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Proton Pick-up from Nuclei in the Middle of the $1p$ Shell

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Abstract. The $(d, {}^3\mathrm{He})$ reaction has been used to excite proton hole states in ^{8}Li, ^{9}Be and ^{10}Be. Angular distributions have been measured and have been analyzed in terms of the DWBA to get spectroscopic factors for the considered transitions. Excitation energies and transition strengths are compared with the results of Cohen and Kurath's intermediate coupling shell model calculations, where the two models of the effective interaction produce different results especially for transitions to final states in mass 8 and 10 nuclei. The experimental results are clearly in favour of the (6–16) 2 BME interaction. A positive parity state in ^{10}Be predicted by the calculations has been looked for and found at 9.60 MeV.

1. Introduction

In the spectroscopy with single nucleon transfer reactions leading to ^{8}Li, ^{9}Be and ^{10}Be the proton pick-up reactions have several interesting features:

^{8}*Li:* Other than for stripping reactions the DWBA analysis is not immediately hindered or complicated by the presence of low lying nucleon emission thresholds in ^{8}Li.

^{9}*Be:* Due to a lack of mass 8 targets ^{9}Be can only be reached with pick-up reactions.

^{10}*Be:* Here as well as in the $^{10}\mathrm{B}(d, {}^3\mathrm{He})^9\mathrm{Be}$ reaction the successful calculations of Cohen and Kurath [1] predict high lying states with large spectroscopic factors which have not been observed so far.

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Proton pick-up reactions on ^{9}Be, ^{10,11}B have been performed previously [2] but either the investigation was restricted to low lying states [3, 4] or the angular momentum matching conditions [5] required for a good DWBA analysis were not fulfilled [6, 7]. The $(d, {}^3\mathrm{He})$ reaction at 52 MeV has proven to be not affected by these restrictions. By studying this reaction we therefore could expect to contribute to the following questions:

(i) The two effective interactions used in Ref. 1 differ significantly in their predictions in the mass 8 to 10 region only. The extraction of reliable spectroscopic factors from our experiments should enable us to decide between the two possibilities.

(ii) The search for the unknown states predicted with large spectroscopic factors for pick-up was of course an experimental challenge.

2. Experimental Procedure

The 52 MeV deuteron beam used for the investigation of the $(d, {}^3\mathrm{He})$ reactions on $^9\mathrm{Be}$, $^{10}\mathrm{B}$ and $^{11}\mathrm{B}$ was produced with the Karlsruhe isochronous cyclotron. A magnetic monochromator system was adjusted to provide deuterons with an energy spread of about 40 keV. The reaction products were detected simultaneously in four $\Delta E - E$ telescopes consisting each of a 200 μm and a 2,000 μm surface barrier counter. Particle identification was accomplished by a conventional $\Delta E - E$ multiplication technique. Details of the experimental set-up has been described elsewhere [8]. Angular distributions were measured in steps of 1° in the angular range from about 10° to 60°. The overall energy resolution achieved was 150–200 keV mainly determined by the kinematical spread and the detector resolution. We used selfsupporting $^9\mathrm{Be}$ and isotopically enriched $^{10}\mathrm{B}$ and $^{11}\mathrm{B}$ targets. Oxidation and contaminations from carbon and nitrogen proved to be inevitable during the target preparation. Consequently the determination of the target thickness was inaccurate, and we give relative cross sections and spectroscopic factors only.

Local, zero range DWBA calculations were performed with the use of optical potentials obtained from the analysis of the elastic scattering of 52 MeV deuterons [9] and the elastic scattering of $^3\mathrm{He}$-particles at 29 MeV (Ref. 10). The separation energy method [11] has been applied for the calculation of the $1p$ proton wave functions. The DWBA calculations have been described in more detail in a previous paper [12].

