PHYSICAL REVIEW VOLUME 81, NUMBER 6 MARCH 15, 1951

Low States of Li^7 in Intermediate Coupling

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(Received October 9, 1950)

The intermediate-coupling transition of the five lowest levels of Li^7-Be^7 is discussed. Some analytical emphasis is placed on the approach from the (jj) coupling extreme with ordinary (nonexchange) interactions, in which case there is a first-order degeneracy which might have helped explain the scarcity of low levels, but second-order perturbations are shown to be too large. The only possibility of obtaining just two isolated low levels with either ordinary or Majorana interactions lies near the (LS) coupling extreme, with angular momentum $I=1/2$ for the excited state.

I. EXPECTED VALUES OF THE COUPLING PARAMETERS

THE determination of the relative magnitude of the spin-orbit energy parameter a and the parameter K representing the specific nuclear interaction in light nuclei remains one of the unsolved problems in the formulation of nuclear structure in terms of two-nucleon interactions. The dynamical theory[1] of spin-orbit coupling which treats a nucleon spin in direct analogy to the spin of an atomic electron suggests a single-nucleon spin-orbit parameter of the order of magnitude 100 kev in a light nucleus like Li^7, which, especially after being reduced by a factor 1/3 corresponding to the three p-nucleons of Li^7, leaves a splitting considerably too small to account alone for the 480-kev excitation of the first known excited state of Li^7 as the splitting of a ^2P. The successful interpretation[2] of extensive regularities among the heavier nuclei in terms of a (jj) coupling scheme which depends on relatively large spin-orbit energy for its realization and also the recent interpretation of the charge dependence of high energy nucleon-nucleon scattering[3] suggest that there must be another origin[4,5] of spin-orbit energy beyond the dynamical relativistic Thomas term, strong enough to make the single-nucleon doublet splitting about 2 Mev or more in heavy nuclei ($A \geqslant 120$) for nucleons having large orbital angular momentum lh, say $l \geqslant 4$. The Thomas term varies with orbital angular momentum and radius as l^3/r^4 [or, more exactly, as $l(l+\frac{1}{2})(l+1)/r^4$], as does also the theory of Gaus[4] and probably other theories arising from the detailed demands of relativistic invariance. If we thus assume that the single-nucleon doublet splitting varies with l and with mass number A as $l(l+\frac{1}{2})(l+1)/A^{4/3}$, we would expect a splitting of about 3 Mev or more for a single nucleon in Li^7, or a nuclear ^2P splitting of about 1 Mev. This is larger than the observed 480-kev splitting of the two low states by a factor of two, but such an estimate must be considered quite uncertain. The 480-kev splitting thus seems compatible with (jj) coupling in heavy nuclei. Observations of the reaction $Be^9(d,\alpha)Li^7$ at two bombarding energies[6,7] indicate a spectrum of Li^7 devoid of sharply defined[8] levels from 480 kev up to beyond 3.6 Mev, as would be characteristic of rather extreme (LS) coupling with a 480-kev wide ^2P well removed from the next multiplet, if no states have been missed by this reaction.

Although the single-nucleon doublet splitting does not differ greatly between light and heavy nuclei, the competing parameters do vary in the right direction to make it possible to have (LS) coupling in light nuclei and (jj) coupling in heavy nuclei. The occurrence of (LS) coupling requires that the parameters representing the two-nucleon interaction be much larger than the spin-orbit parameter a, and they are, indeed, larger for light than for heavy nuclei because they depend on the probability of finding two given nucleons within the interaction range of each other. For p-nucleons there are two such parameters,[9] K and L, and their magnitudes may be estimated by means of the three-dimensional harmonic-oscillator approximation.[9,10]

$$K=B\sigma^{3/2}/\tau^{7/2}, \quad L=(\tau^2-2\tau+3)K, \quad \tau\equiv\sigma+2. \quad (1)$$

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[1] D. R. Inglis, Phys. Rev. **50**, 783 (1936); G. Breit and J. R. Stehn, Phys. Rev. **53**, 459 (1938).

[2] M. G. Mayer, Phys. Rev. **75**, 1969 (1949); **78**, 16 (1950); Haxel, Jensen, and Suess, Phys. Rev. **75**, 1766 (1949); Naturwissenschaften **36**, 155 (1949). See, however, E. Feenberg, Phys. Rev. **76**, 1275 (1949) and G. Racah, Phys. Rev. **78**, 622 (1950), where it is suggested that at least some of the Mayer-Jensen results may be obtained without such large spin-orbit coupling as assumed in the text.

