E_x=3.58$ Mev shows a strong forward peak with maximum at about 50°, typical of the angular distributions for deuteron stripping discussed by Butler[18] and by Bhatia *et al.*[19] The broken lines in Fig. 3 are the angular distributions corresponding to capture of protons in s, p, and d orbits as calculated from Butler's formula with $r_0=0.5\times10^{-12}$

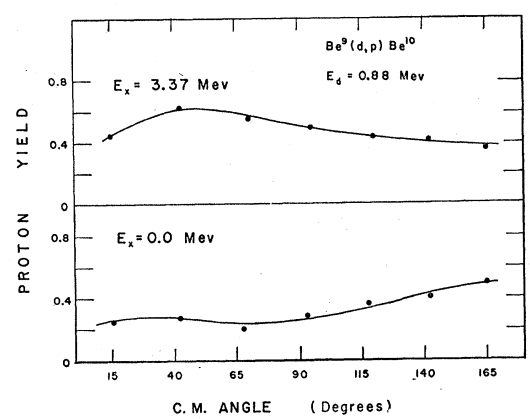

FIG. 4. Proton angular distributions, from Resnick and Hanna (reference 3).

[15] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[16] H. T. Richards, Phys. Rev. **59**, 796 (1941).
[17] The major contribution to this correction came from variation in emulsion thickness. The measured thicknesses of the processed emulsion on the six plates were, in order: 39.7, 50.7, 48.8, 50.3, 44.6 microns. Except for the first and last of these the uniformity is quite good. Since they were processed together, the same shrinkage factor was assumed for all plates.
[18] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 36 (1951).
[19] Bhatia, Huang, Huby, and Newns, Phil. Mag. **43**, 485 (1952).

cm. The experimental points are in satisfactory agreement only with the p curve.

The remaining angular distributions do not fit the stripping theory for any angular momentum of the captured particle (Fig. 5). However, the neutron distributions for $E_x=2.15$ and 1.74 Mev and both proton distributions show some structure in the forward hemisphere suggesting the stripping maximum. The proton distribution for $E_x=0.0$ Mev has been studied by Canavan[4] at bombarding energies from 1.0 to 2.2 Mev. In this range the forward peak increases and agrees very well with stripping theory.[5] At bombarding energies below 0.88 Mev, on the other hand, the structure disappears[3] and the angular distributions can be represented by simple polynomials in $\cos\theta$.

In this transition region it seems reasonable (see reference 5) to fit the observed data by a superposition of the appropriate stripping curves calculated from Butler's theory (see Fig. 5) and simple polynomials in $\cos\theta$. (The inclusion of high powers of $\cos\theta$ in the analysis would not be warranted by the data.)

TABLE II. Values of coefficients in the expansion $Y(\theta)=A+B\cos\theta+C\cos^2\theta+DY_s(\theta)$.

E_x	A	B	C	D
		Neutrons		
0.0 Mev	0.87	−0.28	0.42	0.0
0.72	1.06	−0.56	−0.15	0.34
1.74	0.09	−0.02	0.05	0.11
2.15	0.38	−0.20	−0.06	0.37
3.58	0.10	0.09	0.11	0.83
		Protons		
0.0	0.21	−0.21	0.08	0.19
3.37	0.36	0.02	0.02	0.23

Table II lists the values found by the method of least squares for the coefficients in the expansion

$$Y(\theta)=A+B\cos\theta+C\cos^2\theta+DY_s(\theta),$$

where $Y_s(\theta)$ is the angular distribution for stripping from Fig. 5. The corresponding curves have been drawn as solid lines in Figs. 3 and 4.

The interpretation of these distributions in terms of the properties of the states of B^{10} and Be^{10} is complicated by the apparent presence of two coherent[20] processes, stripping and compound nucleus formation. The polynomial in $\cos\theta$ presumably represents the compound nucleus process plus possible interference effects. There are, however, certain features of the distributions which can be noted, as follows:

1. Wherever it can be identified,[21] the stripping maximum is located about where it is predicted by Butler's formula for capture in a p orbit.

