THE DIPOLE STATES OF MASS–11 NUCLEI

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Abstract

Calculations of the even parity states of mass-11 nuclei in the $1p$–$2h$ basis are presented and the results are compared with experimental data from inelastic electron scattering, the $^{11}B(\gamma, n)$ and $^{11}B(\gamma, p)$ cross sections, and the $^{10}B(p, \gamma_0)$ excitation function.

Introduction

In recent years, several experiments directed at investigating the structure of the giant dipole resonance in ^{11}B and ^{11}C have been performed. These include inelastic electron scattering (Kossanyi-Demay and Vanpraet 1966), measurement of the (γ, n) and (γ, p) cross sections in ^{11}B (Hayward and Stovall 1965; Sorokin *et al.* 1969, 1970), and measurement of excitation functions and angular distributions in the $^{10}B(p, \gamma_0)^{11}C$ reaction (Kuan *et al.* 1970). The present paper gives the results of calculations of the dipole states of the mass-11 nuclei and compares these results with the data from the above experiments. The method of calculating the eigenvalues, eigenvectors, and electric dipole matrix elements was the same as that described by Fraser *et al.* (1970) and will therefore not be discussed here. The states of angular momenta $7/2^+$, $9/2^+$, and $11/2^+$ have also been calculated, and these results are exhibited in Tables 1 and 2.

Calculations and Results

The properties of the dipole states of the mass-11 nuclei have been calculated with both a zero-range interaction and the Gillet interaction (Gillet and Vinh-Mau 1964), using the unperturbed single-particle level energies given by Gillet and Vinh-Mau.

The results of the zero-range interaction calculations are presented in Figures 1(*a*), 1(*b*), and 1(*c*) for the three interaction strengths $V_0\,\alpha^3/4\pi = 8$, 12, and 16 MeV respectively. Here, α is the harmonic oscillator range parameter, since this basis is used for the particle and hole wavefunctions. In this case, increasing the strength of the residual interaction (as represented by the parameter $V_0\,\alpha^3/4\pi$) from 8 to 16 MeV increases the energy at which the absorption strength is concentrated from 21 to 25 MeV. There is no separation in energy of the $T = 1/2$ and $3/2$ components of the giant resonance given by calculations with this interaction.

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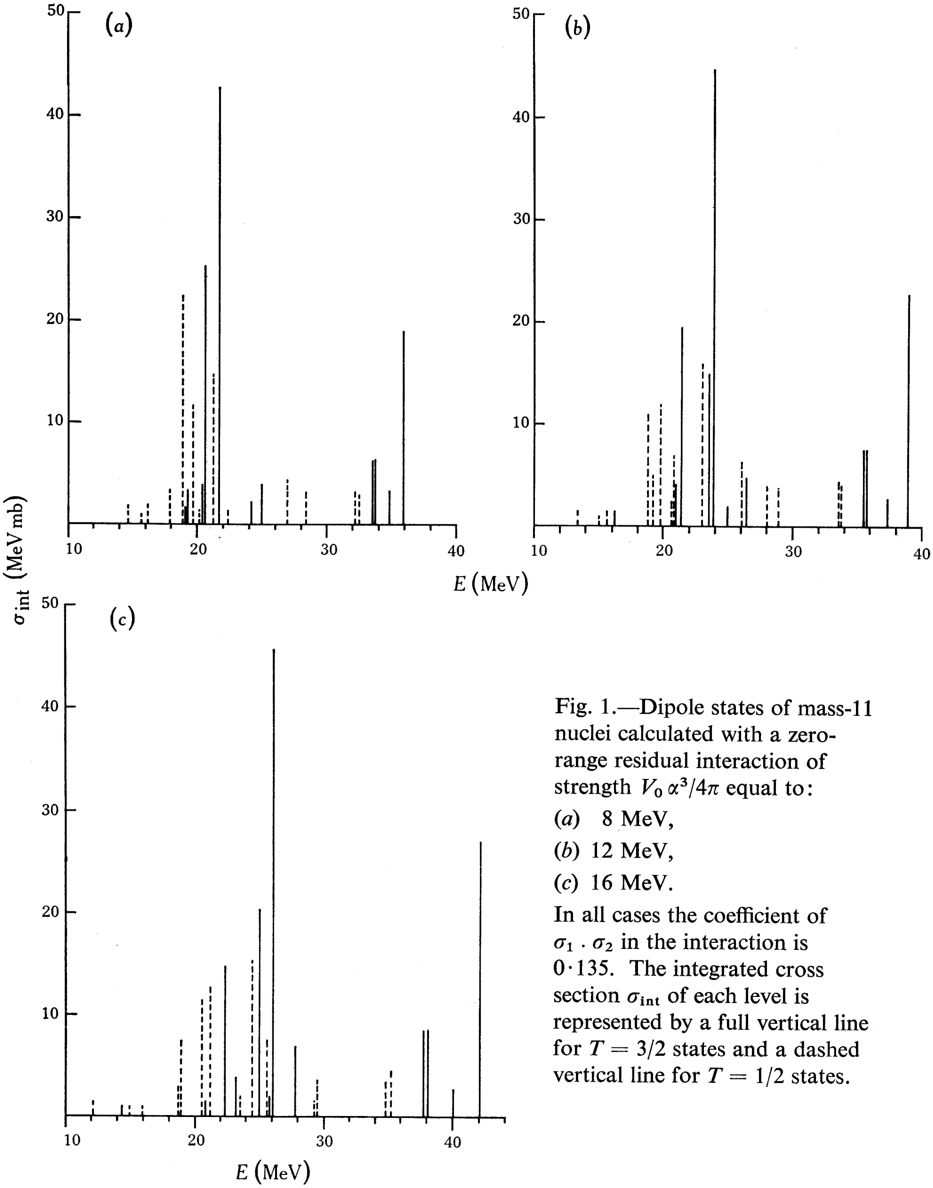

