480 kev in Li^7) as would be satisfactory for the $B^{10}(n,\alpha)$ intensity ratio, but not for that[8,17] of Be^7 K—capture nor for the observed lifetime[8,18] of the 480-kev state. The K-capture and lifetime data are at least roughly compatible[12] with either $I=1/2$ or $I=5/2$, but not with $I=7/2$.

The bearing of various recent experimental results on the identification of the well-known 480-kev state in Li^7 is discussed further in an accompanying paper.[19]

[17] B. Rose and A. R. W. Wilson, Phys. Rev. **78**, 68 (1950).
[18] B. T. Feld, Phys. Rev. **75**, 1618 (1949).
[19] D. R. Inglis, Phys. Rev. **81**, 914 (1951), following paper.

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The $B^{10}(n,\alpha)$ Reaction and the Low Excited State of Li^7

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Conflicting evidence concerning the nuclear spin I of the low excited state of Li^7 is discussed. By comparison of the apparent likelihood of sufficiently unexpected behavior of the matrix elements involved in the interpretation of the various experiments, it is concluded that the original assignment $I=\frac{1}{2}$ is almost certainly correct, although the experiments are unfortunately not completely decisive. One is prejudiced toward this conclusion by theoretical expectations from nuclear models such as discussed in the preceding paper. The only evidence against $I=\frac{1}{2}$ is the strong preference of the thermal-neutron reaction $B^{10}(n,\alpha)Li^7$ for the transition to the excited state. This anomalous intensity ratio is about what would be expected with $I=5/2$; but with $I=\frac{1}{2}$, even the most favorable assumption concerning the state of the compound nucleus, which involves large angular momentum of the outgoing alpha, makes barrier pentrability favor the transition to the ground state and leaves a factor of over thirty in the intensity ratio, or about six in the matrix elements, to be ascribed to unexpected behavior of the incalculable nuclear factors. This could and apparently does happen by cancellation in a matrix element. The large thermal cross section of the reaction is ascribed to a resonance which is abnormally narrow because of the large angular momentum of the alpha, and it must by chance fall within an estimated 30 kev of zero neutron energy. This is compatible with observed deviations from the "$1/v$ law." The strongest evidence for $I=\frac{1}{2}$ is found in the observed approximate lack of alpha-gamma angular correlation in the same reaction, which follows naturally with $I=\frac{1}{2}$. The magnetic dipole radiation is estimated to be about strong enough to account for the observed lifetime. With $I=5/2$, a small admixture of electric quadrupole radiation, but still larger than estimated, would permit the approximate lack of correlation to occur fortuitously. Another experimental result which seems natural with $I=\frac{1}{2}$, the isotropy of the gammas accompanying inelastic scattering of protons from Li^7, could be ascribed to chance properties of the compound nucleus; but it is unlikely that both of these results, each of which favors $I=\frac{1}{2}$, should occur fortuitously.

I. INTRODUCTION

THE anomalous behavior of the thermal neutron reaction $B^{10}(n,\alpha)Li^7$, which favors the transition to the excited state of Li^7 rather than the ground state by an intensity ratio[1] of about 17:1, has been adduced[2] as a reason for seriously doubting the original assignment[3] $I=\frac{1}{2}$ for the excited state, and favoring instead[4] $I=5/2$, even though it seems difficult to reconcile this latter assignment with expectations based on nuclear models.

Some recent results have appeared which favor the assignment $I=\frac{1}{2}$. They are: (1) The reaction $Be^9(d,\alpha)Li^7$ at two bombarding energies[5] has failed to detect further excited states of Li^7 from 480 kev up to 5.6 Mev (aside from a broad level above 2.5 Mev which, if it exists at all, breaks up into a trition plus an alpha almost during the reaction). This isolation of the two low levels makes them look like a doublet, and a study of intermediate coupling[6] makes it difficult to interpret them as anything but a doublet. (2) An investigation of the possibility of angular correlation between the alphas leading to the excited state and the subsequent gammas in the thermal reaction $B^{10}(n,\alpha)Li^{7*}$, as suggested by Feld and by Devons,[7] has been carried out by Rose and Wilson[8] and they observe spherical symmetry (within one or two percent) which strongly favors the assignment $I=\frac{1}{2}$, because with any other value of I a correlation would, in general, be expected; and its fortuitous disappearance (to this accuracy) seems quite unlikely, as is discussed further below. (3) The spherical symmetry of the gammas resulting from the inelastic scattering $Li^7(p,p')Li^{7*}$ observed by Littauer[9] has been interpreted by him as indicating $I=\frac{1}{2}$ for the excited state of Li^7, although it could instead mean merely that the relevant state of the compound nucleus Be^8 has $I_{Be}=0$, since the rather difficult measurement could be made

