The values above indicate only the precision of the measurements, and errors in the assumed counting efficiency could change the numbers by factors of two or more. The partial alpha half-lives calculated from these branching ratios are 35 and 45 years.

While the 5.89-Mev group apparently accounts for more than 75 percent of the observed alpha-disintegrations which decay with a 35-day half-life, it seems likely from the alpha-systematics[5] that the ground-state transition energy would be between that of Cm^{242} (6.08 Mev) and Cm^{240} (6.25 Mev), but particles in this energy range are as yet unobserved.

We wish to express our appreciation to Dr. Glenn T. Seaborg for his continued interest in this work.

† This work was performed under the auspices of the AEC.

[1] Seaborg, James, and Ghiorso, *The Transuranium Elements: Research Papers* (McGraw-Hill Book Company, Inc., New York, 1949), Paper No. 22.2, National Nuclear Energy Series, Plutonium Project Record, Vol. 14B, Div. IV.
[2] K. Street, Jr., Ph.D. Thesis, University of California, 1949.
[3] Ghiorso, Jaffey, and Weissbourd, *The Transuranium Elements: Research Papers* (McGraw-Hill Book Company, Inc., New York, 1949), Paper No. 16.8, National Nuclear Energy Series, Plutonium Project Record, Vol. 14B, Div. IV.
[4] Crane, Ghiorso, and Perlman (to be published).
[5] Seaborg, Perlman, and Ghiorso, Phys. Rev. **77**, 26 (1950).

Short-Range Protons from the Deuteron Bombardment of Li^6*

R. W. GELINAS AND S. S. HANNA
Department of Physics, Johns Hopkins University, Baltimore, Maryland
(Received February 28, 1952)

THE 4.6-Mev state in Li^7 has been observed in the inelastic scattering of protons, deuterons, and alphas from Li^7 [1] and in the $Be^9(d, \alpha)Li^7$ reaction.[1,2] We have examined the spectrum of short-range protons from the $Li^6(d, p)Li^7$ reaction in a region corresponding to this excitation in Li^7. Thin targets of natural lithium, evaporated onto 1000A nickel foils, were bombarded with deuterons of energies 0.91 and 1.03 Mev, and the reaction products were observed at 90° and 110°. Detection was by means of nuclear plates in a magnetic spectrograph employing a second-order focus.[3] The observations reported here extend from an excitation energy of 4.30 to 4.80 Mev in Li^7.

In the first observation [Fig. 1(a)] a weak group of protons is observed in the correct location to be identified with the $Li^6(d, p)Li^7$ reaction. However, a search was made for the proton group from $N^{14}(d, p)N^{15}$, $Q=0.300\pm0.005$ Mev,[4] which would appear in this region. The observation was made with a lithium target, freshly prepared but then exposed to a pure nitrogen atmosphere. This procedure produces satisfactory nitrogen targets and the resulting nitrogen group appears in (*b*) in addition to the group attributed to lithium. Curves (*c*) and (*d*) were obtained at a lower bombarding energy, without and with a nitrogen contamination, respectively. In observation (*d*) the magnetic spectrograph was rotated to 110° to produce a further shift in energy of the proton groups. With the positive identification of the nitrogen group the relative shift in energy with angle and bombarding energy for the other group identifies it as a proton group from $Li^6(d, p)Li^7$. Each curve was obtained from a single three-inch nuclear plate, and the energy scale was determined from the deuterons scattered elastically from Li^7, which are shown (at reduced scale) in Fig. 1(c). The four observations yield an average $Q=0.410\pm0.015$ Mev for the lithium reaction and an excitation energy in Li^7 of 4.610 ± 0.020 Mev. This value agrees with our previous determination of 4.62 ± 0.02 Mev from the $Be^9(d, \alpha)Li^7$ reaction.[2] A value of $Q=0.296\pm0.015$ Mev is obtained for the nitrogen group, which agrees with the value obtained by Malm and Buechner.[4]