Fig. 1.—Dipole states of mass-11 nuclei calculated with a zero-range residual interaction of strength $V_0\,\alpha^3/4\pi$ equal to:
(*a*) 8 MeV,
(*b*) 12 MeV,
(*c*) 16 MeV.
In all cases the coefficient of $\sigma_1 \cdot \sigma_2$ in the interaction is 0·135. The integrated cross section σ_{int} of each level is represented by a full vertical line for $T = 3/2$ states and a dashed vertical line for $T = 1/2$ states.

Calculations with the Gillet interaction used two values for its strength: 40 MeV, the value used by Gillet and Vinh-Mau (1964) in calculating the dipole states of ^{16}O, and 50 MeV. In the latter case there does appear to be a separation of the strongest absorbing states into components with $T = 1/2$ and $3/2$, although that separation is not clean. A similar and more marked difference between calculations with a zero-range interaction and those with Gillet's finite range interaction, in producing a separation of $T = 1/2$ and $3/2$ contributions to the dipole strength, was found for mass-15 nuclei (Fraser *et al.* 1970). The separation of different isospin contributions to the giant resonance is of considerable importance and it would be very interesting to know the effects of the range of the interaction on more complex calculations, i.e. those including the continuum, isospin mixing, and more complicated configurations.

The use of the Gillet interaction here also leads to the prediction of states which show evidence of configurational splitting. This may be characterized as follows. For states whose excitation is between 10 and 15 MeV, most are formed with the configuration $1p_{3/2}{}^{-1}\,2s_{1/2}$ coupled to the $1p_{3/2}$ hole assumed to be present initially; there is some contribution from the $1p_{3/2}{}^{-1}\,1d_{5/2}$ excitations. For states whose excitation is between 15 and 25 MeV, the configuration $1p_{3/2}{}^{-2}\,1d_{5/2}$ dominates the spectrum, with some contributions from excitations of the type $1p_{3/2}{}^{-1}\,1d_{3/2}$ and $1s_{1/2}{}^{-1}\,1p_{3/2}$. Above 30 MeV excitation, transitions of the type $1s_{1/2}{}^{-1}\,1p_{1/2}$ are dominant for dipole states.