[1] G. C. Hanna [Phys. Rev. **80**, 530 (1950)] finds a ratio of 17.1:1 on the basis of better statistics than found in earlier papers, which gave ratios ranging from 12:1 to 15:1; R. S. Wilson, Proc. Roy. Soc. (London) **177A**, 382 (1941); J. K. Bøggild, Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd. **23**, 4, 26 (1945); C. W. Gilbert, Proc. Cambridge Phys. Soc. **44**, 447 (1948); Stebler, Huber, and Bicksel, Helv. Phys. Acta **22**, 372 (1949).
[2] D. R. Inglis, Phys. Rev. **74**, 1876 (1948).
[3] D. R. Inglis, Phys. Rev. **50**, 783 (1936); G. Breit, Phys. Rev. **51**, 248 (1937).
[4] S. S. Hanna and D. R. Inglis, Phys. Rev. **75**, 1767 (1949).
[5] W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949); D. R. Inglis, Phys. Rev. **78**, 104 (1950); R. W. Gelinas and S. S. Hanna, Bull. Am. Phys. Soc. **26**, No. 1, Abstract C3 (1951).
[6] H. H. Hummel and D. R. Inglis, Phys. Rev. **81**, 910 (1951).
[7] B. T. Feld, Phys. Rev. **75**, 1618 (1949); S. Devons, Proc. Phys. Soc. (London) **62A**, 580 (1949).
[8] B. Rose and A. R. W. Wilson, Phys. Rev. **78**, 68 (1950).
[9] R. M. Littauer, Proc. Phys. Soc. (London) **63A**, 294 (1950).

only in the neighborhood of a prominent resonance[10] at $E_p=1030$ kev, having a width of 168 kev. The measurement was indeed made at as low an energy as possible, 800 kev, on the lower edge of this resonance; but it is still not clear to what extent this might reduce the dominant influence of the resonant state. The value $I_{Be}=0$ is possible with entering p-protons, and there seems to be no clear reason in the analysis of the resonances for making another assignment.[11] If repetition at quite another energy should give the same result, the conclusion would be greatly strengthened; but no further convenient resonances have been found.[12] It thus seems premature to conclude from this experiment alone that $I=\frac{1}{2}$: it leaves a rather small probability that I might be 5/2, which is to be multiplied by the considerably smaller probability provided by the evidence of (2), and the product is a very small probability that I might be 5/2. Similar measurements of the angular distributions of the gammas from $Li^6(d,p)Li^{7*}$, as has been discussed by Hanna,[13] and of $B^{10}(p,\alpha)Be^{7*}$, particularly at the 1.5-Mev resonance, would also serve to verify this conclusion. Since $I=\frac{1}{2}$ has the property of giving spherical symmetry, which might, in such an experiment at a single resonance, arise from some other circumstance, several verifications of the identification $I=\frac{1}{2}$ would not seem superfluous.

There are other experimental results concerning the excited state which seem to be about equally compatible[4] with $I=\frac{1}{2}$ or 5/2, such as the intensity ratio[14] in Be^7 K-capture (11 percent to the excited state) and the lifetime[15] of the excited state (10^{-13} sec, magnetic dipole). These depend mainly on ΔI between the excited and ground state, which is 1 in either case. Comparison of the angular distributions of the two proton groups in $Li^6(d,p)Li^7$ is another possible indication; but cannot be considered very significant at present, because there is some disagreement in detail between data from two laboratories.[16]

The two aspects of the reaction $B^{10}(n,\alpha)Li^7$, the intensity ratio on the one hand and the alpha-gamma angular correlation (supported by the $Li^7(p,p')$ gammas) on the other, are thus considered to be opposing bits of evidence, the former favoring $I=5/2$ and the latter $\frac{1}{2}$; but the theoretical considerations on which these conclusions are based are essentially incomplete in both cases. One calculates the obvious factors, such as barrier penetrability and orientation coefficients, but is in each case left with the essentially nuclear factors of the matrix elements which are not calculated. On the basis of estimates or plausible surmises concerning these factors, one arrives at conclusions which are not rigorous but subject to the vagaries of chance within the latitude of the estimate, such as chance cancellation of positive and negative parts of an integration to change an order of magnitude. Whichever value of I is correct, there must have been an unexpected fortuitous behavior of the matrix elements operating in one or the other of these experiments. We therefore here examine the interpretations of both $B^{10}(n,\alpha)$ experiments a little more closely, from the point of view of trying to compare the probabilities that sufficiently unexpected behavior of the matrix elements might occur in one or the other.