In all four spectra a continuous proton background is observed which is above the level expected from instrumental scattering alone. The rapid fall of the background below about 0.84 Mev in curve (*c*) is interesting in connection with a possible

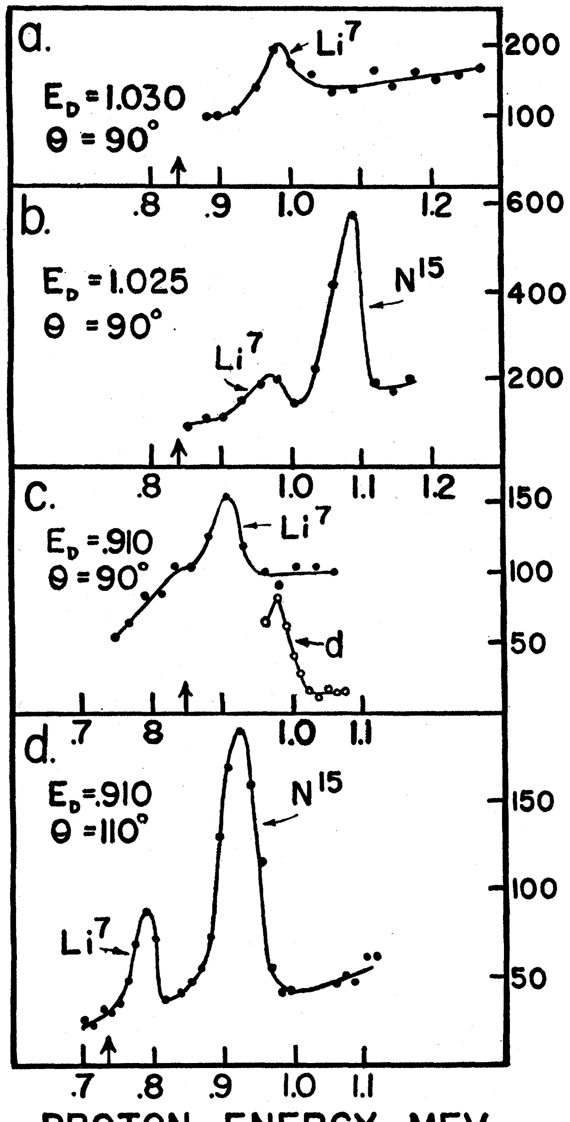

FIG. 1. Spectra obtained from the deuteron bombardment of natural lithium targets, curves (*a*) and (*c*), and of nitrogen contaminated lithium targets, curves (*b*) and (*d*). Li^7 and N^{15} designate, respectively, the $Li^6(d, p)Li^7$ and the $N^{14}(d, p)N^{15}$ reactions.

$Li^6(d, t)Li^5(p)He^4$ reaction. If the Q for $Li^5(p)He^4$ is taken as 1.8 Mev,[5] the mass of Li^5 becomes 5.01395 (instead of 5.0136[5]). This leads to a $Q=0.755$ Mev for the $Li^6(d, t)Li^7$ reaction. The minimum energy for a proton from the disintegration of a recoiling Li^5 nucleus is then 0.84 Mev for the conditions of curve (*c*). This is in excellent agreement with the observed point at which the background begins to fall, and the falling part of the curve is consistent with the great breadth of the Li^5 ground state. In curve (*d*) the minimum proton energy is calculated to be 0.73 Mev, and below this value the background is observed to decline, but the presence of the nitrogen peak makes the structure of the background above this value much less certain. In each graph the arrow marks the calculated position of minimum proton energy (neglecting the breadth of the Li^5 ground state). Unfortunately the measurements in (*a*) and (*b*) do not extend down to this value. The investigation of this background was extended to higher energies (above 3 Mev) in an attempt to observe the upper limit which should be about 2.20 Mev for the bombarding energies used. The observations showed a general decline in background in this region of the spectrum. Unfortunately a sharp limit in the weak background could not be established in the presence of strong groups from carbon and oxygen which, if they do not actually interfere, contribute to the instrumental background.