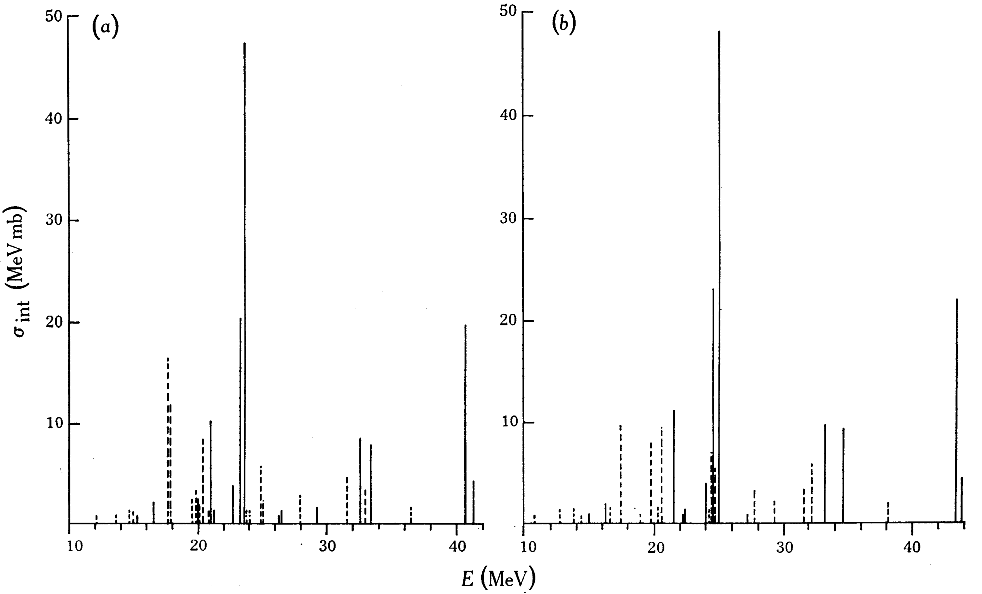

Fig. 2.—Dipole states of mass-11 nuclei calculated with the Gillet and Vinh-Mau (1964) residual interaction of strength (*a*) 40 MeV and (*b*) 50 MeV. The integrated cross sections of the different isospin states are as shown in Figure 1.

The results obtained using the Gillet force are shown in Figures 2(*a*) and 2(*b*), and for the strength parameter $v_0 = 50$ MeV are shown in more detail in Table 1. The results for $v_0 = 50$ MeV are emphasized here as they appear to give the best account of the known experimental data.

DISCUSSION OF RESULTS

General Comparison

This comparison places the calculated information on the dipole states against the data from experiments which indicate the existence of structure within the giant resonance of ^{11}B or ^{11}C. Four such experiments are available. That of Kossanyi-Demay and Vanpraet (1966) gives results of inelastic electron scattering from ^{11}B at 180°. The study of inelastic electron scattering at 180° is known to give data exclusively on magnetic transitions (Barber 1962) and yet, as is clear from Table 1, several peaks are identified at energies corresponding to peaks in the (γ, n) and (γ, p) cross sections of ^{11}B. This may be understood by recognizing that, since the ground state spin and parity of ^{11}B are $3/2^-$, all those states which are reached via E1 transitions in the photon-induced reactions may be excited via M2 transitions in inelastic electron scattering at 180°. (However strong such M2 transitions are, they will form a negligibly small part of the radiative width of the states, being completely swamped by the E1 component of the photon transition.)

TABLE 1

COMPARISON OF CALCULATED EIGENVALUES WITH EXPERIMENTAL DATA FROM $^{11}B(e,e')$, $^{11}B(\gamma,n)$, AND $^{11}B(\gamma,p)$ REACTIONS AND WITH ENERGIES OF LOW-LYING EVEN PARITY STATES