II. THE INTENSITY-RATIO ARGUMENT AGAINST $I=\frac{1}{2}$ FOR THE 480-kev STATE

B^{10} has the large nuclear spin $I=3$, and the strong preference of the thermal reaction $B^{10}(n,\alpha)Li^7$ for the 480-kev state of Li^7 suggests a larger angular momentum I for this excited state than for the ground state, because the compound state formed by a thermal neutron also has large I, and the excited state with large I may then be formed with a smaller angular

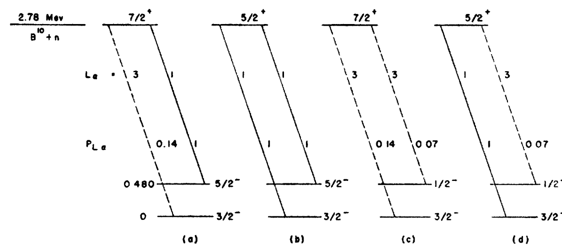

FIG. 1. Transition schemes for the two possible choices of compound state and the two relevant choices of Li^7 states. The lowest alpha-angular momentum $L\alpha$ and the barrier penetrability $P_{L\alpha}$ are indicated for each transition. Barrier penetrabilities, when the energy is not over the barrier, are estimated by the usual WKB approximation with the nuclear radius $R=(7^{\frac{1}{3}}+4^{\frac{1}{3}})e^2/2\ mc^2$.

momentum L_α of the alpha (and, consequently, a smaller centrifugal barrier) than required to form the ground state. More specifically, there are four relevant combinations of choices of compound and final states, as presented in Fig. 1. The compound nucleus has I either 5/2 or 7/2 or both, depending on chance placement of the high levels of B^{11}. We assume it to have even parity, indicated by superscript +, on the basis of the only reasonable models for B^{10} plus an s-neutron, and thus have a choice between $5/2^+$ and $7/2^+$ for the compound nucleus. There can be very little doubt about this, or about the assignment $3/2^-$ to the ground state of Li^7; and it seems almost as certain that the 480-kev state of Li^7 also has odd parity. Only odd values of L_α are thus considered, and only the lowest value permissible in each transition. The transition scheme (a) in Fig. 1 is the one which provides a natural explanation of the observed intensity ratio on the basis of the assumption $I=5/2$ for the 480-kev state. With $7/2^+$ for the compound state, the parity and angular

[10] Fowler, Lauritsen, and Rubin, Phys. Rev. **75**, 1463 (1949); W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).
[11] E. R. Cohen, Phys. Rev. **75**, 1473 (1949).
[12] Richards, Bashkin, Craig, Donahue, Johnson, and Martin, Phys. Rev. **79**, 239 (1950).
[13] S. S. Hanna, Phys. Rev. **76**, 686 (1949).
[14] R. M. Williamson and H. T. Richards, Phys. Rev. **76**, 614 (1949).
[15] L. C. Elliott and R. E. Bell, Phys. Rev. **74**, 1869 (1948); Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1948).
[16] Krone, Hanna, and Inglis, Phys. Rev. **80**, 603 (1950); W. Whaling and T. W. Bonner, Phys. Rev. **79**, 258 (1950).

momentum differences permit $L_\alpha=1$ for the excited state but require $L_\alpha=3$ for the ground-state transition, and the estimated penetration factors provide a ratio 7:1 in favor of the excited state, leaving only a little more than a factor 2 in the observed ratio 17:1 to be attributed to the nuclear matrix elements. The scheme (b) has no particular virtue. With the original assignment $I=\frac{1}{2}$ for the excited state of Li^7, one must choose between schemes (c) and (d); and scheme (d), with a compound state $5/2^+$, is to be rejected because the centrifugal barrier favors the transition to the ground state by a factor of about 14, thus making a discrepancy with the observed intensity ratio by a factor of over two hundred.

With the scheme (c) in Fig. 1, the discrepancy is not so extreme, and it is in terms of this scheme that one may most reasonably hope to reconcile the observed intensity ratio with the evidence favoring $I=\frac{1}{2}$. In this scheme one has the compound state $7/2^+$ and a rather large centrifugal barrier, with $L_\alpha=3$, for both transitions. There is still a preference for the transition to the ground state arising from the energy dependence of the barrier penetrability, but only by about a factor 2, so that the observed ratio of about 17:1 favoring the excited state in this case leaves a discrepancy of about a factor 34.