* Assisted by a contract with the AEC.
[1] H. E. Gove and J. A. Harvey, Phys. Rev. **82**, 658 (1951).
[2] Gelinas, Class, and Hanna, Phys. Rev. **83**, 1260 (1951).
[3] D. R. Inglis, Phys. Rev. **78**, 104 (1950).
[4] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[5] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

Spectroscopic Isotope Shift and Nuclear Shell Structure*

G. Breit
Yale University, New Haven, Connecticut
(Received March 4, 1952)

FROM a theoretical standpoint views of nuclear shell structure, NSS, present the difficulty of reconciliation of a one-body, individual particle approach with the apparent existence of many particles within each other's range of force. An analogy with the theory of solids brought out by Weisskopf[1] is helpful in removing some of the contradiction. In the similar atomic electron problem the exclusion principle plays an important role, as in Weisskopf's explanation; in addition the geometrical relations, which make orbits that are added with higher Z have larger radii, also matter, producing an ordering according to values of the principal quantum number n. In the present note it is speculatively considered whether the centrifugal barrier associated with high values of the azimuthal quantum number L contributes to the possibility of assigning the usual shell structure quantum numbers as reasonably "good" quantum numbers. The considerations are based on empirical evidence from the spectroscopic isotope shift, SIS, which shows marked irregularities at the closure of nuclear neutron shells.[2] The recent finding of an anomaly in the addition of two neutrons after the completion of the neutron number 126 substantiates the view[3] that magic numbers and anomalies in the SIS are intimately connected, as mentioned by Kopfermann and Brix themselves.[2] A way of correlating the facts which appears adequate for explaining the apparent goodness of the NSS quantum numbers is as follows: (A) It is supposed that there exists a nuclear core[4] and that for even Z the protons form a part of it. (B) The radius of the core is smaller than the radius of the maximum of $|r\psi|^2$ for the $1i_{13/2}$ neutrons when $Z\sim 80$ and the $1h_{11/2}$ neutrons when $Z\sim 50$. (C) Within the core the neutrons with higher L move somewhat as hypothesized by Weisskopf; outside the core neutrons move essentially as free particles. (D) The density of the core is approximately constant.

The second part of (C) is hardly a hypothesis, since on a sphere of radius $1.5\times 200^{1/3}\times 10^{-13}$ cm one can arrange 14 neutrons at distances of $\sim 0.83\times 10^{-12}$ cm from each other. The jump in the SIS at $N=126$ is explicable as the result of adding two $1i_{13/2}$ neutrons to Pb^{206} to form Pb^{208} and two $2g_{9/2}$ neutrons to Pb^{208} to form Pb^{210}. Taking the radius to be $\hbar/(Mmc^2)^{1/2}$ the centrifugal potential barrier, B, for i neutrons is 21 mc^2 and the neutron density of an i neutron falls off by a factor 1/2.7 in a fractional radius change $\Delta r/r\sim 1/13$. For g neutrons $B=10$ mc^2 and $\Delta r/r\sim 1/9$. The ratio of surface thicknesses affected is $\sim(21/10)^{1/2}=1.45$ on the JWKB approximation. The agreement of this number with the observed ratio 1.5 in the SIS of the $(210-208)/(208-206)$ differences is probably fortuitous but there is seen to be no difficulty in accounting for the observed magnitude of the effect. For $N=82$, $B\sim 20$ mc^2 for an h neutron and $\Delta r/r\sim 1/11$. The ratio of core thicknesses affected by h and by f neutrons is $\sim(20/12)^{1/2}=1.58$. It should be remarked that if the $f_{7/2}$ neutrons were to have a maximum of their radial density distribution slightly inside the core, a much larger ratio would result; the neutron density at the core surface and the core thickness affected would both be larger. The observed jump in the SIS on closing $N=82$ corresponds to a factor ~ 4. The existence of further anomalies close to $N=90$ suggests that the above explanation must be combined with other considerations, and there is a strong suggestion[5] of the participation of the effect of deviations from spherical symmetry for such nuclei. It is not intended, therefore, to explain all of the anomalies as an effect of a change in the penetrability of the core to the neutron wave function. The fact that the calculated isotopic shift is usually larger than the observed fits with the proposed outlying character of the $1i_{13/2}$ shell for $N=126$; the SIS in most of the isotopes Pb, Hg, Tl has presumably to do with the addition of i neutrons and the usual calculations assume a uniform density model of the nucleus, overestimating the expected effect. The general possibility of such a connection has already been noted by Kopfermann. The considerations on the effect of the centrifugal barrier presented above increase the probability of this view. For stable elements with $Z\cong 50$, the above picture when combined with the Bethe-Levinger-Courant view[6] of $\gamma-n$ and $\gamma-p$ reactions gives an increase in $\sigma(\gamma-n)/\sigma(\gamma-p)$ for these elements in comparison with the value of this quantity for lighter elements.[7] A proton in the nuclear core has to move through an envelope of neutrons before emergence, so that there results an increased probability of neutron emission as a result of collisions.