Calculated values*			Experimental data					
E (MeV)	σ_{int}^{E1} (MeV mb)	J^π, T	Levels (MeV) excited in $^{11}B(e,e')$	$^{11}B(\gamma,n)$	$^{11}B(\gamma,p)$	$\sigma_{int}(\gamma,p)$ $+\sigma_{int}(\gamma,n)$†	Low-lying levels (MeV) ^{11}B	^{11}C
7·72	0·01	$1/2^+, 1/2$					6·79	6·34
9·58	0·29	$5/2^+, 1/2$					7·30	6·90
10·72	0·88	$5/2^+, 1/2$					9·27	8·69
11·31	0·30	$3/2^+, 1/2$	7·9				7·98	7·51
11·35	—	$7/2^+, 1/2$					9·19	8·65
12·43	—	$9/2^+, 1/2$	11·3				11·27	10·68
12·48	0·01	$3/2^+, 1/2$	9·5				9·87	
12·67	0·65	$1/2^+, 1/2$					10·38	
13·50	—	$7/2^+, 1/2$	10·6				10·60	10·09
13·82	1·64	$5/2^+, 1/2$						
			12·2		12·4(1/2, 3/2, $5/2^-$)	0·17		
14·29	1·4	$3/2^+, 1/2$	12·65		12·8			
			13·2	13·0	13·1($5/2^-$)	0·5		
14·85	1·12	$1/2^+, 3/2$		14·2	14·0			
14·85	—	$7/2^+, 1/2$	14·55					
15·01	—	$11/2^+, 1/2$						
15·54	0·02	$3/2^+, 1/2$			15·1($5/2^+$)	0·75		
			15·55		15·5($5/2^+$)	1·2		
16·16	2·16	$5/2^+, 3/2$			15·85($5/2^+$)	1·2		
					16·2($5/2^+$)	1·2		
16·32	—	$9/2^+, 1/2$						
16·43	—	$7/2^+, 1/2$						
16·59	1·68	$5/2^+, 1/2$			16·5($5/2^+$)	1·2		
					16·9($5/2^-$)	1·3		
17·38	9·88	$5/2^+, 1/2$			17·5($5/2^+$)	1·6		
17·62	0·60	$1/2^+, 1/2$						
17·64	11·28	$3/2^+, 1/2$			17·8($5/2^+$)			
18·33	—	$7/2^+, 1/2$						
18·86	—	$9/2^+, 1/2$						
18·90	0·92	$5/2^+, 1/2$		18·1	18·2	6·1		
19·53	0·20	$1/2^+, 1/2$						
19·84	8·01	$5/2^+, 1/2$		20·0	20·2	7·1		
20·01	0·01	$3/2^+, 3/2$						
20·42	1·50	$3/2^+, 1/2$						
20·50	1·53	$3/2^+, 1/2$						
20·63	9·66	$1/2^+, 1/2$						
21·32	—	$7/2^+, 1/2$						
21·46	11·55	$3/2^+, 3/2$		21·9	21·6	12·5		
22·16	1·58	$5/2^+, 3/2$						
22·19	1·08	$3/2^+, 1/2$						
22·78	—	$9/2^+, 3/2$						
22·98	—	$7/2^+, 3/2$						

TABLE 1 (*Continued*)

Calculated values*			Experimental data						
E (MeV)	$\sigma_{\mathrm{int}}^{\mathrm{E1}}$ (MeV mb)	J^{π}, T	Levels (MeV) excited in ^{11}B(e, e′)	^{11}B(γ, n)	^{11}B(γ, p)	$\sigma_{\mathrm{int}}(\gamma, \mathrm{p}) + \sigma_{\mathrm{int}}(\gamma, \mathrm{n})$†	Low-lying levels (MeV) ^{11}B	^{11}C
23·17	0·07	5/2$^+$, 1/2						
23·95	4·16	1/2$^+$, 3/2		23·4	23·2	16·4		
24·25	1·24	3/2$^+$, 1/2						
24·26	0·20	1/2$^+$, 1/2						
24·34	7·69	5/2$^+$, 1/2						
24·64	22·45	3/2$^+$, 3/2		24·3	24·5	13		
24·69	5·53	1/2$^+$, 1/2						
24·96	50·78	5/2$^+$, 3/2		25·4	25·5	28		
26·94	—	7/2$^+$, 3/2						
27·22	1·09	1/2$^+$, 3/2		26·2		14		
27·22	1·20	3/2$^+$, 3/2						
27·56	0·50	5/2$^+$, 3/2						
27·78	3·33	3/2$^+$, 1/2		27·8	27·7	30		
29·31	2·21	3/2$^+$, 1/2			29·2			
31·52	3·57	5/2$^+$, 1/2						
32·16	6·07	1/2$^+$, 1/2						
33·21	9·80	3/2$^+$, 3/2						
34·64	9·21	1/2$^+$, 3/2						
38·13	1·77	3/2$^+$, 1/2						
43·36	21·97	5/2$^+$, 3/2						
44·26	4·52	3/2$^+$, 3/2						

* For a Gillet and Vinh-Mau (1964) interaction with strength parameter $v_0 = 50$ MeV.
† From measurements by Sorokin *et al.* (1969, 1970).

With the above points in mind, Table 1 presents a comparison of the energies of the peaks observed in the inelastic electron scattering studies by Kossanyi-Demay and Vanpraet (1966), in Hayward and Stovall's (1965) measurement of the ^{11}B(γ, n) cross section, and in the measurements of Sorokin *et al.* (1969, 1970) on the cross section and angular distributions of protons from the ^{11}B(γ, p) reaction. In the last case, the angular distribution measurements led to assignments of spin and parity for the levels observed, and these are shown in Table 1 also. Figure 3 supplements the results in Table 1 with a graphical comparison between the experimental and calculated (γ, n) and (γ, p) cross sections for ^{11}B.