Such a factor represents the *square* of a ratio of nuclear matrix elements (as has been emphasized in this connection by Fermi); and unexpected behavior of nuclear matrix elements by a factor of 6 is not very unlikely, since we know very little particularly about the highly excited state of the compound nucleus. With (LS)-coupling wave functions, which are simpler than one has a right to expect, one does not obtain so large a factor. For example, with the compound state c assumed to be a ${}^2G_{7/2}$, and with the wave function ψ_g of the final ground state of the system compounded with the usual coefficients of $L_\alpha=3$ for the alpha and ${}^2P_{3/2}$ for Li^7, and similarly with ${}^2P_{\frac{1}{2}}$ for ψ_e of the excited state, one finds for the transition matrix elements $(c|H|g)=G$, $(c|H|e)=1.9G$, where the spin-orbit coupling in the hamiltonian H is neglected and G is an integral involving the ${}^2G_{7/2}$ (with projection $M=7/2$) and that linear combination of ψ_g and ψ_e which most closely corresponds to it. The nuclear factor in the intensity ratio in this case favors the excited state, but only by a factor 3.6, which is not enough to account for the "anomalous" ratio 34. A compound state c' consisting simply of a ${}^2F_{7/2}$ gives similarly $(c'|H|g)=3^{\frac{1}{2}}F$, $(c'|H|e)=-F$, where F is a parameter similar to G. This contributes to the intensity ratio a factor 3 in favor of the ground state. But a less simple compound state c'' consisting of an arbitrary linear combination of c and c' would have a matrix element to the ground state $(c''|H|g)$ which is an arbitrary linear combination of F and G (subject to normalization), which might even be zero; and the *a priori* chance that this be as small as one-sixth of another such combination $(c''|H|e)$ is of the order of magnitude one-tenth, not really very small at all. This illustrates the danger of estimates ignoring nuclear matrix factors where superpositions are involved and suggests why their success in simpler problems, such as the relation between parities and the asymptotic low energy behavior of the lithium-two-alpha-reactions,[17] does not imply their safe applicability elsewhere. Because of the expected complexity of the compound state, it is not even necessary to superpose a small amount of another compound state with $I=5/2$, or to invoke a more complicated ${}^2P$ in Li^7, such as suggested by the possibility of a positive quadrupole moment.[18]

III. RESONANCES IN THE REACTION $B^{10}(n,\alpha)Li^7$

Whether we can thus perforce escape from the intensity-ratio difficulty by use of the transition scheme shown in Fig. 1(c) depends further on whether the absolute intensity of the reaction is compatible with $L_\alpha=3$. Since matrix elements may be expected to have a natural maximum value corresponding to little orthogonality, they may more easily be fortuitously small than fortuitously large, so we would prefer to assume that the matrix element to the excited state is the normal one and that the ground-state transition is abnormally weak. At first sight, it might seem unlikely that this otherwise normal matrix element could include the unfavorable penetration factor associated with $L_\alpha=3$, because this reaction is so exceptionally strong that it, although in the rarer isotope, leads to the prevalent use of boron as a slow-neutron absorber. This may, however, also be ascribed to a fortuitous circumstance, namely, that a fairly normal resonance for incident neutrons on this particular light nucleus happens to fall almost exactly at thermal energy. An examination of the energy variation of the cross section shows that no further strange behavior of the matrix elements is required.

The Breit-Wigner one-level dispersion formula for the cross section σ of the transition to one state of the final nucleus is

$$\sigma=4\pi\lambda\lambda_R\Gamma_{n,R}\Gamma_\alpha/(\Gamma^2+\Delta E^2); \qquad (1)$$

and when the deviation ΔE of the energy from exact resonance is considerably less than the resonance width Γ, it may, of course, be written

$$\begin{aligned}\sigma&=4\pi\lambda\lambda_R\Gamma_{n,R}\Gamma_\alpha/\Gamma^2\\&=2.6(EE_R)^{-\frac{1}{2}}\Gamma_{n,R}\Gamma_\alpha/\Gamma^2\text{ Mev-barns,}\end{aligned} \qquad (2)$$

where $\lambda=(\text{neutron wavelength})/2\pi=\hbar/Mv_n$, the subscript R means "at resonance," Γ_n is the neutron width, and Γ_α the partial width for alpha-emission leading to,

[17] R. Resnick and D. R. Inglis, Phys. Rev. **76**, 1318 (1949).