[3] K. M. Case and A. Pais, Phys. Rev. **80**, 138 (1950).

[4] H. Gaus, communication from W. F. Weizsacher.

[5] A. M. Feingold and E. P. Wigner, Phys. Rev. **79**, 221 (1950).

[6] W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949).

[7] D. R. Inglis, Phys. Rev. **78**, 104 (1950).

[8] With B^9+d, in addition to the sharply-defined alpha-energies corresponding to the two low levels of Li^7, a continuum of alpha-energies is observed in reference 7 and attributed to the formation of two alphas and a triton. These alpha-energies would correspond to Li^7 excitation energies between 2.5 Mev and 3.6 Mev (the limit of the observations). If one should choose instead to attribute these alphas to a broad state of Li^7, its lifetime would be not much more than the time for an alpha and a triton to fly apart beyond a reasonable range of interaction, and the existence of a state described in these terms would not be expected to interfere with the existence of sharp states describable more nearly by the shell model. These could be alternative modes of excitation with very small matrix elements between them.

[9] E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937), Eq. (23).

[10] D. R. Inglis, Phys. Rev. **51**, 531 (1937). In the notation of this paper,

$$K=\int x_1x_2y_1y_2R^2(r_1)R^2(r_2)R\exp(-\alpha r_{12}^2)dr_1dr_2=f_{1100}^2f_{0000}(\sigma/r)^{3/2}B;$$

$$L=\int x_1^2x_2^2R^2(r_1)R^2(r_2)B\exp(-\alpha r_{12}^2)dr_1dr_2=f_{1111}f_{0000}^2(\sigma/r)^{3/2}B.$$

TABLE I. First-order energies, (jj) coupling.

I of state	Ordinary interaction $\nu-\nu$	 $\nu-\pi$	 Total	Majorana interaction $\nu-\nu$	 $\nu-\pi$	 Total	 Total, $L=6K$
7/2	$L-7K/3$	$2L-8K/3$	$3L-5K$	$\frac{1}{3}(-L+5K)$	$\frac{2}{3}(2L-K)$	$L+K$	$7K$
5/2	$L-7K/3$	$2L-8K/3$	$3L-5K$	$\frac{1}{3}(-L+5K)$	$2(4L-3K)/9$	$(5L+21K)/9$	$17K/3$
$3/2(J_\nu=2)$	$L-7K/3$	$2L-8K/3$	$3L-5K$	$\frac{1}{3}(-L+5K)$	$\frac{1}{6}(L+17K)$	$(-L+27K)/6$	$7K/2$
1/2	$L-7K/3$	$2L-8K/3$	$3L-5K$	$\frac{1}{3}(-L+5K)$	$10K/3$	$-\frac{1}{3}L+5K$	$3K$
$3/2(J_\nu=0)$	$L+\frac{1}{3}K$	$2L-8K/3$	$3L-7K/3$	$\frac{1}{3}(L+7K)$	$\frac{2}{3}(L+2K)$	$L+11K/3$	$29K/3$
3/2(First excited)			$3L-17K/3$			$[5L+49K-(129L^2-230LK+105K^2)^{\frac{1}{2}}]/12$	$1.75K$
3/2(Ground)			$3L-5K/3$			$[5L+49K+(129L^2-230LK+105K^2)^{\frac{1}{2}}]/12$	$11.42K$

Here B is the effective depth of the interaction, say, $50mc^2$, and $\sigma^{\frac{1}{2}}$ is the ratio of the range of the interactions to the radius of the nucleon distribution. That is, $\exp(-\alpha r^2)$ appears in the interaction and $\exp(-\sigma\alpha r^2/2)$ in the wave function. For lithium a value of σ about 1 is appropriate[9] (which means that a nucleon at the center of the nucleus can just interact with one at the edge), and the nuclear volume is proportional to $\sigma^{-3/2}$, which is proportional to mass number A, so for a moderately heavy nucleus with $A=120$, a corresponding value would be $\sigma=0.15$. For Li^7 we thus estimate that K is five times and L nine times as great as in a moderately heavy nucleus. While one is actually not much interested in p-nucleons in the empirical study of spin-orbit coupling in moderately heavy nuclei, the trend suggested by this estimate (as compared with a 50 percent increase in the spin-orbit parameter a) is about strong enough to reconcile, if necessary, the occurrence of (LS) coupling in light nuclei with (jj) in heavy. It seems to be somewhat more likely from this rough evaluation of the integrals that Li^7 and Be^7 might be in a coupling condition intermediate between the (LS) and (jj) extremes, but nearer to (LS) coupling than are heavy nuclei.