In making the comparison of calculated results and experimental data, it was required that the dipole states which were calculated to have large integrated dipole cross sections should match the strong peaks observed in the (γ, n) and (γ, p) cross section measurements. It may be noted that Table 1 shows the good agreement between the results of these reaction studies. One result of this fitting of the dipole states is that the calculated energies of the low-lying even parity states are too high (Ajzenberg-Selove and Lauritsen 1968) by 2 MeV or so (see Table 1). This is a well-known phenomenon and has been noted, for example, by Gillet *et al.* (1966) and LeTourneaux and Eisenberg (1966) for the case of ^{208}Pb and by Margolis and deTakacsy (1966) for ^{17}O. The phenomenon is simply that if the dipole state energies are adjusted to their correct values by an adjustment of the residual interaction strength then the low-lying states are calculated to come at too high an energy. In the present case it is expected that the inclusion of higher particle–hole configurations (e.g. $3p$–$4h$ excitations) is necessary to obtain a better approach to the experimental values for the low-lying states.

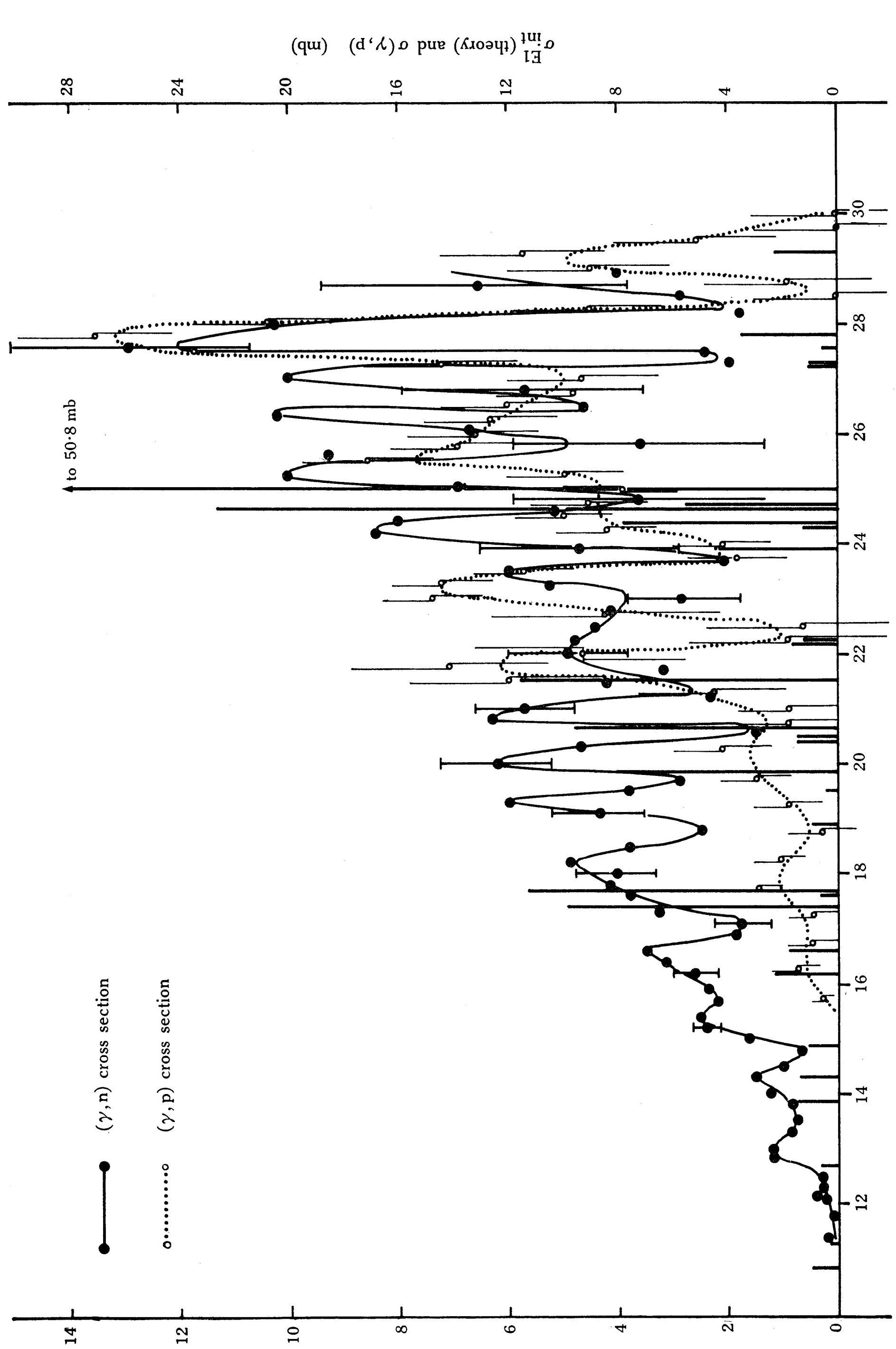

Fig. 3.—Comparison of the measured $^{11}B(\gamma,n)$ and $^{11}B(\gamma,p)$ reaction cross sections with the results of the calculation which used the Gillet and Vinh-Mau (1964) interaction and a strength of 50 MeV. The calculated energy of each dipole state is indicated by a vertical line whose height is proportional to the calculated integrated cross section of the line.

The result of the match at giant resonance energies and the consequent mismatch at the low excitations is a "grey region" at about 13 MeV, where it becomes difficult to know how to make the comparison. It then becomes necessary to look more closely at the calculated wavefunctions of the dipole states, and this has been done for the comparison with the results from the $^{10}B(p, \gamma_0)^{11}C$ reaction (see following subsection).

In the region above 15 MeV, it is of interest to note that the present calculation accounts for the major part of the predominance of $5/2^+$ states indicated by the $^{11}B(\gamma, p)$ experiment (Sorokin *et al.* 1970). A possible effect of the inclusion of the continuum may be inferred from a comparison of the bound state calculations (Fraser *et al.* 1970) with the continuum calculation (Barrett *et al.