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STUDY OF ^{11}B AT HIGH EXCITATIONS WITH THE $^{9}Be(^{3}He,p)^{11}B$ AND $^{9}Be(\alpha,d)^{11}B$ REACTIONS

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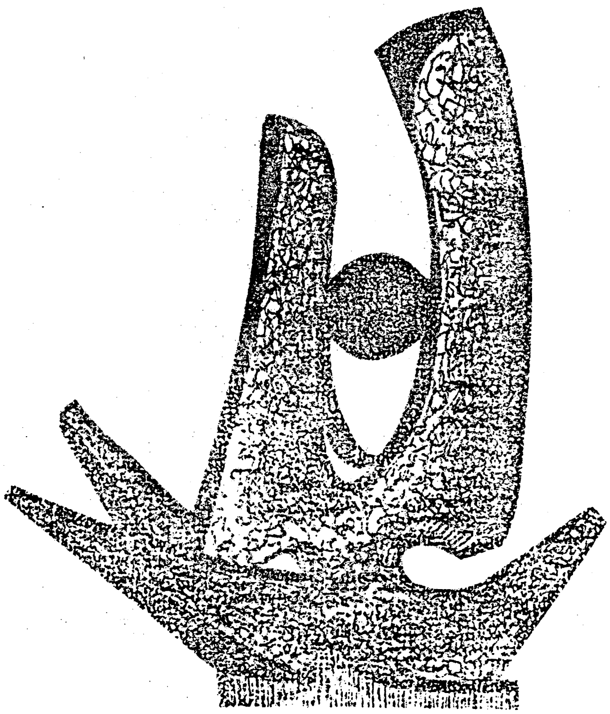

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Study of ^{11}B at High Excitations with the $^{9}Be(^{3}He,p)^{11}B$ and $^{9}Be(\alpha,d)^{11}B$ Reactions

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Abstract

The nucleus ^{11}B has been studied over the excitation energy range from 8.5 MeV to 21.5 MeV with the $^{9}Be(^{3}He,p)^{11}B$ reaction at $E_{^{3}He} = 38$ MeV. The analogs of the parent states in ^{11}Be have been located at 12.56, 12.92, 14.40, 16.44, 17.69, 18.0, 19.15 and 21.27 MeV. A complementary measurement with the $^{9}Be(\alpha,d)^{11}B$ reaction at $E_{\alpha} = 48$ MeV demonstrates that the 16.44, 17.69, 18.0 and 19.15 MeV resonances have rather pure isospin $T_f = 3/2$. The 14.40 MeV state is a strongly isospin-mixed analog of the $5/2^+$ 1.78 MeV state in ^{11}Be. It is argued that spin $S = 1$ transfer is involved in the excitation of the 16.44 MeV state and its 3.887 MeV parent in ^{11}Be in a two-step stripping process. The $T_f = 1/2$ states and the lowest three $T_f = 3/2$ states are compared with the predictions of DWBA utilizing shell-model form factors. It is concluded that the $T_f = 1/2$ strength is more strongly fragmented than is implied by the calculations of Teeters and Kurath.

NUCLEAR REACTIONS: $^{9}Be(^{3}He,p)^{11}B, E_{^{3}He} = 38$ MeV, $^{9}Be(\alpha,d)^{11}B, E_{\alpha} = 48$ MeV, measured $\sigma(E_p,\theta), \sigma(E_{\alpha})$, natural target; deduced energies, widths, isospin purity, L values, DWBA normalization factors, DWBA analysis with shell-model form factors.

I. Introduction

This work presents the results of a study of ^{11}B in the excitation energy range from 8.5 to 21.5 MeV with the $^{9}Be(^{3}He,p)^{11}B$ reaction at a ^{3}He bombarding energy of 38 MeV. There were several motivations for undertaking this study. The main motivation was to identify with the aid of the T=1, S=0 deuteron transfer, the $T_f = 3/2$ analogs of the states in the parent ^{11}Be and to determine the purity of their isospin. This latter objective was achieved with the aid of the $^{9}Be(\alpha,d)^{11}B$ reaction at $E_\alpha = 48$ MeV. Since only the T=0, S=1 deuteron can be transferred in this reaction, these states can be excited only to the extent that they contain $T_f = 1/2$ admixtures.

In spite of a considerable experimental effort[1-4] to locate the isobaric analogs, only four levels are at present considered[5] to have $T_f = 3/2$. These are the $1/2^+$ $(3/2^+)$ 12.56 MeV, $1/2^-$ 12.91 MeV, $5/2^{(+)}$ $(3/2^-)$ 14.33 MeV, and $(3/2,5/2,7/2)^+$ 15.32 MeV states, the former three being the probable analogs of the ground and of the two lowest excited states in ^{11}Be. The recent $^{9}Be(t,p)^{11}Be$ studies at $E_t = 20$ MeV (Ref. [6]) and $E_t = 23$ MeV (Ref. [7]) revealed 13 states in the excitation energy range from the ground state to 10.6 MeV in the parent ^{11}Be. However, the lack of a well defined angular momentum transfer signature in this reaction, and in (t,p) reactions on other 1p-shell nuclei for angular momentum transfers larger than L=0, prevented the authors of Ref. [7] from making spin-parity assignments on the basis of DWBA. Upon undertaking this experiment it was anticipated that with the bombarding energy of $E_{^{3}He} = 38$ MeV, available from the MSU K50 cyclotron, a direct transfer will dominate for orbital transfers higher than L=0, permitting the assignment of L-values for more states in ^{11}B than had been done in the parent nucleus.

There is also considerable interest in the spectroscopy of the highly excited states with $T_f = 1/2$. The energy range covered in the present experiment contains most of the presently known positive parity $T_f = 1/2$ states in this nucleus. These states have not yet been studied with the two-nucleon transfer reactions. Recently Kurath and collaborators[8,9] have calculated the wave functions for the positive parity states in the A=11 nuclei in the complete $1\hbar\omega$ basis. The basis consists of a 2s1d particle coupled to the $(1p)^6$ states of the mass 10 core and a 1s hole coupled to the $(1p)^8$ states of the mass 12 core. The two-nucleon stripping may serve as a particularly stringent test of the "particle" part of these wave functions since for the $T_f = 1/2$ states the interaction of the 2s1d nucleon with the relatively densely spaced levels of the odd-odd core causes mixing of many core components. There are most probably also negative parity "intruder" states resulting from $2\hbar\omega$ excitations into the higher shells in this energy range. The systematics of the "intruder" states of a particular type, viz. those resulting from coupling of the S=1, T=0 pair in the $(1d_{5/2})^2_{5^+}$

state to the ground state of the target, has been established in the work of the Berkeley group 10) in the upper part of the 1p shell. The purpose of the present work is to determine whether the states of this configuration are strongly excited in ^{11}B.

Interest in the properties of highly excited states in light nuclei has been significantly increased recently because of studies of pion inelastic scattering and reactions (see e.g. Ref. 11) for a survey of the recent results). The asymmetry under π^+ and π^- excitation, at the (3,3) resonance in the pion-nucleon interaction, proved to be a sensitive measure of the relative contributions of neutrons and protons to a given transition. To complement the previous study on the odd neutron ^{13}C target,12) the odd proton ^{11}B target would be an interesting object of investigation. The present study adds some information on the properties of its highly excited states. The subject of particular interest is the neutron to proton ratio in the transition to the 14.40 MeV state. This single-particle $1d_{5/2}$ resonance, nominally with $T_f=3/2$, appeared to have strongly mixed isospin in the two-nucleon transfer reactions.

2. Experimental method and results of measurements

^3He ions were accelerated to 38.0 MeV and α-particles to 48 MeV by the MSU K50 isochronous cyclotron. A self-supporting foil of spectroscopically pure metallic beryllium

with a thickness of 470 $\mu g/cm^2$ served as a target. Reaction products were momentum analysed with the Enge split-pole spectrograph. The entrance aperture of the spectrograph subtended 2^o in the reaction plane. The $^9Be(^3He,p)^{11}B$ and $^9Be(\alpha,d)^{11}B$ experiments were performed in separate runs and utilized different detection techniques. A 20 inch proportional counter with a delay-line readout was used in the $^9Be(^3He,p)^{11}B$ measurements. The $^9Be(\alpha,d)^{11}B$ measurements utilized a 10 inch resistive-wire proportional counter. In both these detection systems the readout counters were backed by a ΔE transmission proportional counter and a plastic scintillation counter. These served for particle identification by ΔE x E and time-of-flight methods. Careful separation of the reaction products of interest was a necessity since neither protons nor deuterons were produced intensely in the present experiment. The FWHM resolution attained was typically 80 keV in both experiments. Particle groups originating from carbon deposit on the Be layer were the most troublesome contaminants in the spectra. In particular, the intense lines originating from the states around 13.0 MeV in ^{14}N fell into the region of the isobaric analogs in the $^9Be(^3He,p)^{11}B$ spectra. Therefore the measurements with the ^9Be target were interlaced with measurements with a thin carbon target to permit the subtraction of the carbon contribution. Energy calibration of the spectra was performed with the program DOALL 13) which assumes a quadratic dependence of momentum vs. position along the focal plane of the spectrograph. The coefficients of the calibration curve were determined from a least-squares fit to the calibration lines with known excitation energies. Peak positions and areas were determined by fitting Gaussians to the measured lines. An instrumental width was subtracted in quadrature from the measured widths to yield the level widths. The results of these measurements are summarized in Tables 1 and 2. The energies assumed for calibration are marked with an asterisk.

The statistical errors of the cross section measurements do not exceed 4% in most cases. The systematic errors in determining the cross sections are of the order of 15% for the lines with widths of the order 100-250 keV. For the broad peaks at 13.16 MeV and 18.0 MeV the uncertainty in separation of a line from the underlying background increased the systematic error to about 20%.