It is to be anticipated that further states of Li^7 and Be^7 will be observed beyond the two low states which have as yet been observed with certainty in each, and it will be of interest to try to interpret their spacing in terms of coupling schemes and assumed interactions. We here study energies of the five lowest states as they approach intermediate coupling from both extremes, and then infer the intermediate-coupling transition between them by interpolation.

II. EXTREME (jj) COUPLING

In addition to the usual binding forces approximated by a central potential well, the hamiltonian is, for the sake of obtaining the (jj) coupling scheme, assumed to contain the zero-order term $\Sigma a\mathbf{l}_i\cdot\mathbf{s}_i$ coupling the nucleon spins to their individual orbits. With the sign of a determined by the usual rule, the p-shell of Li^7 then contains the lowest "jj-configuration" $(P_{3/2})^2_{\text{neut}}(P_{3/2})_{\text{prot}}$. As the first-order term in the hamiltonian one introduces the symmetric (that is, charge-independent) interaction between all pairs of particles. The evaluation of the neutron-neutron part is strongly dependent on the antisymmetry of the wave function in the two neutrons, and as a first step may be said to give rise to the neutron states with total angular momentum $J_\nu=0$ and 2, of which 0 is the ground state. The excited states may be described first in terms of a coupling of this $J_\nu=2$ to the proton vector $j_\pi=3/2$, giving rise, with the ground state, to a set of states in which the energy is not yet diagonal because of the existence of two states with $I=3/2$. The diagonal elements are given in Table I, and the nondiagonal elements for ordinary and Majorana interactions are $(2/3)5^{\frac{1}{2}}K$ and $(5^{\frac{1}{2}}/3)(L-K)$, respectively. The signs are here consistent with the choice of phase made by Condon and Shortley.[11] The proper values after diagonalization are given in the last two rows of Table I. Both K and L appear for Majorana interactions, and the specialization is made $L/K=6$. This corresponds to the reasonable value $\sigma=1$, and the ratio is not very sensitive to variation of σ. With ordinary interactions the states with $I=1/2$, 5/2, and 7/2 are degenerate, and there is some interest in investigating the extent to which the second-order perturbations lift this degeneracy.[12]

III. (jj) COUPLING IN SECOND ORDER WITH ORDINARY INTERACTIONS

The zero-order excited states within the p-shell, of which the perturbing effect has been considered, may be grouped in "jj-configurations" according to whether the proton has been excited to the $p_{\frac{1}{2}}$ single-nucleon state, or a neutron, or both, or both neutrons. (The excitation of all three leads to zero matrix elements because of the two-body interactions assumed.) These are listed across the top of Table II, and below them are tabulated their approximate contributions to the energy of the various states of the lowest "jj-configu-

TABLE II. Depression of $(P_{3/2})_\nu^2(P_{3/2})_\pi$ levels by higher levels, ordinary interaction. ΔE in units of K^2/a.

Perturbing configuration I of low state	$(P_{3/2})_\nu^2$ $\times[P_{1/2}]_\pi$	$(P_{3/2})_\nu$ $\times[P_{1/2}]_\nu$ $\times(P_{3/2})_\pi$	$(P_{3/2})$ $\times[P_{1/2}]_\nu$ $\times[P_{1/2}]_\pi$	$[P_{1/2}]_\nu^2$ $\times(P_{3/2})_\pi$	Total
7/2	...	4/3	...	...	4/3
5/3	...	8/27	7/27	...	5/9
3/2	20/81	40/27	40/27	25/81	95/27
1/2	256/135	1024/405	16/45	...	1936/405
3/2(Ground)	100/81	8/27	2/27	125/81	85/27

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[11] E. U. Condon and G. H. Shortley, *Theory of Atomic Spectra* (The Cambridge University Press, New York, 1936).

[12] D. R. Inglis, Phys. Rev. **77**, 724 (1949).

ration," calculated with ordinary (nonexchange) interactions.

IV. (LS) COUPLING

Since the number of states in the configuration $p^2_{\text{neut}}p_{\text{prot}}$ with a given value of I ranges up to eight for $I=3/2$, the secular determinants whose solution would be required for a complete description of the intermediate-coupling transition are of rather high order. In order to avoid handling them, it is desirable to approximate the intermediate-coupling transition for the low states which have most potential experimental interest by interpolation between the two extreme coupling schemes.