An obvious objection to the explanation of irregularities in the SIS is found in the fact that the spin of Pb^{207} is 1/2 and that this value cannot be explained as the spin of the $i_{13/2}$ shell with one missing neutron. On the other hand this objection disappears if one supposes that in Pb^{207} a neutron from an inner shell, perhaps the $3s_{1/2}$ shell, has been promoted to the $1i_{13/2}$ shell. The observed direction of staggering of the SIS could then be thought of as being partially caused by a decrease in nuclear volume produced by promoting the neutron from a penetrating to an external orbit. Since there is another way[5] of explaining odd-even SIS staggering, a quantitative consideration appears to be too difficult at this time.

It is desired to acknowledge a helpful discussion with Maurice Goldhaber regarding the plausibility of postulating the $1i_{13/2}-2g_{9/2}$ competition.

* Assisted by the joint program of the ONR and AEC.
[1] V. Weisskopf, Science **113**, 101 (1951.)
[2] P. Brix and H. Kopfermann, Festschrift Akad. Wiss. Göttingen, Math.-physik. Kl., 17 (1951).
[3] Brix, Buttlar, Houtermans, and Kopfermann, Nachr. Akad. Wiss. Göttingen, Math.-physik. Kl., Nr. 7 (1951). The writer would like to express his indebtedness to Professor H. Kopfermann for the opportunity of seeing the results before their publication.
[4] T. Schmidt, Z. Physik **106**, 358 (1937).
[5] P. Brix and H. Kopfermann, Z. Physik **126**, 344 (1949). Considerations regarding supplementary considerations have been discussed by Breit, Arfken, and Clendenin, Phys. Rev. **78**, 390 (1950).
[6] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950); see especially p. 128.
[7] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948); G. Friedlander and M. L. Perlman, Phys. Rev. **74**, 442 (1948); **75**, 988 (1949); J. Halpern and A. K. Mann, Phys. Rev. **83**, 370 (1951); A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).

jj-Coupling in Nuclei

B. H. Flowers*
Department of Mathematical Physics, The University, Edgbaston, Birmingham, England
(Received February 21, 1952)

ACCORDING to the Mayer-Jensen spin-orbit coupling shell model of nuclear structure,[1,2] the states of a single nucleon moving in the average field of the rest of the nucleus are defined by the quantum numbers $nljm$, the degeneracy in j being destroyed by strong spin-orbit forces. One is, therefore, led to investigate the splitting of the states of the nuclear configuration $(l_j)^N$ under the influence of central forces considered as a perturbation.