Typical spectra measured in the present work from the ^{9}Be(^{3}He,p)^{11}B and ^{9}Be(α,d)^{11}B reactions are shown in Fig. 1. The spectrum for ^{9}Be(α,d) was taken in two passes with different magnetic field settings. For the sake of comparison, this spectrum has been compressed into the common excitation energy scale with the spectrum for ^{9}Be(^{3}He,p). One notes from Fig. 1 that the peaks corresponding to the 16.44 (peak No. 4'), 17.69 (5'), 18.0 (6') and 19.15 MeV (7') states do not occur in the ^{9}Be(α,d) spectrum. Since both T=0 (S=1) and T=1 (S=0) deuterons can be transferred in the direct (^{3}He,p) reaction, whereas only T=0 can be transferred in (α,d), these states therefore have $T_f=3/2$. We postulate that the 21.27 MeV state (peak No. 8') has also $T_f=3/2$ since its energy is close to the expected energy of the analog of the 8.816 MeV state in ^{11}Be. The 16.44 MeV (4') and 17.69 MeV (5') states probably contain small admixtures of $T_f=1/2$, since they have been seen as weak resonances$^{14,15)}$ in the isospin forbidden ^{9}Be + d reaction. Their selective decay into the isospin allowed ^{10}Be + p channel led the authors of Ref. $^{16)}$ to suggest that they might have $T_f=3/2$. The 18.0 (6'), 19.15 (7'), and 21.27 MeV (8') states are newly observed. The 14.47 MeV (3') and 14.56 MeV (13) lines occur with comparable intensities in both spectra. An occurrence of a line in both spectra indicates that the corresponding level has $T_f=1/2$ or is a level with strongly mixed isospin. Arguments are presented in Sect. 4.2 to show that the 14.47 MeV line corresponds to a strongly isospin mixed analog of the $J^{\pi} = 5/2^{+}, 3/2^{+}$ E_x = 1.78 MeV state in ^{11}Be. The asymmetry of the line, as is clearly seen in Fig. 2, plays an important role in the discussion. Figure 3 presents a detailed comparison between the levels of the $T_{fz}=3/2$ and $T_{fz}=1/2$ members of the A=11 isoquadruplet. A more detailed discussion of the arguments which led to the assignments presented in Fig. 3 is contained in Sect. 4.2.

3. DWBA calculations

DWBA calculations were performed with the two-nucleon form factor of the program DWUCK4.$^{17)}$ The form factor was constructed with the single-particle orbitals bound by half the deuteron separation energy. For the states unbound with respect to nucleon emission ($E_x \geq 18.0$ MeV) a more appropriate procedure would be to use the scattering solutions in a potential well, an option not available at present with DWUCK. We have therefore (rather arbitrarily) assumed for these states that the nucleon orbitals are bound by 0.8 MeV. It was verified previously[18] with the $^{10}Be(d,p)^{11}Be$ reaction to the 1.78 MeV $1d_{5/2}$ resonance in ^{11}Be, that the angular distribution for a weakly unbound state, calculated with the scattering solution as a form factor, does not differ appreciably from a distribution which instead uses a weakly bound orbital. The optical potentials applied in the calculations are listed in Table 3. In the entrance channel the potential determined from the fits[19] to the elastic scattering on an adjacent ^{11}B nucleus at 40 MeV is utilized. The proton potential of Perey[20] is used in the exit channel.

The calculated cross-sections $\sigma^{DW}_{LSJ}(\theta)$, corresponding to transferred orbital, L, spin, S, and total momenta, J, are combined incoherently to yield the resulting cross section $d\sigma/d\Omega$, to be compared with the data:

$$\frac{d\sigma}{d\Omega} = 9.72\,\frac{2J_f+1}{2J_i+1}\,D_o^2 \sum_{LSJ} \epsilon_{LSJ}\, C^2_{T_i T T_f}\, b^2_{ST}\, D^2(S,T)\,\frac{\sigma^{DW}_{LSJ}(\theta)}{2J+1} \;. \tag{3.1}$$

Here J_i and J_f are the spins of the target and of the final state, respectively; D_o^2 is an empirical normalization constant to be determined from experiment, $C^2_{T_i T T_f}$ is an isospin Clebsch-Gordan coefficient coupling the transferred isospin, T, to the isospin of the target, T_i, to yield the isospin of the final state, T_f, b^2_{ST} is the spectroscopic factor for the light particles; $b^2_{ST} = 1/2$ for the (^3He,p) reaction. The coefficient $D^2(S,T)$ determines the exchange character of the stripping interaction. We used the values $D^2(0,1) = 0.72$ and $D^2(1,0) = 0.30$ (ratio $R = D^2(1,0)/D^2(0,1) = 0.42$) tested with (p,t) and (p,^{3}He) reactions to mirror states in 2s1d shell nuclei using a reliable spectroscopy.[21] Previously, a similar choice was made from the pick-up studies[22] on 1p-shell nuclei. The quantity ϵ_{LSJ} is a normalization coefficient indicating the degree of agreement between the experimental and the calculated cross sections. A value of $\epsilon_{LSJ} = 1$ is perfect agreement.

The spectroscopic amplitudes listed by Cohen and Kurath[23] are used for the negative parity states. An intermediate state expansion[24] is employed to calculate the two-nucleon amplitudes, $S^{1/2}(j_a j_b;J)$, for the positive parity states utilizing the tabulated one-nucleon amplitudes for the 1p[25] and 2s1d-shell[9] nucleons:

$$\begin{aligned} S^{1/2}(j_a t_a j_b t_b;JT) = {} & \left((2J+1)(2T+1)\right)^{1/2} \\ & \times \sum_{yJ_cT_c} \left((2J_c+1)(2T_c+1)\right)^{1/2} \\ & \times W(J_i j_a J_f j_b;J_c J)\,W(T_i t_a T_f t_b;T_c T) \\ & \times S^{1/2}(J_i T_i;j_a t_a,yJ_cT_c) \\ & \times S^{1/2}(J_f T_f;j_b t_b,yJ_cT_c) \;, \end{aligned} \tag{3.2}$$

where the W's are Racah coefficients. In eq. (3.2) the final state is reached in two steps through the intermediate core states yJ_cT_c of the nucleus A_i+1 with a j_at_a nucleon transferred in the first and a j_bt_b nucleon in the second step. The one-nucleon amplitudes are $S^{1/2}(j_a)$ and $S^{1/2}(j_b)$, respectively. The summation in (3.2) extends over all those core states having a nonvanishing one-nucleon overlap with the initial J_iT_i and final J_fT_f states. In the extreme weak-coupling situation only a single core state in (3.2) contributes. In ^{9}Be(^{3}He,p) to T_f=1/2 states in ^{11}B, the intermediate core states are both the T_c=0 and T_c=1 states of A=10, while in the transitions to the T_f=3/2 states only the T_c=1 states contribute. Because the T_c=0 states of the odd-odd ^{10}B are densely spaced in energy, they get strongly mixed upon addition of a 2s1d shell nucleon. Therefore the wave functions for the T_f=1/2 states are generally superpositions of many core components. The lowest $1/2^+_1$ and $5/2^+_1$ T_f=3/2 states, the only T_f=3/2 states for which the $S^{1/2}$ factors are listed, are close to weak coupling, consisting mostly of a 2s1d nucleon coupled to the 0^+_1 and 2^+_1 T_c=1 states of the A=10 core. Because they are widely spaced, the T_c=1 states are less suspectible to mixing. By inserting the experimental $S^{1/2}$ factors, the amplitude (3.2) can be corrected for some deficiencies of the model calculations.

For those states not having obvious counterparts among the calculated shell-model states, use was made of the form factors indicated in Table 4. The shapes of the calculated angular distributions did not differ significantly if, for a given L-value, a schematic form factor of the type indicated was used instead of a realistic form factor. The extracted ε-values give a measure of the strength for these transitions to facilitate comparison with the results of the future shell-model calculations.

4. Discussion

4.1. Transitions to states with T_f=1/2.

The angular distributions for the transitions to the T_f=1/2 states are presented in Fig. 4. Indicated in Fig. 4 are the orbital momentum transfers dominating the calculated cross sections. The normalization factors ε are collected in Table 4. For a number of the states observed the results, including the absolute normalization, agree reasonably well with previous information. These states are presented in Fig. 4 but will not be further discussed. Some of the questions encountered in the study of other individual transitions are discussed below.

The $5/2^+_2$ 9.274 MeV state

The dominance of L=1 transfer predicted for this state by Teeters and Kurath[9] is not observed in the present experiment. The members of the 9.185 (peak No. 2 in Fig. 1) 9.274 MeV (peak No. 3) doublet are excited with nearly identical angular distributions in which the L=1 and L=3 components have comparable contributions. Decreasing the amount of the $2s_{1/2}$ transfer (S_{ex} = 0.17 vs. S_{th} = 0.43) and increasing the $1d_{5/2}$ transfer (S_{ex} = 0.13 vs. S_{th} = 0.05) from $^{10}B_{g.s.}$ by using the experimental [26] spectroscopic factors in eq. (3.2) brings better agreement with the data. However a low normalization factor of 0.32 (see Table 4) indicates that additional reduction of the strength through the higher core states is also required.

The $3/2^-$ 10.26 MeV, $5/2^-_3$ 10.33 MeV and $5/2^-$ 11.90 MeV states

The two-nucleon amplitudes for the fourth and higher eigenvectors of a given spin are not listed by Cohen and Kurath [23] since as a rule they carry negligible two-nucleon strength. Therefore these narrow negative parity states most probably involve excitations into the higher shells since they are excited quite intensely. The 10.26 MeV (peak No. 5) and 10.33 MeV (peak No. 6) states involve nearly pure L=2 transfer. The 10.33 MeV state is enhanced by a factor of 4.5 over the theoretical predictions. The angular distribution for the $5/2^-$ 11.90 MeV (11) state is well accounted for by a combination of L=0 and L=2 transfers (see Fig. 4).