[18] P. Kusch, Phys. Rev. **76**, 138 (1949); R. E. Present, Phys. Rev. **80**, 43 (1950); R. Avery and C. H. Blanchard, Phys. Rev. **78**, 704 (1950). The positive sign is deduced from available estimates of the sign of the quadrupole coupling q, which should probably be doubted at least as much as the simple nuclear models until the evidence becomes more complete. Thanks are due to Dr. H. M. Foley and Dr. E. Eisner for discussions of this point.

let us say, the 480-kev state of Li^7. We then have a similar formula for σ_g, containing $\Gamma_{\alpha g}$, for the transition to the ground state, and $\Gamma=\Gamma_n+\Gamma_\alpha+\Gamma_{\alpha g}$. Experimentally $\sigma_g \ll \sigma$ and thus $\Gamma_{\alpha g} \ll \Gamma_\alpha$ and may be neglected. If the two Γ's are equal, the factor $\Gamma_{n,R}\Gamma_\alpha/\Gamma^2$ in Eq. (2) has its maximum value $\frac{1}{4}$, whereas if the two Γ's are quite different, it is, of course, approximated by the ratio of the smaller Γ to the larger.

Equation (2), which is written explicitly for an (n,α) reaction, applies also to other reactions; but the numerical factor 2.6 becomes 1.3 for deuteron-induced reactions and 0.65 for alpha-reactions. (The reduced-mass correction has been omitted.) The few cross sections which are known for resonances in light nuclei, such as those in $Li^6(n,\alpha)H^3$(?), $C^{12}(d,p)C^{13*}$, $N^{15}(p,\alpha)$, and $Be^9(\alpha,n)$, seem to fall preponderantly within a factor of about 2 of the upper limit (with some of them a bit above the upper limit as though neighboring resonances contribute at a peak, and one or two of them a factor of 10 or 20 below the upper limit), suggesting that there is frequently no great difference between the two Γ's.

There is thus no general indication as to which of the Γ's is expected to be the larger; but we wish to show that the situation may be the same in the thermal resonance and in another typical resonance, without special behavior of the matrix elements. As the most appropriate typical resonance we take the one in the mirror reaction $B^{10}(n,\alpha)Be^{7*}$ at about 1.5 Mev, with a half-width of about 100 kev and a cross section at resonance about 0.14 barn (this value being based on assumed spherical symmetry). This is probably not the mirror resonance, since the corresponding proton energy would be at about 3 Mev, in a region which has not been explored. The width of this resonance is rather typical of such resonances (although they vary considerably), and we assume that it is not narrowed by unfavorable penetration factors arising from high angular momenta. It has a value $\sigma E_R \approx 0.2$ Mev-barns, a factor 3 below the maximum allowed by Eq. (2) (with $E=E_R$); and this factor we attribute to inequality of the Γ's by about a factor 10. We can compare the mirror reactions roughly by noting that a width Γ for a particle with (reduced) mass M and energy E varies as

$$\Gamma \sim M^{\frac{1}{2}}E^{\frac{1}{2}}|H_{ik}|^2,$$

where the matrix element H_{ik} when squared contains a penetration factor φ. If in the $B^{10}(p,\alpha)Be^{7*}$ reaction we have $\Gamma_\alpha > \Gamma_p$, then $\Gamma_\alpha \approx 100$ kev, $\Gamma_p \approx 10$ kev. These include a penetration factor $\varphi_\alpha = 1$ for the alphas if $L_\alpha = 0$ or 1, and for the protons it is either about $\frac{3}{4}$ or $\frac{1}{4}$, depending on whether $L_p = 0$ or 1, which depends on the parity of the resonant level; let us say roughly, $\varphi_p = \frac{1}{2}$. (With these numbers, and $E_\alpha = 2.1$ Mev, the proton and alpha-matrix elements without barrier would be about equal.) For the reaction $B^{10}(n,\alpha)Li^{7*}$, with $L_\alpha = 3$, we have $E_\alpha^{\frac{1}{2}}$ only 15 percent greater and the unfavorable penetration factor $\varphi_\alpha = 0.07$. If we assume that the matrix elements are otherwise roughly equal, we may thus estimate $\Gamma_\alpha = 8$ kev for the neutron reaction. Comparing the neutron width with the proton width without barrier, roughly 20 kev, the matrix elements again being taken otherwise equal, we have

$$\Gamma_n \approx (E_R/1.5 \text{ Mev})^{\frac{1}{2}}\, 20 \text{ kev}.$$

If this were about equal to (or greater than) the alpha-width, 8 kev, we would have the resonant neutron energy $E=\frac{1}{4}$ Mev (or more) with a total half-width of only 16 kev (or slightly more), so zero energy would be far out of the resonant region, and we would have a high resonance above the $1/v$ dependence, which is not observed. Thus, we are led to assume that $\Gamma_n < \Gamma_\alpha$, so that

$$\sigma(EE_R)^{\frac{1}{2}} \approx 2.6(\Gamma_n/\Gamma_\alpha) \text{ Mev barns},$$

and that thermal energy is approximately in the resonant region. The large experimental thermal cross section, 3700 barns, gives us for all energies approximately in the resonant region, including thermal,

$$\sigma E^{\frac{1}{2}} = 3700(4\times 10^7)^{-\frac{1}{2}}(\text{Mev})^{\frac{1}{2}} \text{ barns} = 0.6(\text{Mev})^{\frac{1}{2}} \text{ barns}.$$