The level scheme for extreme (*LS*) coupling has been given by Feenberg and Wigner[13] and by Feenberg and Phillips[14] for the various phenomenological exchange interactions. Their results for Li^7 for ordinary and Majorana interactions are given in Table III. In the above discussion of (*jj*) coupling, we have departed from the extreme coupling scheme and have taken a first step towards intermediate coupling, which in that case involved the second-order influence of higher states. The corresponding first step from extreme (*LS*) coupling towards intermediate coupling consists in the introduction of the spin-orbit energy in the hamiltonian and the inclusion of its diagonal elements in the energy. These are given in Table III. It happens that the extreme (*LS*) coupling scheme leaves degeneracies of levels with the same value of I, which must also be lifted in this step. For the low states whose intermediate-coupling transition we wish to consider here, this involves the diagonalization of a three-row matrix for $I=3/2$. The results of this step are given in Table III.

TABLE III. Energy in (*LS*) coupling.

(*LS*) state	(*LS*) energy ord. int. (maj. $L=6K$)	Spin-orbit energy (*A*) (*LS*)	Spin-orbit energy (diagonalized)
$^4D_{1/2}$	$3L-6K$ $(3K)$	$(a/3)(-9/2)=-3/2a$	
$^4D_{3/2}$		$(a/3)(-3)=-a$	
$^2D_{3/2}, {}^2D_{3/2}$		$(a/6)(-3/2)=-a/4$	
$^4D_{5/2}$		$(a/3)(-1/2)=-a/6$	
$^2D_{5/2}, {}^2D_{5/2}$		$(a/6)(1)=a/6$	
$^4D_{7/2}$		$(a/3)(3)=a$	
$^4P_{1/2}$	$3L-4K$ $(5K)$	$(a/3)(-5/2)=-5/6a$	
$^4P_{3/2}$		$(a/3)(-1)=-a/3$	$-0.447a$
$^2P_{1/2}, {}^2P_{1/2}$		$(a/6)(-1)=-a/6$	0
$^2P_{3/2}, {}^2P_{3/2}$		$(a/6)(1/2)=a/12$	$0.280a$
$^4P_{5/2}$		$(a/3)(3/2)=a/2$	
$^2F_{5/2}$	$3L-3K$ $(15K)$	$(a/3)(-2)=-2a/3$	
$^2F_{7/2}$		$(a/3)(3/2)=a/2$	
$^2P_{1/2}$	$3L+2K$ $(20K)$	$(a/3)(-1)=-a/3$	
$^2P_{3/2}$		$(a/3)(1/2)=a/6$	

V. INTERPOLATED INTERMEDIATE COUPLING

Interpolation between extreme coupling schemes is a familiar device in atomic spectroscopy, both in the intermediate coupling transition from (*LS*) to (*jj*) coupling and in the Paschen-Back transition so important to modern magnetic resonance methods of determining molecular and nuclear moments. In such interpolation the rule[15] is employed which forbids crossing of the energies of states having the same value of I (and M_I). The intermediate-coupling transition for the five low states of Li^7 is shown in Fig. 1, in which the energies of the states are represented as functions of the spin-orbit coupling parameter, a. The transition for these five states is, of course, only part of a larger transition scheme which is indicated schematically in the small insert in Fig. 1, involving many more states for which the details have not been worked out. In order to provide a graph which is more convenient for studying the behavior of the levels near (*jj*) coupling, the same energies are plotted in Fig. 2 after subtraction of the term $(3a/2)$. In drawing the interpolations involved in these curves, there is some arbitrariness but relatively little because one step has been calculated approaching intermediate coupling from each extreme (giving the slope on the left side and the departure of the curve from an asymptote on the right side). The curves are thus not quantitatively reliable in the intermediate region and are these drawn with broken lines.