The $9/2^+_1$ 11.29 MeV state

Within the assumed configuration space this state (peak No. 8 in Fig. 1) should be excited by a pure L=3 transfer. The high-spin $9/2^+$ (and $11/2^+$) states are close to weak coupling according to the predictions of Teeters and Kurath.[9]

The two-nucleon amplitude for $9/2^+_1$ is dominated by the $1d_{5/2}$ transfer from the $^{10}B_{g.s.}$ (3^+_1; T_c=0). The conclusion (see Table 4) that the $S^{1/2}(1d_{5/2})$ factor for this transfer is probably smaller than predicted could be verified by the $^{10}B(d,p)^{11}B$ experiment.

The 11.49 MeV state

This moderately strongly excited state (peak No. 9) has not yet obtained spin-parity assignments. A fit, of comparable quality is obtained assuming both L=0 + L=2 and L=1 transfers, therefore the parity is not indicated uniquely by $^9Be(^3He,p)$. The low cross sections for this state in the resonance reaction [27] suggest a low spin value. Therefore we consider the $1/2^-_2$ and $1/2^+_2$ model states, which were predicted [25,9] in its vicinity (the former at 11.62 MeV, the latter at $\simeq$12.4 MeV) and have not yet been identified in the experimental spectrum, as possible candidates for this state. Both alternatives require enhancement (see Table 4) to reproduce the data.

The $9/2^-$ 13.12 MeV and $5/2^+_3$, $7/2^+$ 13.16 MeV states

This doublet of closely spaced levels of nearly identical widths ($\Gamma_{c.m.}$ = 430 keV) has been suggested by the analyses [28] of ^{10}B + n resonance reactions. The $9/2^-$ 13.12 MeV member of the doublet is a good candidate for the $9/2^-_1$ state of $(1p)^7$, which is not expected [23] to be fed with appreciable strength in $^9Be(^3He,p)$. The positive parity member of the doublet was excited[29] with ℓ_n=2 neutrons in ^{10}B + n with large $^{10}B_{g.s.}$ reduced width. Since the ground state of ^{10}B is connected to the ^{9}Be target by a large $1p_{3/2}$ spectroscopic factor S_{th}=1.2, a strong L=3 transfer in ^{9}Be(^{3}He,p) is therefore expected, if of course, the ground-state component is not cancelled by the transfer through the higher core states. The strong L=3 pattern observed experimentally (see Fig. 4) indicates that the higher core states most probably add constructive contributions. The 13.16 MeV state (peak No. 12) is one of the most intensely excited states in the spectrum of Fig. 1.

The 14.56 MeV state

This state (peak No. 13) has previously[30] been seen as a narrow, ($\Gamma_{c.m.} \leq 120$ keV) weak resonance in the ^{10}B(n,α) reaction. Our better energy resolution allows the establishment of a reduced upper limit for the width of this state; $\Gamma_{c.m.} \leq 30$ keV. The angular distribution suggests that rather pure L=0 (J^π=1/2$^-$, 3/2$^-$ or 5/2$^-$) or L=1 (1/2$^+$ $\leq J^\pi \leq$ 7/2$^+$) transfer is involved. This might imply that transfer occurs with the predominant contribution of the $2s_{1/2}$ orbital, i.e. $(2s_{1/2})^2$ in the former or $1p2s_{1/2}$ in the latter case. The possibility that the 14.56 MeV state has J^π = 5/2$^+$ and is isospin mixed with the J^π = 5/2$^+$ T_f=3/2 state at 14.40 MeV is further discussed in Sect. 4.2.

The study of the transitions to the T_f=1/2 states allows one to draw the following conclusions. The projectile energy of 38 MeV appears to provide enough momentum for the direct stripping to occur for transferred momenta up to and including L=3 at excitation energies as high as $E_x \simeq 13$ MeV. The DWBA calculations allow reproduction of only the most general features of the angular distributions, such as the position of the stripping maximum. Some of the finer details are not accurately predicted. For example, the prominent shoulder in the L=3 angular distributions around $\theta_{c.m.}$ = 55° is predicted to be much weaker than that observed. The example of the 11.49 MeV state illustrates the difficulty in differentiating between the L=1 and L=0+2 transfers, because they both peak at zero degrees. For the states with unknown spin-parity assignments which show this type of angular distributions the parity is not fixed by the experimental data. On the whole the calculations of Teeters and Kurath[9] seem to overestimate (see Table 4) the amount of 2s1d strength in the lowest T_f=1/2 eigenvectors. The missing strength is most probably going into excitation of the higher states lying in the continuum, the 5/2$^+$, 7/2$^+$ 13.16 MeV state being a striking example which illustrates this suggestion.

The states typified by L=4, which would be the possible candidates for $(1d_{5/2})^2_{J^\pi = 5^+}$ configuration have not been encountered. A lower limit for the excitation energy of the centroid of this configuration can be established by extrapolating to ^{11}B the Q_f vs. $A_f = A_i + 2$ dependence found in the (α,d) work of the Berkeley group[10] in the upper 1p shell. The extrapolated energy is equal to about 17.6 MeV, and therefore it comes above the deuteron separation energy of 15.82 MeV in ^{11}B. The ^{9}Be(α,d) spectrum is featureless above the 14.56 MeV peak (see Fig. 1). Since the $1d_{5/2}$ $1p_{3/2}^{-1}$ interaction is known 31) to be more repulsive than the $1d_{5/2}1p_{1/2}^{-1}$ on which is the Q_f vs. A_f dependence is based, the $\left(J_i + (1d_{5/2})^2_{5^+}\right)_{J_f}$ states are most probably shifted to still higher excitation energies at which they are too wide to be observed by final-state interaction methods.

4.2 Transitions to states with T_f=3/2

Four levels in ^{11}B are presently considered 5) to have T_f=3/2. The reaction ^{13}C(p,^{3}He)^{11}Be, which predominantly excites the natural parity states of the $(1p)^7$ configuration, revealed 1) the $1/2^-$, 12.91 MeV state. The ^{10}Be(p,γ)^{11}B reaction 2) excited the 12.55, 12.91 and 14.33 MeV states and a broad anomaly ($\Gamma_{c.m.}$ = 635±180 keV) which is thought to correspond to a state at 15.3 MeV. This latter reaction has properties to a large extent analogous to single-nucleon stripping, exciting strongly those T_f=3/2 resonances in ^{11}B having large overlap with ^{10}Be$_{g.s.}$(0^+_1). The ^{10}Be(d,p)^{11}Be experiment at E_d=25 MeV, performed in this laboratory, 18) examined the parent ^{11}Be up to an excitation energy of 7.0 MeV. It established that only the three lowest states in ^{11}Be - $1/2^+$ 0.0 MeV, $1/2^-$ - 0.320 MeV and $5/2^+(3/2^+)$1.78 MeV states, which are the parents of the above three states in ^{11}B, have a significant ^{10}Be(0^+_1) + n overlap. The ^{9}Be (^{3}He,p)^{11}B, reaction chosen in the present work to locate the T_f=3/2 analogs has the advantage over the two reactions

studied previously that it is able to excite both natural and unnatural parity states built on the excited A=10; T_c=1 configurations (this is apparent from eq. (3.2)). The evidence in favor of weak coupling based on the excited core configurations for some of the T_f=3/2 states is further discussed below.

The experimental angular distributions for the states with T_f=3/2 and the results of DWBA calculations are presented in Fig. 5. The coefficients normalizing theory to the data are collected in Table 4.

The $1/2^+_1$ 12.56 MeV state

The $1/2^+_1$ T_f=3/2 state (peak No. 1' in Fig. 1) according to the predictions of Teeters and Kurath, 9) consists of two A=10 (T_c=1) core components: $\left(0^+_1(T_c{=}1)+2s_{1/2}\right)J^{\pi}_{f=1/2^+}$ and $\left(2^+_1(T_c{=}1) + 1d_{5/2}\right)J^{\pi}_f{=}1/2^+$. The experimental spectroscopic factor for the $2s_{1/2}$ nucleon measured recently 18) in ^{10}Be(d,p)^{11}Be, S_{ex} = 0.77, agrees with the predicted S_{th} of 0.82. The normalization coefficient, ϵ =0.67, found in ^{9}Be(^{3}He,p), is also consistent with this wave function since the ground-state component gives the dominant contribution to the allowed L=1 cross section to this state.

The states near 14.4 MeV

The analog of the 1.78 MeV ($5/2^+$,$3/2^+$) state in ^{11}Be should lie near 14.4 MeV in ^{11}B. There appears to be some disagreement between the results of the present two-nucleon transfer experiment and the properties previously assumed 5) for this analog state. Therefore an extended discussion of this analog pair is presented in this subsection.

The 1.78 MeV state in ^{11}Be has been excited[18] in ^{10}Be(d,p)^{11}Be with ℓ_n=2 and therefore has $J^{\pi}=5/2^+$ or $3/2^+$. The experimental spectroscopic factor, assuming $J^{\pi}=5/2^+$, $S_{ex}(1d_{5/2}) = 0.50$ is in reasonably good agreement with the theoretically predicted[9] $S_{th}(1d_{5/2}) = 0.67$, making the 1.78 MeV level a nearly certain candidate for the $5/2^+_1$ state in ^{11}Be. That the single-particle $1d_{5/2}$ state should lie below the $1d_{3/2}$ state is expected also on the grounds of a simple shell-model. The 14.33 MeV resonance is presently considered[5] to be the analog of this state in ^{11}B. The available information on the 14.33 MeV state comes from the resonance reaction ^{10}Be(p,γ)^{11}B. The state has been assigned $J^{\pi}=5/2^{(+)}$ as the most probable spin and parity on the basis of the angular distribution of the deexcitation γ-rays to the ground state of ^{11}B, which are characteristic of a pure E1-transition. Because the strength of the transition implied ΔT=1 and because of the close proximity to the expected position of the analog, the 14.33 MeV resonance was assumed to have $T_f=3/2$.