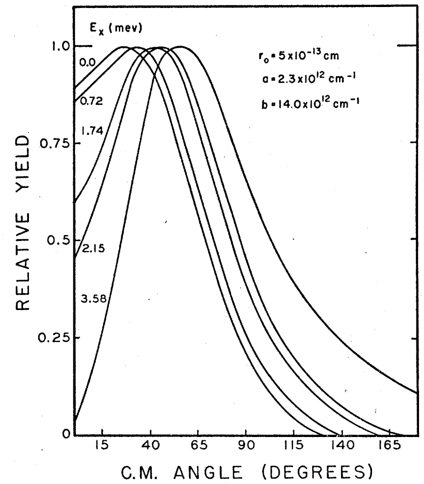

FIG. 5. Deuteron-stripping angular distributions for $Be^9(d,n)B^{10}$. Calculated from Butler's formula (reference 18) for proton capture in p orbits.

2. The neutron yield for $E_x=1.74$ Mev is very low compared with the other neutron groups. The proton yield for $E_x=0.0$ Mev is only about 50 percent of the yield for $E_x=3.37$ Mev despite the fact that the energy available to the protons is about three times as great in the former case.

3. Except for structure which can be attributed directly to stripping, the most noticeable feature in most of the distributions is the strong asymmetry about 90°, which does not seem to be correlated with the amount of pure stripping in the distribution; thus it seems to be an effect of the compound nucleus process. In the ground state proton distribution this asymmetry extends to lower bombarding energies where there is no recognizable evidence for the stripping process. Within the accuracy of the present data, the asymmetry is adequately described by a term in $\cos\theta$.

TABLE III. Allowed values of l' for various states in the compound nucleus B^{11} and final nucleus, B^{10} or Be^{10}.

B^{11}	$l_d=0$ l'	B^{10}, Be^{10}	B^{11}	$l_d=1$ l'	B^{10}, Be^{10}
1/2⁻	1	0, 1, 2	1/2⁺	0	0
	3	3		2	1, 2, 3
3/2⁻	1	0, 1, 2, 3	3/2⁺	0	1, 2
				2	0, 3
5/2⁻	1	1, 2, 3	5/2⁺	0	2, 3
	3	0		2	0, 1
			7/2⁺	0	3
				2	1, 2
				4	0

[20] This is equivalent to saying that it is not possible to devise an experiment in which the two processes could be separated and studied independently.

[21] In an earlier report [Pruitt, Hanna, and Swartz, Phys. Rev. 87, 534 (1952)] it was stated that a stripping maximum could be identified in all the neutron distributions. The additional data in the present work make this interpretation less plausible for $E_x=0.0$ and 0.72 Mev.

4. Because of the complexity introduced by the stripping process, it is not possible to establish the existence of a term in $\cos^2\theta$ in any of the distributions. In the ground-state neutron distribution, however, it is necessary to assume either that the forward maximum is a result of stripping or that a pronounced $\cos^2\theta$ dependence is present; with the present data the least-squares analysis favors the latter assumption (Table II).

5. In the neutron distributions, the relative contribution resulting from stripping seems to increase with increasing E_x (decreasing Q).