From these we have

$$E_R = 20(\Gamma_n/\Gamma_\alpha) \text{ Mev} < 8 \text{ kev},$$

the latter because E_R must be low enouth to leave zero energy in the resonant region; and thus Γ_n is very small, corresponding to the low resonant energy, without requiring any special behavior of the matrix element, and the total width is the alpha-width, which is made small by φ_α.

If, on the other hand, in the reaction $B^{10}(p,\alpha)Be^{7*}$ we have $\Gamma_p > \Gamma_\alpha$, then $\Gamma_p \approx 100$ kev and $\Gamma_\alpha \approx 10$ kev. In the neutron reaction $\Gamma_\alpha \approx 1$ kev because of φ_α, $\Gamma_n \approx (E_R/1.5 \text{ Mev})^{\frac{1}{2}}\, 100 \text{ kev} > E_R$, which means that E_R and Γ_n are both less than about 7 kev. Because of uncertainties concerning the matrix elements, it would not be surprising to find this limit exceeded by a factor of five or so.

We see thus that no unusual behavior of the matrix elements is required to make boron an exceptionally good slow-neutron absorber, in spite of the assumption $L_\alpha = 3$, provided that the resonant level happens to be placed within about 30 kev (or perhaps even 50 kev) of zero energy. (This energy corresponds to a proton bombarding energy of about 3 Mev in the mirror reaction, in a region which has not been explored.) That this does not seem like an improbable occurrence may be seen by examining the variation of σ with energy, so far as it is known. The agreement with the "$1/v$ law" is good up to several hundred electron volts, but not very good, especially beyond that region, as is seen by examination of Fig. 2. There is a gap between 1 and 4 kev, which separates the regions of applicability of two methods of obtaining monoenergetic neutrons, in which there are no data available, and the points bordering this region on either side are more doubtful than the rest, so that one may draw no firm conclusions from

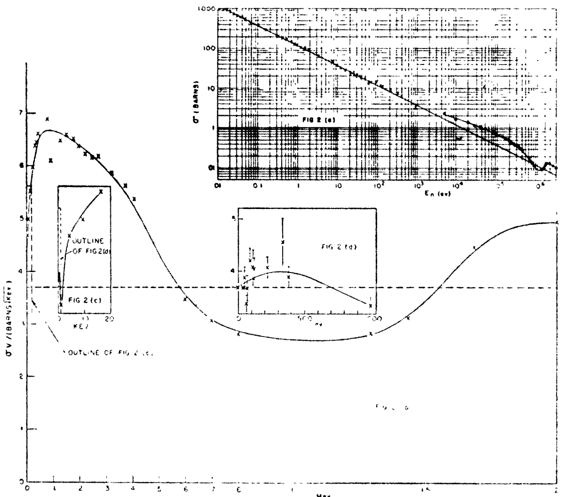

FIG. 2. Energy variation of the cross section for the reaction $B^{10}(n,\alpha)Li^7$. Note that (c) and (d) are successive expansions of the energy scale of the low energy end of (b), displaying the apparent narrow low energy resonance. The bulk of the data in the velocity selector range (0.02 to 1000 ev) are from the work of Sutton, McDaniel, Anderson, and Lavatelli, Phys. Rev. **71**, 272 (1947), which covers a wider range of energy than the similar work of J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946), and in the statitron range (5 kev to 2 Mev) from the work of Bailey, *et al.* (Los Alamos, unpublished), though important check points have been obtained by others (see Goldsmith, Ibser, and Feld, Revs. Modern Phys. **19**, 265 (1947), from which the logarithmic plot is taken). *Note added in proof:* Very recent data of Barshall, *et al.* (private communication) show σv only about $\frac{1}{3}$ to $\frac{2}{3}$ as great as here plotted in the region $\frac{1}{2}$ to 2 Mev, with the 2-Mev resonance more prominent than here. This disagreement casts some doubt on even the existence of a maximum near 100 kev. The main point remains that there is no evidence for a strict $1/v$ dependence beyond 100 ev.