However the accepted energy of this state and its isospin purity disagree with the present measurements. Near the expected position of the analog state, two overlapping lines are observed (peaks No. 3 and 13 in Fig. 1) in both the ^{9}Be(^{3}He,p)^{11}B and ^{9}Be(α,d)^{11}B spectra. Peak No. 13 corresponds to the previously known 14.56 MeV state. The

maximum of the peak No. 13 is at E_x = 14.47 MeV±25 keV, an energy at which no state has previously been reported in ^{11}B. Nevertheless there are strong similarities between the peak at E_x = 14.47 MeV and the state observed in ^{10}Be(p,γ)^{11}B at E_x = 14.33 MeV. First, the state observed in the present experiment has a width of $\Gamma_{c.m.}$ = 260±25 keV which is equal within the limits of errors to the state observed in ^{10}Be (p,γ)^{11}B (see Table 1). (This width was extracted by peak fitting of the spectra in the region near 14.4 MeV. In order for the 14.47 MeV peak to have a symmetric peak shape it was necessary to introduce a third state between the 14.57 and 14.47 MeV states. No such state has been seen in previous experiments in either ^{11}B or in the present ^{11}Be nucleus, and this possibility has not been considered further.) In addition a strong L=3 angular distribution is observed for the 14.47 MeV peak (see Fig. 5) in ^{9}Be(^{3}He,p)^{11}B with a cross section magnitude which is within a factor of two of the value predicted[9] for the $J^{\pi}=5/2^+_1$ $T_f=3/2$ state in ^{11}B. According to the predictions, the dominant contribution to the cross section comes from the $1p_{3/2}$ $1d_{5/2}$ transfer through the 0^+_1;T_c=1 state of the core.

If one assumes therefore that the 14.47 MeV and the 14.33 MeV maxima correspond to the same physical state of ^{11}B one must conclude that this state has a strongly mixed isospin since the 14.47 MeV peak occurs in both ^{9}Be(^{3}He,p)^{11}B (T=0 + T=1 transfer) and ^{9}Be(α,d)^{11}B (T=0 transfer) spectra (see Fig. 1). The available information on this energy region in ^{11}B is not sufficient to specify uniquely the

$J^{\pi} = 5/2^{+}$ T_f=1/2 state which mixes by virtue of the Coulomb interaction with the state in question. However the marked asymmetry of both the 14.47 MeV (see Fig. 2) and the 14.33 MeV peaks (see Fig. 5 in Ref. [2]) is evidence that this T_f=3/2 + 1/2 state interferes strongly with its T_f=1/2 + 3/2 partner. It should be stressed that only the interference of the nonorthogonal states, i.e. the states with the same spin and parity and having nonvanishing overlap of their wavefunctions can survive integration over the unobserved directions of their decay products. The possible candidates for this $J^{\pi}=5/2^{+}$ T_f=1/2 + 3/2 state are discussed below. The character of the asymmetry and therefore the sign of the interference term are opposite in the (p,γ) resonance and the two-nucleon transfer experiments. The 14.47 MeV peak appears repelled towards higher excitation energies, while the 14.33 MeV peak towards lower excitation energies from the unperturbed position of the $J^{\pi}=5/2^{+}$ T_f=3/2 state. Determination of the unperturbed positions of the originally pure $J^{\pi}=5/2^{+}$ T_f=3/2 and T_f=1/2 resonances requires the knowledge of the energies and widths of both of the isospin mixed partners, therefore presently cannot be done. Since however the sign of the interference term is opposite in these two cases one can make an assumption that the unperturbed position of the T_f=3/2 state lies between 14.33 and 14.47 MeV.

An alternative interpretation would invoke at least two overlapping resonances to account for the asymmetry of each of the two peaks in question and therefore would require the presence of at least four states with widths of the order of 250 keV at $E_x \simeq 14.3$ MeV in ^{11}B, an assumption in conflict with the presently known data.

Looking for a suitable candidate for the $J^{\pi}=5/2^{+}$ T_f=1/2 state, which mixes with the 14.40 MeV state, one might take the E1 ground-state transition as a signature of the admixed T_f=3/2 strength. From this point of view the 14.56 MeV resonance does not seem to be a good candidate, since it was not seen in ^{10}Be$(p,\gamma)^{11}$B. Moreover, contrary to the theoretical predictions[9] for the $J^{\pi}=5/2^{+}_{1}$ T_f=3/2 state in ^{11}B, it is excited mostly by L=1 (see Sect. 4.1) rather than L=3 transfer in ^{9}Be(^{3}He,p). The second candidate which should be considered is the $5/2^{+}$, $7/2^{+}$ 13.16 MeV state. Because of the low d-wave proton penetrability, the T_f=3/2 admixture in this state could not be very prominent in ^{10}Be$(p,\gamma)^{11}$B. However a strong E1 excitation of the 13.0 MeV complex was observed in the inverse ^{11}Be(e,e')(Ref. [32]) excitation. Unfortunately, the contributions of the individual levels at 12.56, 12.91 and 13.16 MeV have not been resolved in (e,e'). There is also quite a significant L=3 component leading to the 13.16 MeV state indicating the presence of the $1p1d_{5/2}$ transfer, as was already stressed in Sect. 4.1. Finally, one cannot exclude the possibility of mixing with more distant levels, e.g. with the $J^{\pi}=5/2^{+}$ T_f=1/2 component of the giant dipole resonance, which is believed[33] to be located around E_x = 18 MeV in ^{11}B. In fact, the shape of the ^{10}Be$(p,\gamma)^{11}$B excitation function qualitatively resembles the repulsive interference between the giant dipole and the isobaric analog predicted in Ref.[34] on the basis of a simple model. Summarizing, the present study establishes that the isobaric analog of the 1.78 MeV state in ^{11}Be has a strongly mixed isospin. Further work is needed to identify uniquely the originally pure $T_f=1/2$ state (or states) participating in mixing.

The 16.44 MeV state

The angular distribution for the 16.44 MeV state (peak No. 4') peaks around 30° and decreases rapidly towards both small and large angles. An angular distribution of the same type was observed[7] in the ^{9}Be(t,p)^{11}Be reaction to the 3.887 MeV state. Therefore we conclude that the 16.44 MeV state is an analog of the 3.887 MeV state in ^{11}Be. The peak position may suggest that $L\leq 3$ is involved, however none of the L=3, 4 or 5 transfers fits the data in a satisfactory way. For L=4 and 5 the interference of the dominating partial waves is constructive at zero degrees rather than destructive as suggested by the data. These bell-shaped angular distributions occur systematically for the (t,p) transitions[7] between the natural and unnatural parity states for the even-mass target nuclei throughout the 1p-shell. The noteworthy examples being the ^{10}B(3^+)(t,p)^{12}B(0^+ 2.733 MeV) and ^{6}Li(1^+)(t,p)^{8}Li (6.53 MeV) transitions, the latter having most probably also $J^\pi=0^+$. These, however, cannot proceed by a direct one-step transfer of a pair with S=0, since the initial states contain (at least) two unpaired

spins, whereas in the final states all spins are saturated. This is most conveniently expressed with the quantum numbers of the shell-model L-S basis--an S=0 transfer cannot connect states with $S_{LS}=1$ and $S_{LS}=0$. The 16.44 MeV state (and its 3.887 MeV parent in ^{11}Be) probably has three unpaired spins coupled to $S_{LS}=3/2$, otherwise it would be difficult to understand an S-forbidden shape of its angular distribution. Parity conservation does not limit the J^π values of the final states reached in a direct transfer process in case of an odd-mass target. The 16.44 MeV state is most probably excited by a two-step process involving a consecutive transfer of a nucleon. Whether $J^\pi\leq 7/2$ as suggested in Ref.[7] is compatible with such a process requires a separate investigation. It is noteworthy that the angular distributions of this bell-shaped type have not been encountered among the transitions to the $T_f=1/2$ states. We conclude that the two-step component, even if present, is masked in this case by an allowed S=1 transfer.

If $S_{LS}=3/2$ for the 16.44 MeV state, as is suggested here, its decay by nucleon emission to the 0_1^+ and 2_1^+ states of A=10(T_c=1) is hindered, since the main wave-function components of these final states have $S_{LS}=0$. This may offer an explanation for the extremely narrow widths of the 3.887 MeV state in ^{11}Be($\Gamma_{c.m.}\leq 10$ keV) and its 16.44 MeV analog in ^{11}B($\Gamma_{c.m.}\leq 30$ keV).

The 17.69 MeV state

This state has been seen[15] as a resonance in the isospin forbidden ^{9}Be (d,p$_1$)^{10}Be reaction, decaying exclusively to the ^{10}Be(2_1^+) state. There might be at least two reasons for this behaviour. First, it may possess a high spin value such that it cannot decay by emitting a valence nucleon to ^{10}Be$_{g.s.}$(0_1^+). This suggests $J^\pi \geq 5/2^-, 7/2^+$. In the ^{9}Be(^{3}He,p)^{11}B reaction to this state either L=0 + L=2 (J^π=3/2$^-$) or a pure L=1(J^π = 1/2$^+$, 3/2$^+$, 5/2$^+$) transfer is involved (see Fig. 5). We tend therefore to take an alternative interpretation, ascribing the absence of a ground-state decay to the structure factors, assuming that it is a weak-coupling state based on the ^{10}Be(2_1^+). Therefore any of the J^π = 1/2$^+$, 3/2$^+$, 5/2$^+$, 3/2$^-$ could be the possible spin-parity value. There are indications[35] that the state was excited by an E1 excitation in the ^{11}B(γ,p)^{10}Be(2_1^+) reaction. Therefore positive parity for this state is more probable.