3. Experimental Results

3.1. *The Reaction* $^9\mathrm{Be}(d, {}^3\mathrm{He})^8\mathrm{Li}$

As can be seen from Fig. 1 the spectrum of the $^3\mathrm{He}$-particles suffers from a continuous background which originates partly from the $(d, {}^3\mathrm{He})$ reaction on the $^{14}\mathrm{N}$ contaminant and partly from break-up channels. The three lowest states of $^8\mathrm{Li}$ are excited with large cross section. The measured angular distributions show the typical behaviour of $l=1$ transitions (see Fig. 2). Obviously some of the DWBA difficulties which we already met in the description of the $^{12}\mathrm{C}(d, {}^3\mathrm{He})^{11}\mathrm{B}$ reaction [12] are still more pronounced for these lighter nuclei.

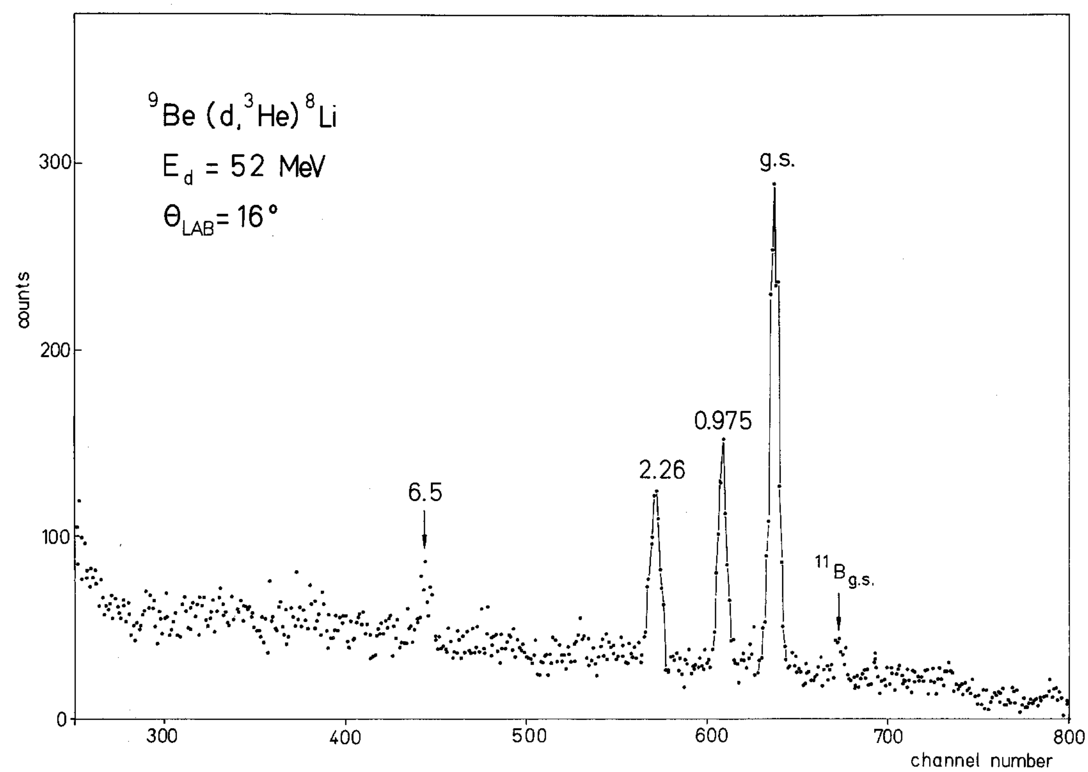

Fig. 1. Energy spectrum of $^3\mathrm{He}$-particles from the $^9\mathrm{Be}(d, {}^3\mathrm{He})^8\mathrm{Li}$ reaction