them. It appears quite possible that there is rather sharp resonance, only about 1 kev wide and with $E_R\approx\frac{1}{2}$ kev, responsible for the $1/v$ dependence at low energies. This would probably correspond to the first case discussed above, with the total width equal to the alpha-width, which may be made so narrow partly by the penetration factor arising from $L_\alpha=3$ and partly by variations among the matrix elements. The experimental appearance of such a very narrow resonance depends solely on the low point near 1 kev, which is not considered reliable enough to establish the existence of the resonance. There is a very sharp rise in the region 5 to 30 kev, and then a peak too broad to be attributed to a single level. It is possible either that the sharp level below 1 kev exists and the sharp rise indicates an angular momentum greater than zero for the neutrons in the higher resonances, preventing their contributing to the thermal reaction, or more likely, that the point at 1 kev is erroneous and the thermal cross section arises mainly from a resonance perhaps 50 kev wide in the neighborhood of 30 kev, one of two or more responsible for the peak near 100 kev. The resonance denominator would change very little over the 1-kev region in which the $1/v$ variation has been observed, in spite of the apparent sharpness of the rise on a contracted energy scale. This possibility does not require any very exact fortuitous placement of a level, and either pattern of the deviations from a $1/v$ variation is consistent with a resonance width compatible with $L_\alpha=3$.

We conclude that no second unlikely circumstance, but only the one associated with the intensity ratio itself, is required to permit the interpretation represented by Fig. 1(c).

Recent measurements[19] at various rather widely-spaced energies up to about 4 Mev show that the $B^{10}(n,\alpha)Li^7$ intensity ratio strongly favors the excited-state transition only at energies well below $\frac{1}{2}$ Mev. This new information is not surprising, and does not alter the dilemma, since the participation of p and d neutrons becomes possible at the higher neutron energies. The deviations from the "$1/v$ law" suggest two or more states in the region 50 to 400 kev, not necessarily formed by s neutrons, and it is not expected that the narrow state chiefly responsible for the thermal behavior should be dominant at higher energies.

IV. THE ALPHA-GAMMA ANGULAR CORRELATION IN $B^{10}(n,\alpha)Li^{7*}(\gamma)Li^7$

With $I=\frac{1}{2}$ for the excited state of Li^7 one would have no angular correlation between the alphas and the subsequent gammas from the reaction $B^{10}(n,\alpha)Li^{7*}$ (just as spin $\frac{1}{2}$ can carry no quadrupole moment); but with $I=5/2$ for Li^{7*} and 7/2 for the compound nucleus B^{11}, as in Fig. 1(a), one expects a correlation of the form $(1+A\cos^2\theta)$, and Devons[7] has calculated

$$A=(a^2-0.4b^2-4.5ab\sin\delta)/(7a^2+5.1b^2-1.5ab\sin\delta),$$

where a^2 is the probability of magnetic dipole radiation, b^2 that of electric quadrupole, with $a^2+b^2=1$, and δ is a relative phase which is arbitrary[19a] because of the possible complexity of the compound state and the different nature of the electric and magnetic operators. It is to be noted that $|A|\ll 1$ for both of the extreme cases of unmixed radiation:

$A=\ \ 0.079$ for magnetic dipole radiation ($b=0$);
$A=-0.143$ for electric quadrupole radiation ($a=0$),

as was calculated also by Feld,[7] and the uncertainty[8] in the observation $A\approx 0$ covers about one-seventh of the range between them. The lifetime for magnetic dipole radiation may be estimated[20] as

$$\tau\approx[(4/3\hbar)(\omega/c)^3\mu^2\sigma_{mn}{}^2]^{-1}$$
$$\approx(3/8)1837^2\ 137^2(3\times10^{-13}/3\times10^{10})\ \mathrm{sec}\approx 2\times10^{-13}\ \mathrm{sec},$$

where we have put $\hbar\omega=mc^2$, the spin magnetic moment $\mu=1.4e\hbar/Mc$, and the nondiagonal matrix element of the spin operator, $\sigma_{mn}\approx 1$. It appears that the matrix

[19] P. Huber, personal conversation; also, Petree and Barschall.

[19a] *Note added in proof:* See, however, S. P. Lloyd, Phys. Rev. **81**, 161 (1951), whose result, $\sin\delta=\pm 1$, which was also derived independently by E. N. Adams, II, shows that the cancellation would have a probability $\frac{1}{2}$ if b should be just large enough.