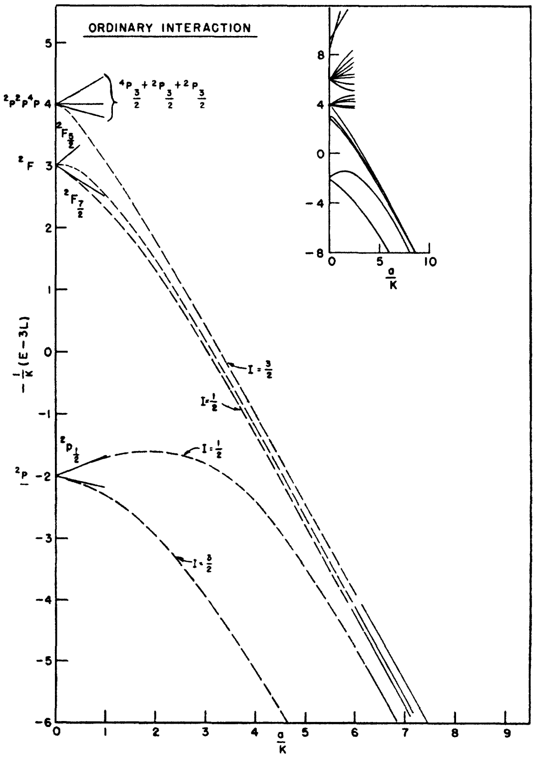

FIG. 1. Energy level diagram of the five low states of Li^7 with intermediate coupling (ordinary interactions).

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[13] E. Feenberg and E. P. Wigner, Phys. Rev. **51**, 95 (1937).

[14] E. Feenberg and M. Phillips, Phys. Rev. **51**, 597 (1937).

[15] J. Von Neumann and E. Wigner, Physik. Z. **30**, 467 (1929).

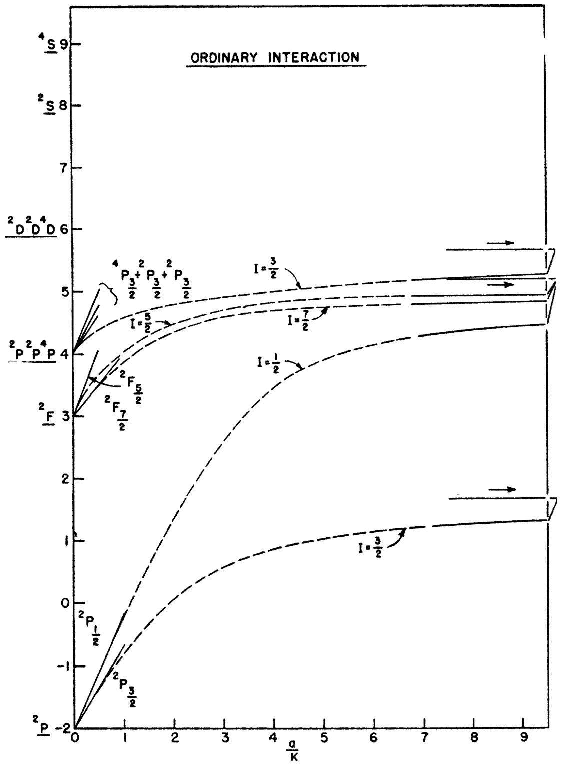

FIG. 2. Revised form of the energy level diagram of Fig. 1. The variation of $-(E-3L+3a/2)/K$ with a/K is shown.

VI. INTERMEDIATE COUPLING WITH SPACE-EXCHANGE INTERACTIONS

The estimated variation of the energies with Majorana (space-exchange) interactions, rather than ordinary (nonexchange) interactions is given in Fig. 3, plotted in the same way as in Fig. 2. With these exchange interactions the second-order departure from (jj) coupling has not been carried out, so that only the asymptote is known on the right side; and the interpolation is considerably less reliable than in the preceding curves, but is presented as a schematic indication of the sort of modification that may be introduced by exchange. The slope on the left side is given by the same calculation as before.

VII. DISCUSSION

One sees from Figs. 2 and 3 that a great variety of patterns for the excited states of Li^7—Be^7 is possible. In Fig. 2, the states with $I=\frac{1}{2}$, 5/2, and 7/2 approach the same asymptote in extreme (jj) coupling. The suggestion has been made[12] that one might resort to this first-order degeneracy to try to understand the scarcity of low states of Li^7 in the face of the enigmatic intensity ratio of the reaction B$^{10}(n,\alpha)$Li^7 which seems to require the inclusion of a state with $I=5/2$ in the 480-kev level, rather than just $I=1/2$, for a rational explanation. The second-order splitting of these states indicated on the right side of Fig. 2 is, however, so great that an implausibly large ratio a/K would be required to keep within the experimental resolution (perhaps 15 kev) of the 480-kev level; and, furthermore, a higher level to correspond to $I=3/2$ has failed to appear in most of the observations. Within the scope of Figs. 2 and 3, there is no other way to assign $I=5/2$ to the 480-kev level. If one chooses to ignore the B$^{10}(n,\alpha)$ intensity ratio as fortuitous, an otherwise natural explanation of the scarcity of states is had by selecting a pattern on the left side of Fig. 2 or Fig. 3, with $a/K \leqslant 1$, near (LS) coupling with the ground state and 480-kev state as the two states of a low ^2P as in the original assignment. Somewhere above 3.6 Mev, to which available observations extend, further excited states are expected, the pattern of which depends strongly on the exchange nature of the interactions. Although the apparently most reliable and extensive experiments reveal only two low states of Li^7 (or Be^7), a pattern of four states below 1 Mev in Be^7 has been reported by Grosskreutz and Mather[16] on the basis of cyclotron observations, of Li$^7(p,n)$Be^7 at 5 Mev, and in Fig. 3 with $a/K \approx 3$ one can find a pattern similar to theirs. Because of their 200-kev state, this would make the assignment $I=7/2$ to the 430-kev state in Be^7 (or