The 18.0 MeV state

This broad state (peak No. 6') is excited by L=0 + L=2 (J^π=3/2$^-$) or L=1+L=3 (J^π = 3/2$^+$, 5/2$^+$) transfers, the latter combination giving a slightly better fit to the data. The broken line in Fig. 5 assumes that this state is a $3/2_1^-$ T_f=3/2 state of (1p)^7, which is predicted[23] to be excited predominantly by (1p$_{1/2}$)^2. The normalization coefficients are 0.75 for L=0 and 0.9 for L=2. One may therefore conclude that if the $3/2_1^-$ T_f=3/2 is excited in the present experiment, the 18.0 MeV state seems to be its most probable counterpart.

The 19.15 MeV state

The position of the stripping peak suggests L=3, therefore J^π=3/2$^+$, 5/2$^+$, 7/2$^+$ or 9/2$^+$ for the 19.15 MeV state (peak No. 7' in Fig. 1).

The 21.17 MeV state

The allowed character of the β-decay[36] from the J^π=(1/2$^-$)^{11}Li$_{g.s.}$ to the 8.84 MeV state in ^{11}Be suggests J^π=(1/2$^-$ or 3/2$^-$) for the latter state and for its 21.17 MeV analog in ^{11}B (peak No. 8' in Fig. 1). Since the shape of the angular distribution in Fig. 5 is such that it requires both L=0 and L=2 components, a probable candidate for this state is the $3/2_2^-$ T_f=3/2 state of (1p)^7. This state is predicted to be at 18.50 MeV by Cohen and Kurath[25] and at 19.5 MeV by Norton and Goldhammer.[37] A fit to the data (see solid line in Fig. 5) requires a significant enhancement of the L=2 transfer, indicating a transition with strongly coherent character. It is noteworthy that the 1.99 MeV neutron group ascribed in Ref.[36] to the ground-state decay of the 2.69 MeV state in ^{11}Be could as well originate from the decay of the 8.84 MeV state to ^{10}Be(0_2^+). This would indicate a weak-coupling interpretation for the 8.84 MeV and 21.17 MeV states based on the monopole excitation in A=10 (T_c=1).

Because $J^{\pi}=1/2^-$ for $^{11}Li_{g.s.}$ has not been rigorously demonstrated and because of a close similarity with the experimental angular distribution for the 12.56 MeV state, which has L=1, an alternative interpretation in terms of positive parity is also possible. The dominance of L=1 indicates a low spin value $J^{\pi}=1/2^+$ or $3/2^+$. The most probable spin-parity for $^{11}Li_{g.s.}$ would be $J^{\pi}=1/2^+$, with neutrons filling pairwise the available orbits and the odd proton in the $2s_{1/2}$ state as in the case for the odd neutron in ^{11}Be.

5. Conclusions and summary

The ^{11}B nucleus has been investigated in the present work with the $^9Be(^3He,p)^{11}B$ reaction at 38 MeV over the excitation energy range from 8.5 to 21.5 MeV with the double purpose of augmenting the existing experimental information on this nucleus and providing a discriminating test for the shell-model wave functions for some of the states in this energy range. Because of the recent calculations[8,9] the test for the positive parity states seemed to be of particular importance.

On the experimental side the most important results concern the $T_f=3/2$ states in this nucleus. It has been demonstrated by comparing the yields of the direct transfer $^9Be(^3He,p)^{11}B$ and $^9Be(\alpha,d)^{11}B$ reactions (E_{α} = 48 MeV) that the 16.44, 17.69, 18.0 and 19.15 MeV states have rather pure isospin $T_f=3/2$. We assign also $T_f=3/2$ to the 21.27

MeV state the excitation energy of which is close to the expected energy of the analog of the 8.816 MeV state in ^{11}Be. The 18.0, 19.15 and 21.27 MeV states have not been previously reported. The analog of the $J^{\pi}=5/2^+$ 1.78 MeV state in ^{11}Be is observed near 14.4 MeV excitation energy and is found to have strongly mixed isospin. Its interference with the originally pure $J_f^{\pi} = 5/2^+$ $T_f=1/2$ state(s) is the reason that it appears to be produced at different excitation energies in the two-nucleon transfer (E_x = 14.47 MeV) and in the $^{10}Be(p,\gamma)^{11}B$ (E_x = 14.33 MeV) reaction. Because the spins and parities of the states lying nearby have not yet been uniquely determined, it is not possible to indicate the $J^{\pi}=5/2^+$ $T_f=1/2$ state(s) participating in the mixing. Pairs of states with strongly mixed isospin have previously been reported (see Ref. [38]) for a summary) in the even-even self-conjugate nuclei. The present study demonstrates that such close-by mixed states also occur in the odd systems. The feature unifying this resonance and the cases previously reported is that they all have strong single-nucleon parentage to the ground state of the T_f-1/2 core.

It is quite striking that most of the $T_f=3/2$ states have narrow widths in spite of the fact that they are unbound by several MeV with respect to the decay into the A=10 $(0_1^+,T_c=1)$ core and a nucleon. Because of the purity of isospin for $E_x \geq 16.44$ MeV, nucleon emission is the principal decay mode for these states. The 16.44 MeV state is probably a rather pure $S_{LS}=3/2$ state of the shell-model L-S basis as is suggested by its one-step forbidden angular distribution; its decay into A=10 (0_1^+ and 2_1^+, T_c=1) which are mostly S_{LS}=0, is therefore hindered. The 17.69, 19.15 and 21.27 MeV states have a large one-nucleon overlap, most probably, with the excited states of the T_c=1 core. The narrow widths are due to the barrier factors.

A weak coupling interpretation for the lowest three T_f=3/2 states based on the ground state of ^{10}Be was suggested by the shell-model calculations and verified previously in the ^{10}Be(d,p)^{11}Be study.[18] The normalization factors of Table 4 indicate also the validity of this model for their analogs in ^{11}B. Some of the alternatives in spin-parity assignments suggested by the present work could be resolved by establishing the character of the $^{11}\mathrm{Li}_{g.s.}$ β-decay to the corresponding states in the parent ^{11}Be, provided the spin-parity of $^{11}\mathrm{Li}_{g.s.}$, presently tentatively assigned ($1/2^-$), is rigorously determined.

The $5/2_2^+$, $7/2_1^+$ and $7/2_2^+$ T_f=1/2 states are found to have their strength depleted in comparison with the shell-model predictions.[9] It is concluded on this basis and from the fact that the $5/2_4^+$ (or $7/2_4^+$) 13.16 MeV state is very strongly excited, that the interaction of a 2s1d nucleon with the T_c=0 core leads to a stronger fragmentation of the strength than the theory implies. None of the states observed in the present work seems to correspond to the stretched $(J_i + (1d_{5/2})^2_{J^\pi=5^+}$ configuration. This probably lies well above the deuteron threshold and should be looked for with the deuteron induced resonance reactions.

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Figure Captions

FIG. 1. Spectra of particles for the $^9Be(^3He,p)^{11}B$ reaction at $E_{^3He}$ = 38 MeV and θ_{lab} = 27.5 deg. (lower spectrum) and for the $^9Be(\alpha,d)^{11}B$ reaction at E_α = 48 MeV and θ_{lab} = 25 deg. (upper spectrum). The upper spectrum has been scaled to have the same excitation energy scale as the lower spectrum. Smooth background has been subtracted from both spectra. The primed numbers refer to the states with T_f=3/2 (see Table 1), the unprimed numbers to the states with T_f=1/2 (see Table 2). Peaks from contaminants are labelled with the residual nucleus and excitation energy.

FIG. 2. A portion of the $^9Be(\alpha,d)^{11}B$ spectrum demonstrating the asymmetry of the 14.47 MeV peak discussed in the text.

FIG. 3. Parent-analog correspondence for the T_f=3/2 states in ^{11}Be and ^{11}B. Indicated are some of the isospin-allowed decay channels of ^{11}Be and ^{11}B referred to in the text.

FIG. 4. Differential cross sections for the $^9Be(^3He,p)^{11}B$ reaction at $E_{^3He}$ = 38 MeV for the T_f=1/2 states in ^{11}B and the results of the DWBA calculations. Curves are labelled with the shell-model state assumed in the calculations and the dominant L-values involved in the transfer reaction. The two-nucleon configurations indicated in the fourth column of Table 4 were used for the states without shell-model labelling. The normalization factors are listed in the fifth column of Table 4.

FIG. 5. Differential cross sections for the $^9Be(^3He,p)^{11}B$ reaction at $E_{^3He}$ = 38 MeV for the T_f=3/2 states in ^{11}B and the results of the DWBA calculations. See caption to Fig. 4 for other details. The normalization factors are listed in the tenth column of Table 4.

Table 1. Parameters of some T_{ξ}=3/2 analog states in ^{11}B and their parents in ^{11}Be.

	This work$^{a)}$		Compilation$^{b)}$					
ID No.	E_x in ^{11}B (MeV±keV)	$\Gamma_{c.m.}$ (kev)	E_x in ^{11}B (MeV±keV)	J^{π}	$\Gamma_{c.m.}$ (keV)	E_x in ^{11}Be (MeV±keV)	J^{π}	$\Gamma_{c.m.}$ (keV)
1'	12.563±20	202±25	12.56±30	$1/2^+(3/2^+)$	240±50	0.0	$1/2^+$	
2'	12.920±20	155±25	12.91±20	$1/2^-$	240±30	0.320±0.2	$1/2^-$	
3'	14.40$^{c)}$	261±25	14.33±20	$5/2^{(+)},(3/2^-)$	250±40	1.778±12	$(5/2,3/2)^+$	100±20
4'	16.437±20	≤30	(16.43±15)		≃40	3.887±15	7/2	<10
5'	*17.690	91±25				5.240±21		45±10
6'	18.0 ±100	870±100				(5.86)		≃300
7'	19.146±30	115±25				6.705±21		40±20
8'	21.27 ±50	300±30				8.816±32		200±50

a) Calibration point is marked with an asterisk. The remaining calibration points are indicated in Table 2.

b) Reference 5.

c) This state has mixed isospin T_{ξ}=3/2+1/2 (see Sect. 4.2).