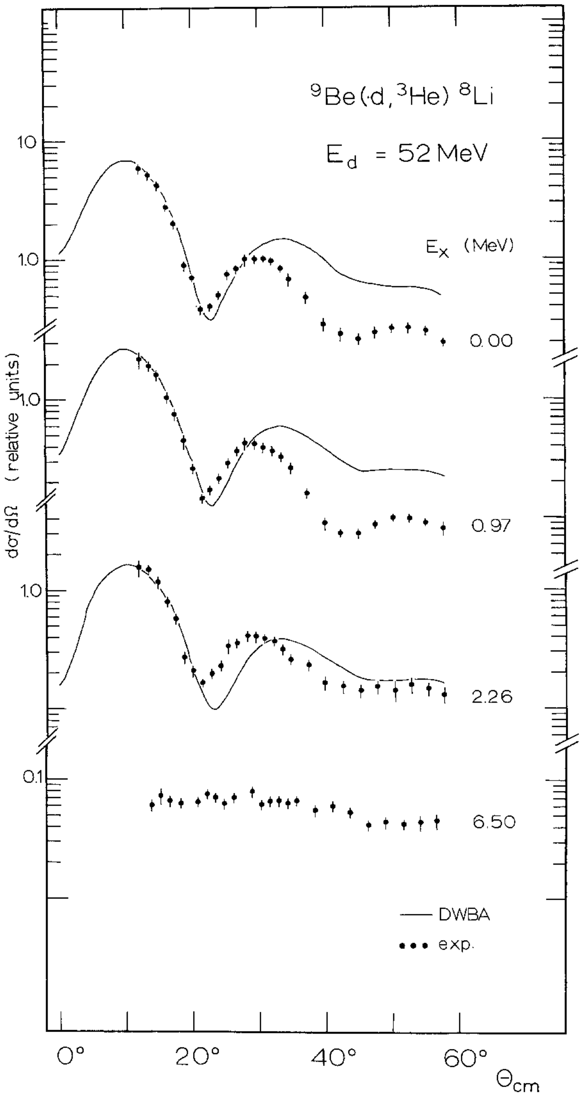

Fig. 2. Angular distributions from the ^{9}Be(d, ^{3}He)^{8}Li reaction together with $1p_{3/2}$ DWBA curves

3.2. *The Reaction* ^{10}B(d, ^{3}He)^{9}Be

The spectrum in Fig. 3 shows the strong excitation of states at 0 and 2.43 MeV. In addition there is an indication for the positive parity states at 1.68 and 1.06 MeV which seem to be weakly excited. Very broad states are observed at 6.66 and 11.3 MeV, the latter unfortunately masked by strong transitions resulting from both ^{12}C and ^{16}O contaminants of the target. This made the determination of the cross section highly uncertain and no angular distribution is therefore given in Fig. 4. The 6.66 MeV state is identified with the 6.76 ± 0.06 MeV level of Ref. 2 which has a width of 2 ± 0.2 MeV. A high resolution (t, α) spectrum [6] contains no additional information. The observed width agrees with the value (575 ± 50 keV) of the 11.28 MeV state quoted in Ref. 2. The angular distributions for the transitions to states at 0, 2.43 and 6.66 MeV are given in Fig. 4 together with $l=1$ DWBA calculations.