To discuss the compound-nucleus effects, we may assume that B^{11} states are formed by incoming deuterons with orbital angular momentum $l_d=0$ or 1 (we expect that higher values of l_d are improbable by considerations of penetrability). Possible B^{11} states are listed (spin and parity) in Table III, along with values of orbital angular momentum l' for the outgoing particle corresponding to various possible final states of B^{10} or Be^{10} (listed by spin; parity assumed +). On the basis of penetrability alone, one could account for a relatively low yield to the states $E_x=1.74$ Mev in B^{10} and $E_x=0.0$ Mev in Be^{10} by assuming in agreement with others[1] that these are both states of $J=0$ and that the B^{11} states involved are some combination of $5/2^-$, $3/2^+$, $5/2^+$, and $7/2^+$ or perhaps $3/2^-$ and $7/2^+$. Two B^{11} states of opposite parity are needed to account for the $\cos\theta$ terms on the basis of compound nucleus formation. A model which assumes only the B^{11} states $5/2^-$ and $3/2^+$ is in agreement with these considerations. In addition, it leads to similar angular distributions, with very little $\cos^2\theta$, for states in B^{10} and Be^{10} having spins 1 or 2 and to a more pronounced $\cos^2\theta$ term for states with spin 3 (ground state of B^{10}).

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Nuclear Quadrupole Coupling in the Li_2 Molecule*†

R. M. STERNHEIMER, *Brookhaven National Laboratory, Upton, New York*

AND

H. M. FOLEY, *Columbia University, New York, New York*

(Received August 3, 1953)

The effect of the quadrupole moment induced in the 1s shell on the nuclear quadrupole coupling q in the Li_2 molecule has been investigated for several wave functions. For the most accurate variational wave function of James, the inclusion of the induced moment gives $q/2e=-0.00106a_H^{-3}$. This result, together with the quadrupole coupling $eqQ=+0.060$ Mc/sec for Li^7, leads to a negative value of the quadrupole moment $Q(Li^7)$. However the value of q is so close to zero that the magnitude and even the sign of Q is uncertain. The value of $1/q$ which determines Q is very sensitive to changes in the molecular wave function, and it is shown that a small modification of the James wave function would lead to a negative $Q(Li^7)$ which agrees in order of magnitude with the prediction of the nuclear shell model. Calculations of q were also carried out for the Heitler-London and Coulson-Duncanson wave functions for the Li_2 molecule.

I. INTRODUCTION

In a recent investigation of the quadrupole coupling in the Li_2 molecule, Harris and Melkanoff[1] have shown that the sign of the electric field gradient at the Li nucleus is very sensitive to the detailed behavior of the molecular wave function, since the gradient is the difference between the nuclear and the electronic terms which nearly cancel each other. These authors confirm an earlier result of Foley[2] that the Bartlett-Furry wave function for Li_2 gives a positive quadrupole coupling q which would lead to a positive quadrupole moment Q, in view of the experimental observation[3] that eqQ is positive (+0.060 Mc/sec). However, Harris and Melkanoff[1] also carried out a calculation of q with the more accurate variational wave function obtained by James.[4] The electronic term of q as calculated with this wave function is appreciably larger than for the Bartlett-Furry function; the resultant q is negative, although small. This work does not enable one to draw a definite conclusion about the sign of q, although it shows that a negative sign of q is not excluded. This result is of interest since a positive $Q(Li^7)$ would be hard to understand on the basis of any simple model of the nucleus.[5,6]

Harris and Melkanoff[1] did not take into account the effect of the quadrupole moment induced[7] in the 1s shell by the nuclear Q. The induced moment around the

* The part of the work carried out at Brookhaven National Laboratory was done under the auspices of the U. S. Atomic Energy Commission.

† Supported in part by a grant from the National Science Foundation.

[1] E. G. Harris and M. A. Melkanoff, Phys. Rev. 90, 585 (1953).

[2] P. Kusch, Phys. Rev. 76, 138 (1949).

[3] Logan, Coté, and Kusch, Phys. Rev. 86, 280 (1952).

[4] H. M. James, J. Chem. Phys. 2, 794 (1934).

[5] R. D. Present, Phys. Rev. 80, 43 (1950).

[6] R. Avery and C. H. Blanchard, Phys. Rev. 78, 704 (1950).

[7] R. M. Sternheimer, Phys. Rev. 80, 102 (1950); 84, 244 (1951). The latter paper will be referred to as I.