* 1972) of the total γ-absorption in ^{15}N. The bound state calculation gives a small amount of dipole strength between 11 and 13 MeV with a gap from 13 MeV to about 17 MeV, the lowest energy strongly excited state occurring at 17·5 MeV. The continuum calculation, however, brings this strength to lower energy, giving two broad levels between 13 and 17 MeV. A similar effect on the strength of the strong spin 5/2 state in mass-11 nuclei, calculated to come at 17·38 MeV, would bring the calculations closer to the results of the (γ, p) experiments (Sorokin *et al.* 1970). However, any prediction of the large number of peaks with spin 5/2 seen in this experiment will probably require inclusion of more complex particle–hole states in this energy region than the $1p$–$2h$ excitations considered here.

The present adjustment of interaction strength gives good agreement in the region from 20 to 25 MeV, the calculated peaks of 21·46, 23·95, 24·64, and 24·96 MeV corresponding very well to the measured strong peaks at 21·9, 23·4, 24·3, and 25·4 MeV. The strength between 26 and 30 MeV is not reproduced by the calculations. This is usually the case for simple particle–hole, bound state or continuum, calculations and is generally attributed to the importance of the influence of more complicated configurations.

$T = 1/2$ States from $^{10}B(p, \gamma_0)^{11}C$ Reaction

The comparison of the calculated level properties with the data of Kuan *et al.* (1970) on the $^{10}B(p, \gamma_0)^{11}C$ reaction may be made more specific because only intermediate states in ^{11}C with $T = 1/2$ may be populated in this reaction. Kuan *et al.* reported both excitation functions and angular distributions for the capture reactions. Ajzenberg-Selove and Lauritsen (1968) reported on a resonance in the excitation function at 1·14 MeV proton energy, with the further information that the angular distribution of the ground state γ-rays was $1+0\cdot5\cos^2\theta$. This resonance is below the energy range covered by Kuan *et al.* and occurs at 9·73 MeV excitation in ^{11}C. Such an angular distribution strongly suggests a spin and parity of $5/2^+$ for this level. It is identified in the calculation with the $5/2^+, T = 1/2$ state given at 13·82 MeV. This state has the major component $1d_{5/2}\,(1p_{3/2})^{-2}_{3^+;0}$ and so is quite consistent with the notion of forming the state by adding a $1d_{5/2}$ proton to the ^{10}B ground state. The radiative width of this level has been measured to give $(2J+1)\Gamma_\gamma \approx 10$ eV (Ajzenberg-Selove and Lauritsen 1968). For 9·8 MeV excitation energy Weisskopf's (1951) formula gives estimates of 470 eV for E1 radiation and 30 eV for M1 radiation.