Table 2. Parameters of some T_{ξ}=1/2 states in ^{11}B observed in ^{9}Be(^{3}He,p)^{11}B reaction.

	This work$^{a)}$		Groce et al.$^{b)}$	Compilation$^{c)}$		
ID (No.)	E_x (MeV±keV)	$\Gamma_{c.m.}$ (keV)	E_x (MeV±keV)	E_x (MeV±keV)	J^{π}	$\Gamma_{c.m.}$ (keV)
1	8.934±15			8.920±1.5	$5/2^-$	5.2 eV
2	9.183±15			9.185±1.5	$1/2^+$	3.0 eV
3	9.265±15	10±10		9.274±1.5	$5/2^+$	7.0
4	9.887±15	104±15	9.87 ±20	9.875±10	$3/2^+$	130±30
5	10.265±25	168±25	10.26	10.26 ±20	$3/2^{-d)}$	150±40
6	10.337±20	123±20	10.337±15	10.33 ±20	$5/2^{-d)}$	70±20
7	10.580±20	122±20	10.594±12	10.601±10	$7/2^+$	70±10
8	11.254±20	110±20	*11.266± 7	11.29 ±30	$9/2^+$	90±50
9	11.437±20	103±20	11.462±10	11.49 ±50		
10	11.588±30	180±30		11.61 ±50	$5/2^+$	150±50
11	11.889±20	204±20	11.884±12	11.90 ±20	$3/2^-$	150±50
12	13.137±40	426±40	13.3 ±100	13.16	$5/2^+,7/2^+$	430
13	14.565±15	≤30	*14.563±15	14.53 ±50		<120

a) Calibration points are marked with an asterisk.

b) $E_{^3He}$ = 10 MeV. D.E. Croce, J.H. McNally and W. Whaling, Bull. Am. Phys. Soc. 8 (1963) 486

c) Reference 5.

d) These assignments are from J.P. Stoquert, N. Bendjaballah, H. Beaumevieille, C. Gerardin and R. Seltz, J. de Phys. 40 (1979) 813.

Table 3. Optical model potentials[a)] for the DWBA calculations[b)].

Particle	V_R (MeV)	r_R (fm)	a_R (fm)	W_D (MeV)	r_I (fm)	a_I (fm)	$V_{S.O.}$ (MeV)	$r_{S.O.}$ (fm)	$a_{S.O.}$ (fm)	Ref.
^{3}He	123.8	1.069	0.827	13.74	1.181	0.797				19)
p	36.8	1.25	0.65	15.5	1.25	0.47	6.0	0.98	0.75	20)
n,p	var.	1.25	0.65				$\lambda=25$[c)]	1.25	0.65	

a) The notation for the parameters is standard (see Ref. [19)]).

b) A lower integration radius R_c=4.0 fm was used.

c) λ is a spin-orbit parameter for the bound-state in DWUCK[17)].

Table 4. Comparison of experimental and theoretical transition strengths in ^{9}Be(^{3}He,p)^{11}B reaction at $E_{^3He}$ = 38.0 MeV.

$T_f=1/2$					$T_f=3/2$				
J^π	E_x (MeV)	L[a)]	Shell-model state[b)] or two-nucleon configuration	ε[c)]	J^π	E_x (MeV)	L	Shell-model state[b)] or configuration	ε[c)]
$5/2^-$	8.920	0+2	$5/2^-$	1.0[d)]	$1/2^+,(3/2^+)$	12.56	1	$1/2^+_1$	0.67
$7/2^+$	9.185	(1)+3	$7/2^+_1$	0.50	$1/2^-$	12.91	2	$1/2^-_1$	0.77
				0.74[e)]	$5/2^{(+)},(3/2^-)$	14.40	1+3	$5/2^+_1$	1.3 (1) 2.0 (3)
$5/2^+$	9.274	1+3	$5/2^+_2$	0.32[e)]		16.44	f)		
$3/2^+$	9.875	1	$3/2^+_2$	0.84		17.69	1	g)	0.73
$3/2^-$	10.26	2 (S=1,J=2)	$3/2^{-}$[h)]	0.029			0+2	h)	2.3 (0) 4.5 (2)
$5/2^-$	10.33	(0)+2	$5/2^-_3$	4.5		18.0	0+2	$3/2^-_1$	0.7 (0) 11.3 (2)
$7/2^+$	10.601	1+3	$7/2^+_2$	0.42			1+3	g)	1.6 (1) 0.56 (3)
$9/2^+$	11.29	3	$9/2^+_1$	0.61		19.12	3	g)	0.51
	11.49	1	$1/2^+_2$	3.7		21.22	0+2	$3/2^-_2$	1.7 (0) 17.1 (2)
		2	$1/2^-_2$	4.7			1+3	g)	0.65 (1) 0.20 (3)

Table 4. con't.

$T_f=1/2$					$T_f=3/2$				
J^π	E_x (MeV)	L[a)]	Shell-model state[b)] or two-nucleon configuration	ε[c)]	J^π	E_x (MeV)	L	Shell-model state[b)] or configuration	ε[c)]
$5/2^+$	11.61	1+3	$5/2^+_3$	9.8					
$5/2^-$	11.90	0+2 (S=1,J=1)	$5/2^{-}$ h)	0.10					
$5/2^+,7/2^+$	13.16	1+3 (S=1,J=2)	$5/2^{+}$ g)	0.13					
	14.56	0 (S=1,J=1)	$\sqrt{21}(2s_{1/2})^2$	0.25					
		(S=1,J=2)	g)	0.31					

a) Calculations include all S and J values compatible with angular momentum and isospin conservation for those states for which the shell-model wave-functions were available (see the fourth and ninth column). For the remaining states the particular S and J values assumed in the calculations are indicated (in parentheses).

b) The negative parity states are labelled as in Ref. 23), the positive parity states as in in Ref. 9). For the unlabelled states the two-nucleon configurations assumed in the calculations are explicitly indicated.

c) ε-value for the states with known spin-parity assignments, $(2J_f+1)\varepsilon$ for the states with unknown spin-parity assignments.

Table 4. con't.

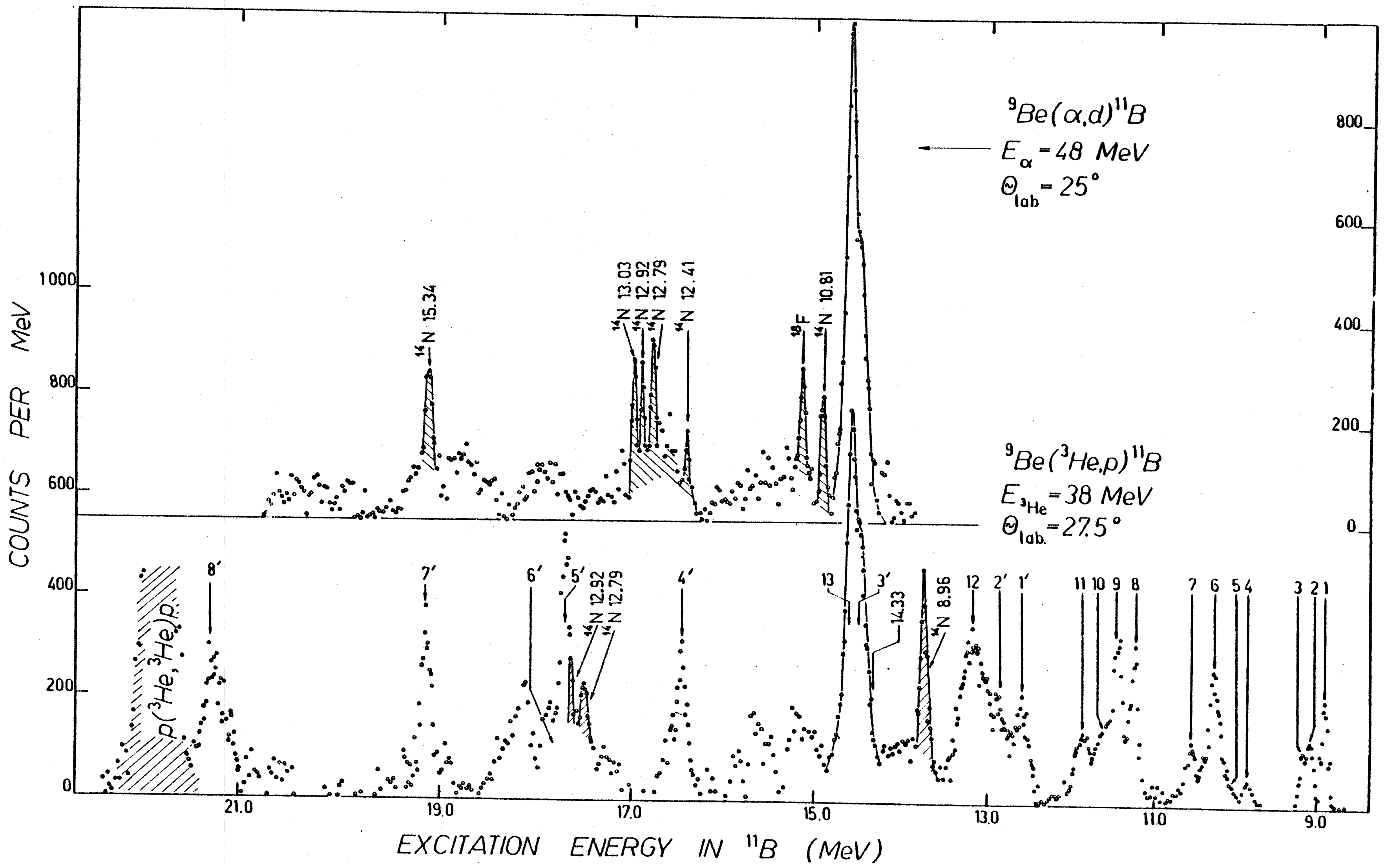
d) An overall normalization (D_o^2 = 22 x 10^4 MeV^2 fm^3) in (3.1) is chosen so that ε=1.0 for this state.

e) Experimental[26)] spectroscopic factors for the transition from $^{10}B_{g.s.}$ are used.