3.3. *The Reaction* ^{11}B(d, ^{3}He)^{10}Be

As Fig. 5 shows, the spectrum of the ^{3}He-particles suffers from ^{12}C and ^{16}O contaminations in the ^{11}B target. On the other hand, the reactions ^{12}C(d, ^{3}He)^{11}B and ^{16}O(d, ^{3}He)^{15}N have been investigated previously at the same deuteron energy of 52 MeV (Refs. 12, 13). So it was possible to correct the measured spectra – when necessary – for the contaminant peaks to get the net ^{11}B(d, ^{3}He)^{10}Be cross sections. In addition to the ^{10}Be ground state we observed transitions to the well known 2^+ state at an excitation energy of 3.36 MeV and to the close 2^+, 1^- doublet at 5.96 MeV of which presumably only the 2^+ member is excited. Other negative parity states as e.g. the 2^- state at 6.26 MeV, weakly excited in the ^{11}B(t, α)^{10}Be reaction [7] and the 3^- state at 7.37 MeV are not excited in the (d, ^{3}He) reaction, though their analogs at 7.54 MeV and at 8.89 MeV in ^{10}B have been observed with small cross section in the ^{11}B(^{3}He, α)^{10}B reaction [14]. There these states are probably excited predominantly via compound processes, which are unimportant for the (d, ^{3}He) reaction at 52 MeV. A strong state which was not known before is observed at (9.60 ± 0.50) MeV. Its width is distinctly larger than for the other states (250 keV). Unfortunately the corresponding Q-value coincides with the narrow 5.03 MeV state in ^{11}B from the ^{12}C contamination. From the measured ^{12}C(d, ^{3}He) reaction we know, however, that the contaminant peak contributes 10% at most to the counting rate of the 9.60 MeV state. In addition the observed group behaves kinematically correct (mass 10) in the measured angular region. It is probable that the analog of this new state at 9.60 MeV has been observed at (11.53 ± 0.04) MeV in the ^{11}B(^{3}He, α)^{10}B reaction [14] with a comparably large width (270 ± 50) keV. In stripping reactions the state has not been observed neither in the reactions ^{9}Be(d, p)^{10}Be and ^{9}Be(p, π^+)^{10}Be nor in proton stripping (d, n) on ^{9}Be where the analog state could have been excited (Refs. 15, 16, 17). The angular distributions observed in the present (d, ^{3}He) experiment, displayed in Fig. 6, show the typical $l=1$ pattern for pick-up from the $1p$ shell, which is reproduced by the DWBA calculation, where we assumed $1p_{3/2}$ pick-up, since the amount of $1p_{1/2}$ admixtures for allowed transitions to 1^+, 2^+ states cannot be deduced from the measured angular distributions.

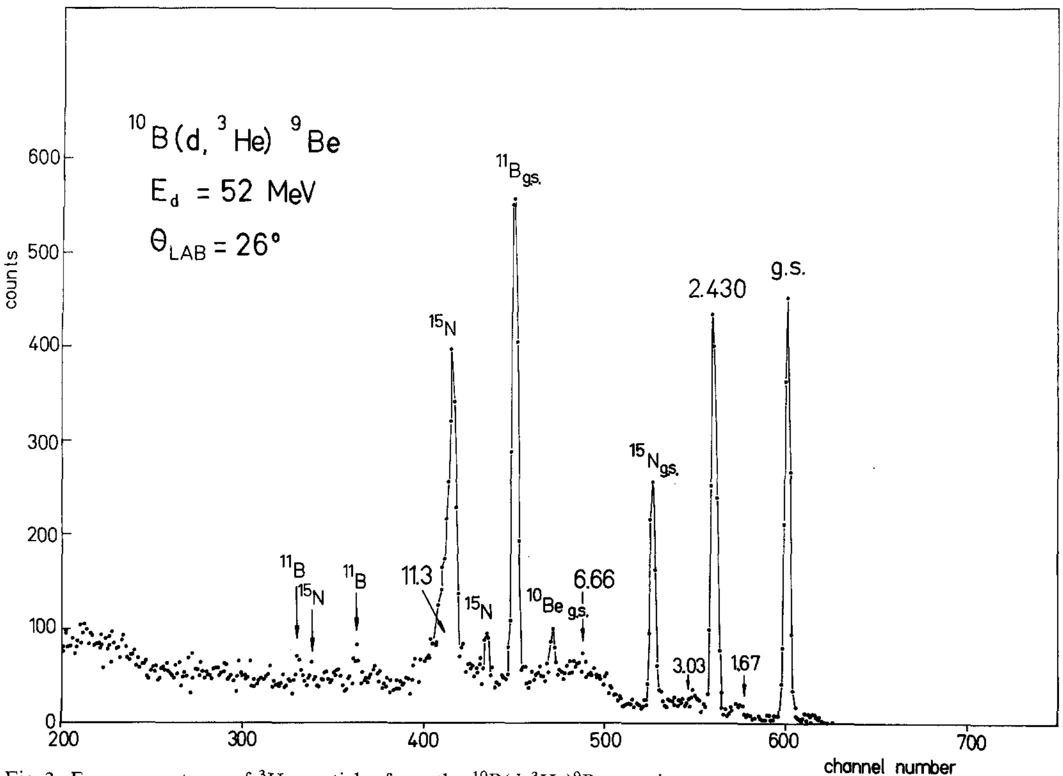

Fig. 3. Energy spectrum of ^{3}He-particles from the ^{10}B(d, ^{3}He)^{9}Be reaction