Using our calculated dipole strength and an energy of 9·8 MeV, we obtain $(2J+1)\Gamma_\gamma = 209$ eV. The estimates of the Weisskopf formula favour M1 radiation and the earlier possible spin and parity assignments for this level of $3/2^-$ or $5/2^-$. However, the assignment $J^\pi = 5/2^+$ is strongly favoured, while our calculated dipole strength is sensitive to small changes in the wavefunction, being the difference of larger contributions from several configurations. Further, the large α-decay width of this state suggests a reasonable admixture of more complicated particle–hole configurations so that such a small electric dipole radiative width is quite feasible.

The excitation function reported by Kuan *et al.* (1970) exhibits major peaks at excitation energies of 12·4, 15·0, and 16·7 MeV together with weaker structure at 13·1, 18, and 21 MeV. The angular distribution of photons emitted from the 12·4 MeV resonance is isotropic (Kuan *et al.*) and this indicates that s-wave protons are captured or that the spin of the ^{11}C state is 1/2. The latter possibility would require identification with the spin 1/2 state calculated at 12·67 MeV. The states readily formed by s-wave capture of protons will be those with a large admixture of the configuration comprising two holes coupled to $J^\pi = 3^+$, $T = 0$ and a particle in the $2s_{1/2}$ level. The calculated 13·50 MeV level with $J^\pi = 7/2^+$, $T = 1/2$ has a large admixture of this configuration but can decay to the ground state of ^{11}B only through M2 radiation. The $J^\pi = 5/2^+$, $T = 1/2$ states calculated at 9·58 and 10·72 MeV have admixtures of 25% and 50% respectively, while all the other $J^\pi = 5/2^+$ levels below 20 MeV have less than 5% admixture of the configuration, these levels having been suppressed in energy by the strong hole–hole interaction. When a weaker residual interaction ($v_0 = 40$ MeV) is used the wavefunction of the 10·72 MeV level remains essentially unchanged except for a shift in energy to 12·06 MeV. Thus the suggestion of Kuan *et al.* that this level is formed by s-wave capture, similar to the low energy part of the E1 resonance in other p-shell nuclei, cannot be ruled out by these calculations.

The weak structure at 13·1 MeV has an angular distribution which, when fitted with a Legendre polynomial series $W(\theta) = \Sigma_n a_n P_n(\cos\theta)$, has a positive value of a_1 and maintains $a_2 = 0$. Therefore it is concluded that this structure is due to a state of odd parity which interferes with the state at 12·4 MeV.

The state at 15·0 MeV exhibits an angular distribution with the coefficient $a_2 = 0{\cdot}5$. As shown by Kuan *et al.* (1970), considerable interference effects are necessary to achieve a magnitude for a_2 as large as this, and d-wave capture leading to an ^{11}C state of spin 3/2 or 5/2 is required. With this in mind, tentative identification is made with the state calculated at 15·54 MeV ($3/2^+$, 1/2). The wavefunction calculated for this state has a 52% admixture of configurations with a particle in the $1d_{5/2}$ level, including a 15% admixture of the state comprising two holes coupled to $J^\pi = 3^+$, $T = 0$ (the ^{11}B ground state) plus a $1d_{5/2}$ particle.

Similar arguments tentatively identify the 16·6 MeV peak with the $5/2^+$, 1/2 state calculated to come at 16·59 MeV, and the 18·0 MeV peak with the $3/2^+$, 1/2 state calculated at 17·64 MeV.

The above assignments must be considered in all cases to be tentative because of the neglect of the continuum and of the influence of the coupling in more complicated configurations; nevertheless, each of them is quite consistent with the isospin requirements and the angular distribution information.

$T = 3/2$ States: Levels of ^{11}Be

The lowest even parity $T = 3/2$ state is calculated to be at 14·85 MeV relative to the ground state of ^{11}B and to have spin and parity $1/2^+$. Ajzenberg-Selove and Lauritsen (1968) indicate that the energy difference between ^{11}B and ^{11}Be ground states, after correction for Coulomb effects, is 12·89 MeV. Thus, since the ground state of ^{11}Be is known to have even parity (Ajzenberg-Selove and Lauritsen), the present calculation gives this energy difference about 2 MeV too large. This problem has been noted before (see e.g. the calculations for ^{17}O by Margolis and deTakacsy 1966) and it occurs presumably because of the neglect of higher particle–hole configurations. In spite of this problem with energy, some interesting facts emerge from the comparison.