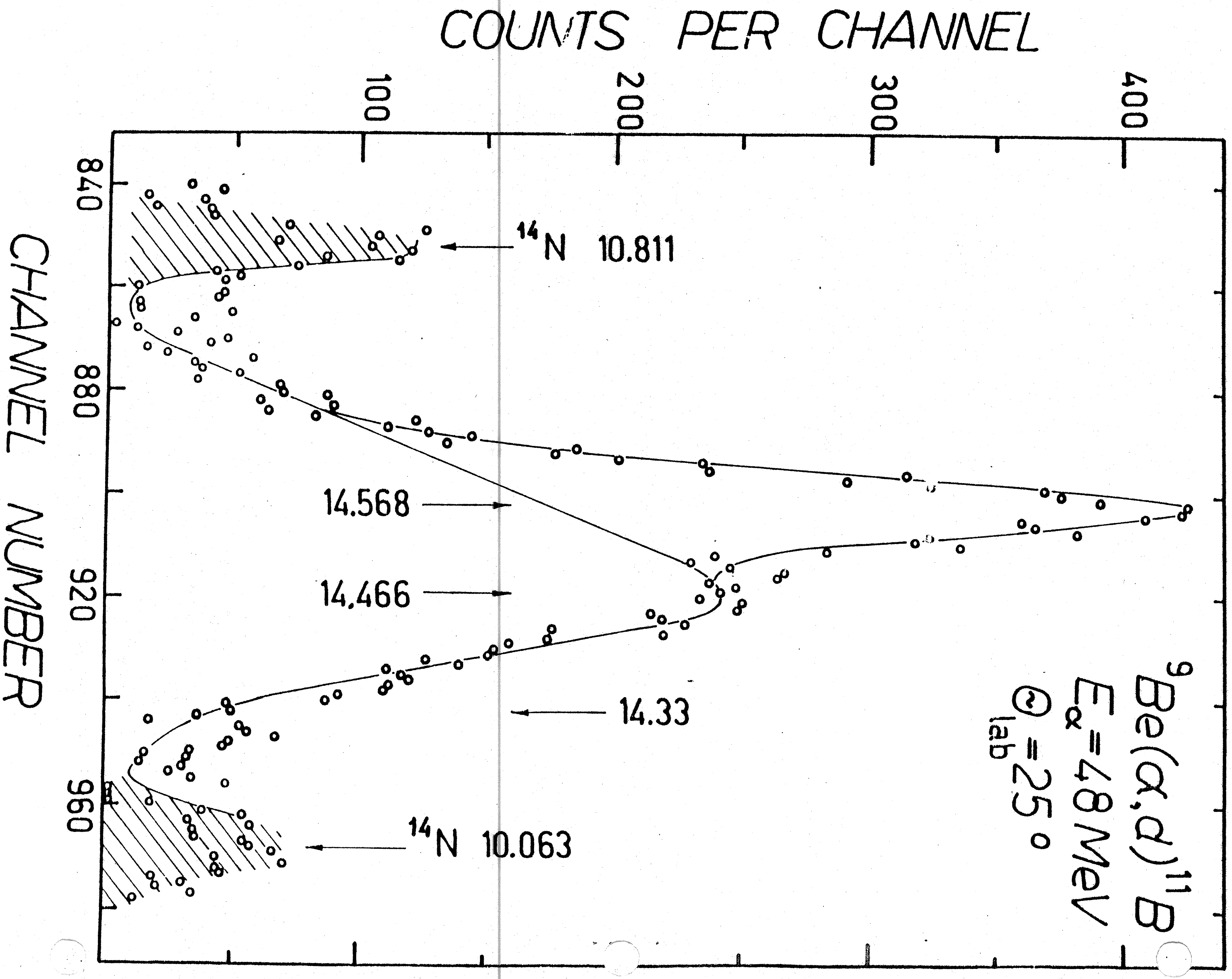
f) This state is most probably excited by a two-step process (see Sect. 4.2 for further details).

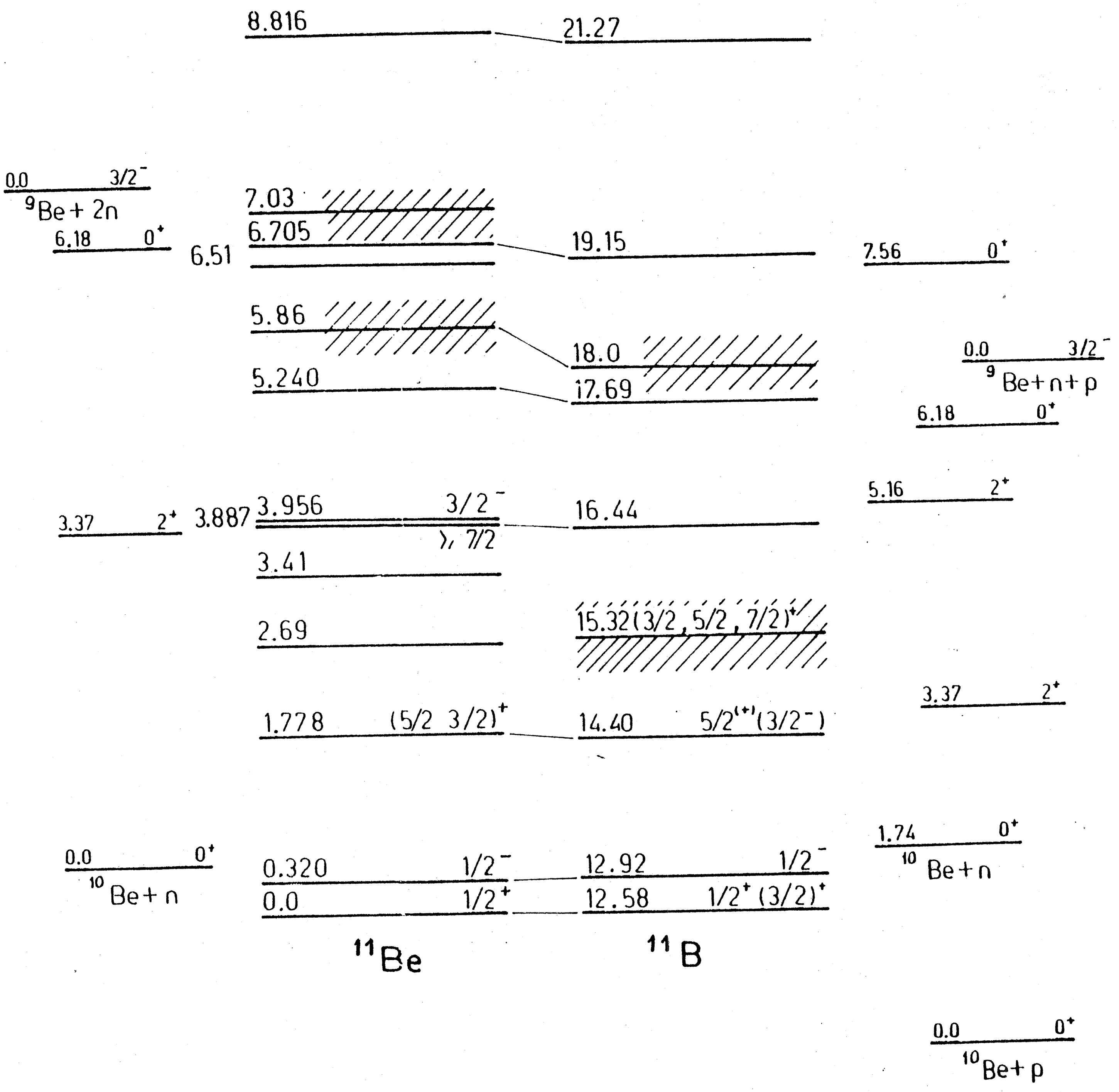
g) $\sqrt{21}[\,0.45(1d_{5/2}1p_{3/2}) + 0.87(2s_{1/2}1p_{3/2})]$.