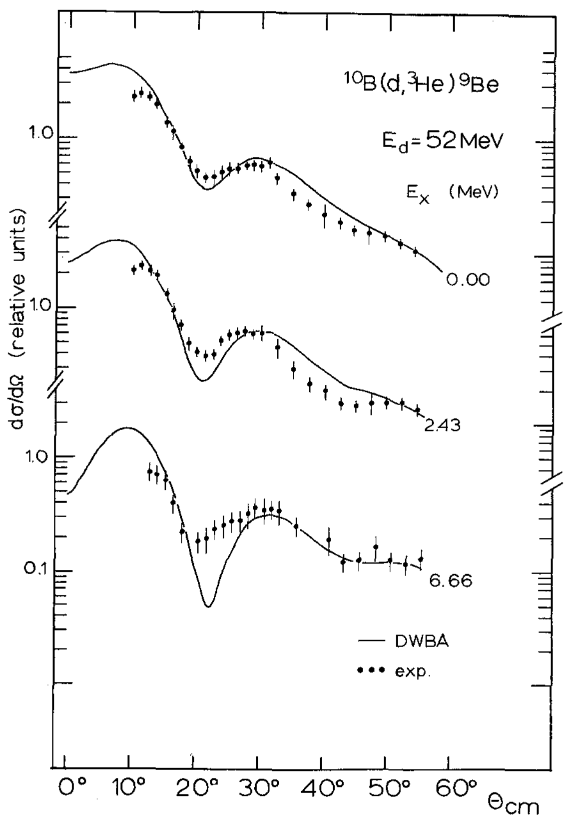

Fig. 4. Angular distributions from the ^{10}B(d, ^{3}He)^{9}Be reaction together with $1p_{3/2}$ DWBA curves

4. Discussion

Table 1 contains a compilation of all calculated states which can be reached with proton pick-up reactions on ^{9}Be, ^{10}B and ^{11}B and which are predicted with a spectroscopic factor larger than 0.1. For comparison we give the numbers obtained from the present experiments, sometimes tentatively connecting calculated and observed states on the basis of the spectroscopic factors. The theoretical results are taken from Table 1 of Ref. 1. This implies that they are obtained from the (6–16) 2BME model in the case of the final nucleus ^{8}Li and from the (8–16) POT model in the case of ^{9}Be and ^{10}Be. The comparison in Table 1 demonstrates that there exists in general satisfactory agreement between theoretical predictions and experimental results. This concerns excitation energies as well as spectroscopic factors. The majority of the predicted strong transitions have really been observed, one notable exception perhaps being the high lying $5/2^-$ state in ^{9}Be.

As has been pointed out by Cohen and Kurath [1] there are no essential differences in the results of the shell model calculations for the two different models called (6–16) 2BME and (8–16) POT, except for some transitions to $T=1$ states in mass 8 and 10 nuclei as far as pick-up reactions are concerned. Exactly these states are excited in the (d, ^{3}He) reaction on ^{9}Be