TABLE 2

COMPARISON OF CALCULATED AND EXPERIMENTAL PROPERTIES OF ENERGY LEVELS IN ^{11}Be

Experimental data*		Calculated properties		
E (MeV)	J^π	E (MeV)	J^π	Dominant configuration
0	$1/2^+(3/2^+, 5/2^+)$	0	$1/2^+$	$[J = 0, T = 1]$ plus $2s_{1/2}$ neutron
0·319	$1/2^-, 5/2^-, 7/2^-$			
1·78	$1/2^\pm, 3/2^\pm, 5/2^+$	1·31	$5/2^+$	$[0^+, 1]$ plus $1d_{5/2}$ neutron, with $[2^+, 1]$ plus $1d_{5/2}$ neutron
2·70	$1/2^\pm, 3/2^\pm, 5/2^+$			
3·41	$1/2^\pm, 3/2^\pm, 5/2^+$			
3·89				
3·96				
		5·16	$3/2^+$	$[0^+, 1]$ plus $1d_{3/2}$ neutron, with $[2^+, 1]$ plus $2s_{1/2}$ neutron
		6·61	$3/2^+$	$[2^+, 1]$ plus $2s_{1/2}$ neutron, with $[0^+, 1]$ plus $1d_{3/2}$ neutron
		7·31	$5/2^+$	$[2^+, 1]$ plus $2s_{1/2}$ neutron
		7·93	$9/2^+$	$[2^+, 1]$ plus $1d_{5/2}$ neutron
		8·13	$7/2^+$	$[2^+, 1]$ plus $1d_{5/2}$ neutron
		9·10	$1/2^+$	$[2^+, 1]$ plus $1d_{5/2}$ neutron
		9·79	$3/2^+$	$[2^+, 1]$ plus $1d_{5/2}$ neutron
		10·11	$5/2^+$	$[2^+, 1]$ plus $1d_{5/2}$ neutron
		12·09	$7/2^+$	$[2^+, 1]$ plus $1d_{3/2}$ neutron
		12·37	$1/2^+$	$[2^+, 1]$ plus $1d_{3/2}$ neutron
		12·37	$3/2^+$	$[2^+, 1]$ plus $1d_{3/2}$ neutron
		12·71	$5/2^+$	$[2^+, 1]$ plus $1d_{3/2}$ neutron

* Margolis and deTakacsy (1966).

Firstly, the spin and parity of the lowest $T = 3/2$ state is given as $1/2^+$, in agreement with the suggestion by Talmi and Unna (1960) that the seventh neutron in the ^{11}Be ground state should be $2s_{1/2}$. Indeed, this calculation gives the wavefunction as essentially the pure configuration of two $1p_{3/2}$ holes coupled to $J^\pi = 0^+$, $T = 1$ with a $2s_{1/2}$ particle. The calculated properties of the ^{11}Be even parity states are shown together with the experimental information in Table 2. The calculated energies are given relative to the lowest $T = 3/2$ state.

Comparison of the calculated and experimental excitation energies in Table 2 leads to the suggestion that only the ground state and the $1\cdot78$ MeV level are of even parity among the states of ^{11}Be which are known at present. However, the inclusion of higher particle–hole configurations or alteration of the residual interaction strength (in particular, an increase in the strength of the hole–hole over that of the particle–hole interaction) may bring other calculated even parity $T = 3/2$ levels closer in energy to that of the ^{11}Be ground state. The present results suggest that if any of the other known states have even parity then they will have $J = 3/2$ or $5/2$.

Conclusions

The one-particle–two-hole model of the dipole states of the mass-11 nuclei has been shown to give a reasonable account of their properties, even in the case of comparison with the ^{10}B(p, γ_0)^{11}C reaction where a more detailed comparison than with other reactions is possible. Although the energy difference between the ground state of ^{11}B and its first $T = 3/2$ state has not been correctly given, the even parity $T = 3/2$ states of the mass-11 nuclei have been given, and it is suggested that five of the seven presently known states of ^{11}Be are of odd parity.

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