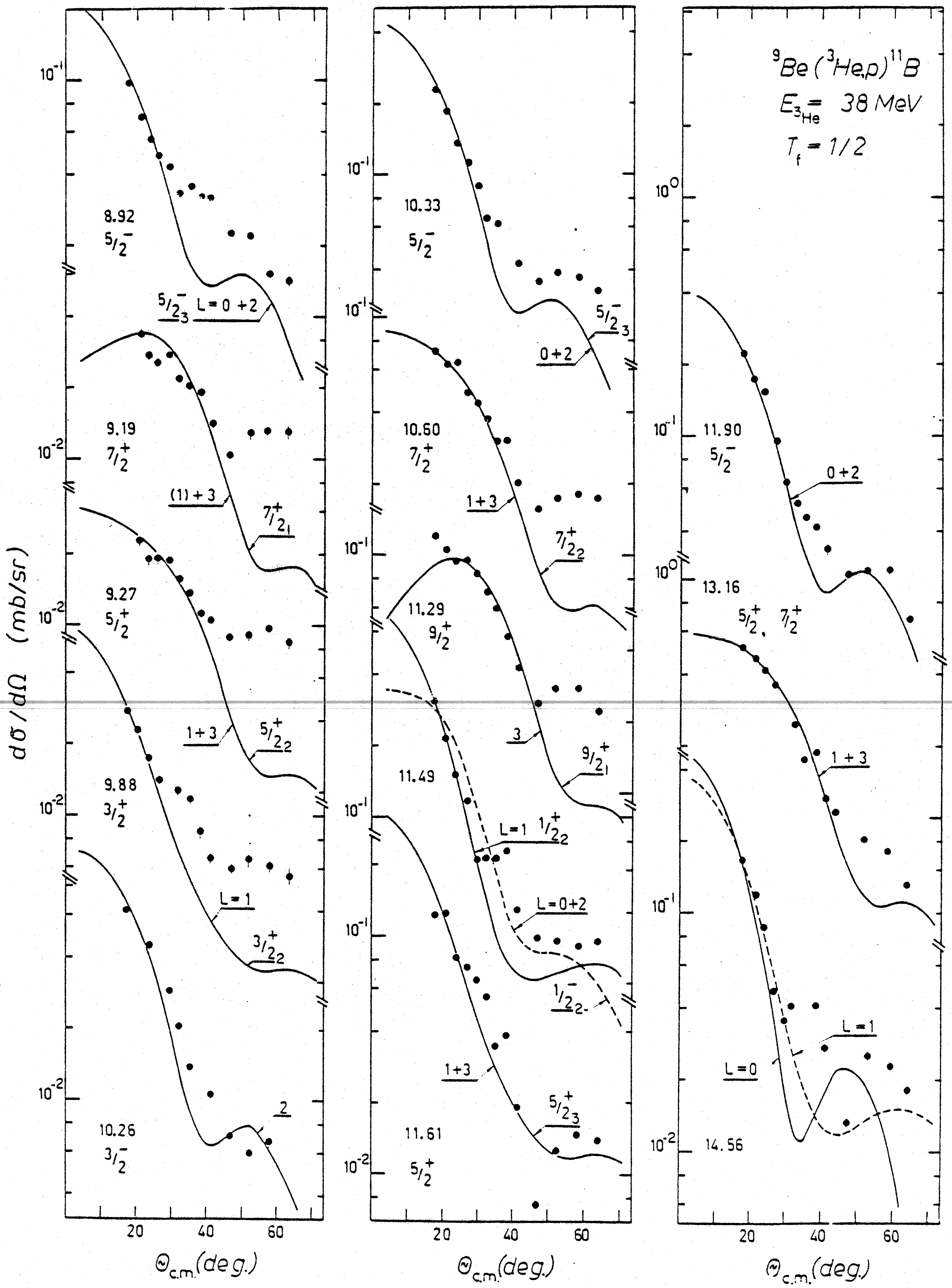
h) $\sqrt{21}[\,0.45(1p_{3/2})^2 + 0.87(1p_{3/2}1p_{1/2})]$.

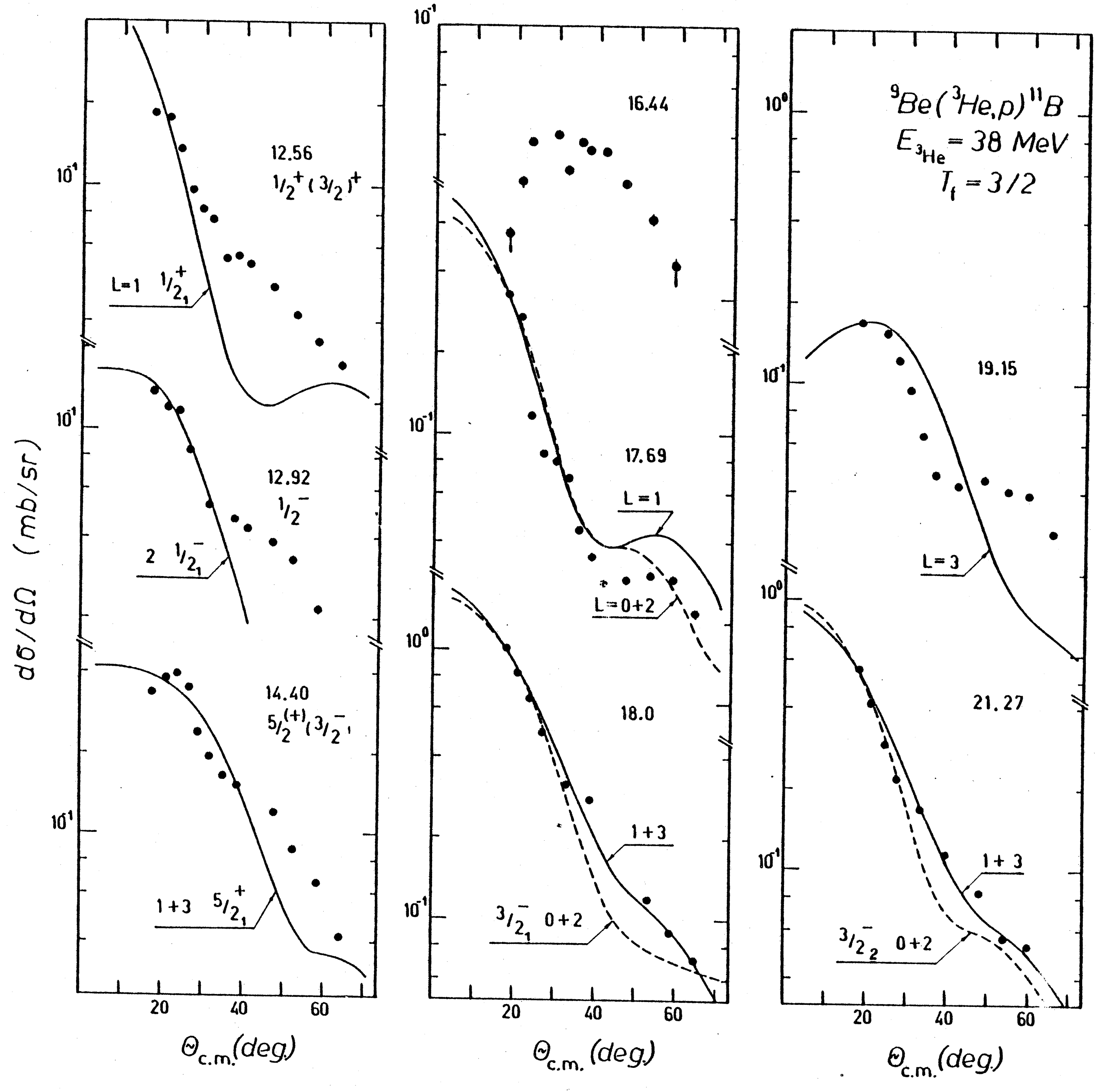


$^9Be(\alpha,d)^{11}B$
$E_\alpha = 48$ MeV
$\Theta_{lab} = 25°$
$^9Be(^3He,p)^{11}B$
$E_{^3He} = 38$ MeV
$\Theta_{lab.} = 27.5°$
^{14}N 15.34
^{14}N 13.03
^{14}N 12.92
^{14}N 12.79
^{14}N 12.41
^{18}F
^{14}N 10.81
8′
7′
6′
5′
^{14}N 12.92
^{14}N 12.79
4′
13
3′
14.33
^{14}N 8.96
12
2′
1′
11
10
9
8
7
6
5
4
3
2
1
$p(^3He,^3He)p$
COUNTS PER MeV
1000
800
600
400
200
0
800
600
400
200
0
21.0
19.0
17.0
15.0
13.0
11.0
9.0
EXCITATION ENERGY IN ^{11}B (MeV)


COUNTS PER CHANNEL
100
200
300
400
840
880
920
960
CHANNEL NUMBER
^{14}N 10.811
14.568
14.466
14.33
^{14}N 10.063
^{9}Be(α,d)^{11}B
E_α=48 MeV
Θ_{lab}=25°


8.816
21.27
0.0 3/2⁻
⁹Be + 2n
6.18 0⁺
7.03
6.705
6.51
19.15
7.56 0⁺
5.86
18.0
0.0 3/2⁻
⁹Be+n+p
5.240
17.69
6.18 0⁺
5.16 2⁺
3.37 2⁺
3.887
3.956 3/2⁻
≥ 7/2
16.44
3.41
2.69
15.32(3/2, 5/2, 7/2)⁺
3.37 2⁺
1.778 (5/2 3/2)⁺
14.40 5/2⁽⁺⁾(3/2⁻)
1.74 0⁺
¹⁰Be+n
0.0 0⁺
¹⁰Be+ n
0.320 1/2⁻
12.92 1/2⁻
0.0 1/2⁺
12.58 1/2⁺ (3/2)⁺
¹¹Be
¹¹B
0.0 0⁺
¹⁰Be+ p


$^9Be(^3He,p)^{11}B$
$E_{^3He}$ = 38 MeV
$T_f = 1/2$
dσ / dΩ (mb/sr)
8.92 $5/2^-$
$5/2^-_3$ L = 0 + 2
9.19 $7/2^+$
(1) + 3
$7/2^+_1$
9.27 $5/2^+$
1 + 3
$5/2^+_2$
9.88 $3/2^+$
L = 1
$3/2^+_2$
10.26 $3/2^-$
2
10.33 $5/2^-$
$5/2^-_3$
0 + 2
10.60 $7/2^+$
1 + 3
$7/2^+_2$
11.29 $9/2^+$
3
$9/2^+_1$
11.49
L = 1 $1/2^+_2$
L = 0 + 2
$1/2^-_2$
11.61 $5/2^+$
1 + 3
$5/2^+_3$
11.90 $5/2^-$
0 + 2
13.16 $5/2^+$, $7/2^+$
1 + 3
14.56
L = 1
L = 0
10^{-1}
10^{-2}
10^0
20
40
60
$\Theta_{c.m.}$(deg.)
$\Theta_{c.m.}$(deg.)
$\Theta_{c.m.}$(deg.)



⁹Be(³He,p)¹¹B
E₃He = 38 MeV
T_f = 3/2
dσ/dΩ (mb/sr)
Θc.m.(deg.)
20
40
60
10⁻¹
10⁰
12.56
1/2⁺(3/2)⁺
L=1 1/2⁺₁
12.92
1/2⁻
2 1/2⁻₁
14.40
5/2⁽⁺⁾(3/2⁻)
1+3 5/2⁺₁
16.44
17.69
L = 1
L = 0+2
18.0
1+3
3/2⁻₁ 0+2
19.15
L = 3
21.27
1+ 3
3/2⁻₂ 0+2