[20] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 251; Fermi, Orear, Rosenfeld, and Schluter, *Nuclear Physics* (University of Pennsylvania Press, Philadelphia, 1941), Chapter V.

element is about 50 percent larger than here estimated (as could perhaps happen for example by superposition of spin and orbital effects), since this should be the large term and the observed lifetime[15] is 0.75×10^{-13} sec. For electric quadrupole radiation, we assume that the charge is, in effect, associated with the protons, in keeping with Siegert's theorem extended to higher electric multipoles,[21] and then have as a similar rough estimate of the lifetime

$$\tau > [(2/\hbar)(\omega/c)^5 e^2 (r_{\parallel} r_{\perp})_{mn}{}^2]^{-1} \approx [(137)^6/2\times10^{23}]\ \text{sec} = 4\times10^{-11}\ \text{sec}.$$

(For heavy nuclei, the magnetic moments μ are about the same because of the suppressing effect of shell structure, and the electric quadrupole reciprocal lifetime grows relative to magnetic dipole by a factor $\omega^2 A^{4/3}$, making the two about equal for $\hbar\omega = 5mc^2$, $A = 100$, in keeping with the customary classification of degrees of forbiddenness.) For this rather soft radiation from a light nucleus one thus expects the electric quadrupole radiation to be something like 200 times weaker than the magnetic dipole radiation, implying $b/a \leqslant 1/15$. The numerical coefficient 4.5 in the expression for A is, however, so large that the rather small value $b/a \approx 1/5$ would make it possible for A to be zero (as was pointed out by Adams). Thus, an electric quadrupole matrix element three times larger than this rough upper limit[21a] would make it possible for A to vanish fortuitously. For $I = 5/2$, this would require either a failure of Siegert's theorem to hold to this accuracy, or a concerted action of more than one proton in spite of the stability of the s-shell, or a considerably larger nucleus than estimated, as might be associated with the weak stability of Li^7 relative to $\alpha + T$, or a combination of these effects and a surprising lack of cancellation in the matrix element, but in any case with the simultaneous circumstance that $\sin\delta$ have the right sign, this seems much less likely than that one matrix element in the intensity ratio should be small because of cancellation by a factor 6.

The observed approximate lack of alpha-gamma angular correlation, together with the expectation of predominantly magnetic dipole radiation and the isotropy of the $Li^7(p,p')$ gammas, thus seem to demonstrate[22] that $I = \frac{1}{2}$ considerably more conclusively than does the thermal intensity ratio suggest that $I = 5/2$, and thus practically forces one to ascribe the anomalous intensity ratio to chance misbehavior of a matrix element. This conclusion is happily in keeping with theoretical expectations based on nuclear models, that $I = \frac{1}{2}$ with odd parity.

Gratitude is expressed to Professor E. Fermi and Dr. E. N. Adams, II, of the University of Chicago and to Professor S. Devons of Imperial College, London, for discussion of these and related topics.

[21] A. Seigert, Phys. Rev. **52**, 727, (1937), and recent discussions of R. G. Sachs.

[21a] *Note added in proof:* An empirical tendency of electric multipole matrix elements to be much smaller than such a roughly estimated upper limit, especially when compared with magnetic multipoles to which meson exchange currents may contribute, has been pointed out by M. Goldhaber, Bull. Am. Phys. Soc. **26**, No. 1, M4 (title only) (1951).

[22] There is another possibility not represented in Fig. 1 which would give no angular correlation (Reference 7) and require the unexpected behavior to provide only a factor 17 instead of 34, namely, $5/2^+$ for both the compound state and the 480-Kev state; but this parity for Li^7 seems too unlikely, on the basis of models and the observed isolation of the two low states, to merit further consideration.

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Variation with Energy of Nuclear Collision Cross Sections for High Energy Neutrons

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Nuclear total cross sections for high energy neutrons have been measured for approximately known neutron energies in the range 90 to 270 Mev. It is observed that cross sections in every case drop rather rapidly between 100 and 180 Mev to a level which continues with little further variation up to the highest neutron energies available in the experiment. Comparisons are made with nuclear attenuation data for cosmic rays.

I. INTRODUCTION

Nuclear collision cross sections for high energy neutrons have been measured at three different energy regions for neutrons produced by the University of California 184-inch cyclotron. Stripping of 90-, and 190-Mev deuterons by beryllium targets produced neutrons[1,2] of mean energies 40 and 90 Mev, respectively. Measurements[3,4] utilizing the $C^{12}(n,2n)C^{11}$ reaction for detection provided total nuclear cross sections at estimated mean neutron detection energies of 42 and

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[1] Helmholz, McMillan, and Sewell, Phys. Rev. **72**, 1003 (1947).

[2] R. Serber, Phys. Rev. **72**, 1008 (1947).

[3] R. Hildebrand and C. Leith, in preparation for publication.

[4] Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).