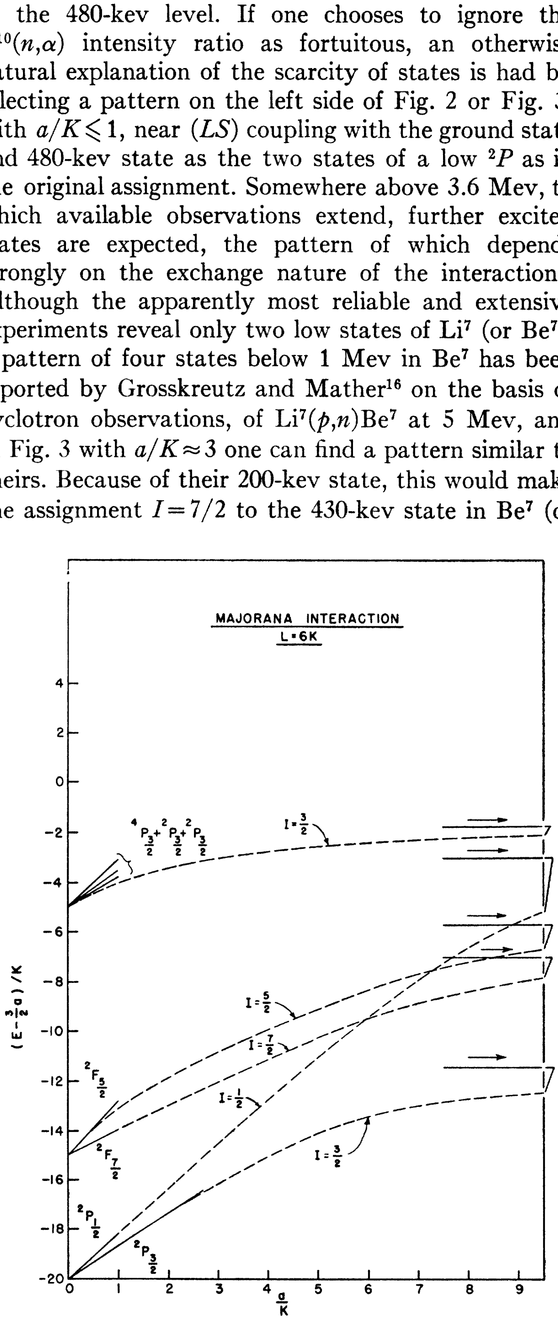

FIG. 3. Energy level diagram of Li^7 with Majorana interactions.

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[16] J. C. Grosskreutz and K. B. Mather, Phys. Rev. **77**, 580 (1950).

480 kev in Li^7) as would be satisfactory for the $\mathrm{B}^{10}(n,\alpha)$ 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]

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[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.

PHYSICAL REVIEW VOLUME 81, NUMBER 6 MARCH 15, 1951

The $\mathrm{B}^{10}(n,\alpha)$ 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 $\mathrm{B}^{10}(n,\alpha)\mathrm{Li}^7$ 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 $\mathrm{B}^{10}(n,\alpha)\mathrm{Li}^7$, 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 $\mathrm{Be}^9(d,\alpha)\mathrm{Li}^7$ 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 $\mathrm{B}^{10}(n,\alpha)\mathrm{Li}^{7*}$, 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 $\mathrm{Li}^7(p,p')\mathrm{Li}^{7*}$ 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 $I_{\mathrm{Be}}=0$, since the rather difficult measurement could be made

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[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).

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[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).

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[8] B. Rose and A. R. W. Wilson, Phys. Rev. **78**, 68 (1950).

[9] R. M. Littauer, Proc. Phys. Soc. (London) **63A**, 294 (1950).