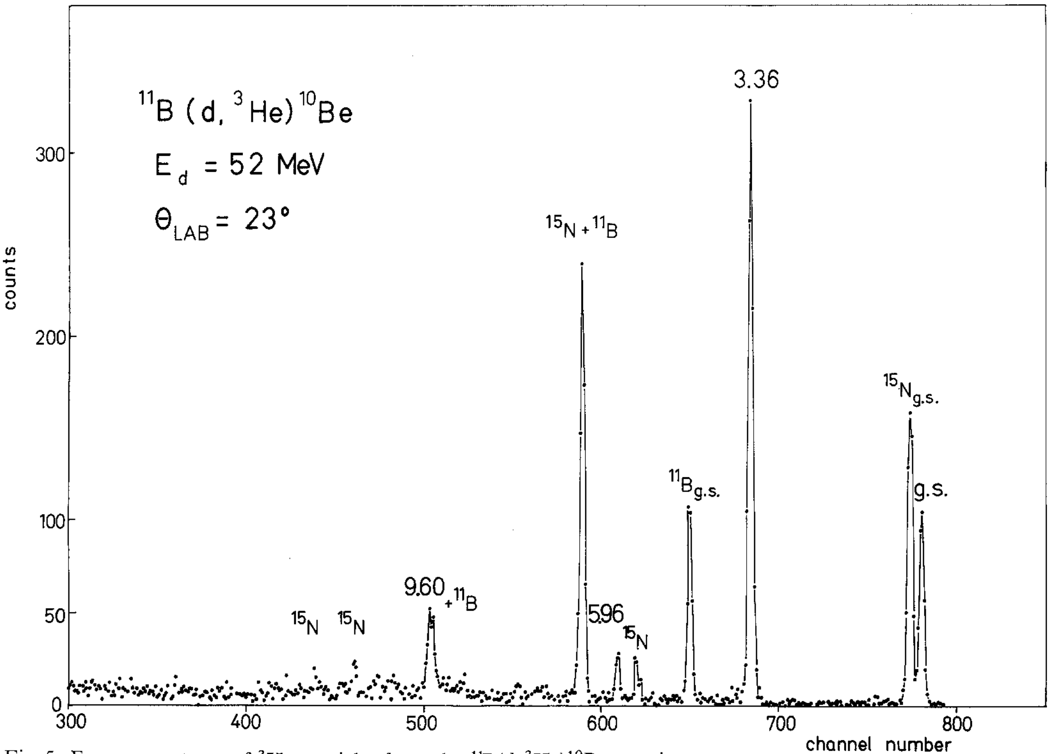

Fig. 5. Energy spectrum of ^{3}He-particles from the ^{11}B(d, ^{3}He)^{10}Be reaction

Table 1. Comparison of theoretical and experimental spectroscopic data

Reaction	Theory[a]			Experiment		
	I^π	E^x (MeV)	S $p_{3/2}+p_{1/2}$	I^π	E^x (MeV)[b]	S^c $p_{3/2}$
^{9}Be(d, ^{3}He)^{8}Li	2^+	0.00	1.35+0.15	2^+	0.00	1.50[d]
	1^+	1.08	0.31+0.30	1^+	0.98	0.63
	3^+	1.69	0.53	3^+	2.26	0.50
	2^+	5.15	0.03+0.18	$(2, 3)^+$	5.4	–
^{10}B(d, ^{3}He)^{9}Be	$3/2^-$	0.00	1.20	$3/2^-$	0.00	1.20[d]
	$5/2^-$	2.94	0.85+0.06	$5/2^-$	2.43	1.23
	$7/2^-$	6.20	1.54+0.01	$7/2^-$	6.76	0.70
	$5/2^-$	7.38	0.23+0.03			–
	$7/2^-$	9.68	0.91+0.34	$(\ )^-$	11.28	strong
	$5/2^-$	12.52	0.39+0.17			–
^{11}Be(d, ^{3}He)^{10}Be	0^+	0.00	0.65	0^+	0.00	0.65[d]
	2^+	4.16	1.63+0.08	2^+	3.36	2.03
	2^+	5.80	0.71+0.19	2^+	5.96	0.13
	2^+	9.16	0.66+0.16	$(\ )^{+}$ [c]	9.60[c]	1.19
	3^+	9.76	0.11			–
	1^+	10.22	0.11+0.08			–

[a] Ref. 1. [b] Ref. 2. [c] This work.
[d] Normalized to the theoretical value for the ground state transition.

and ^{11}B. In Table 2 we therefore compare the two different theoretical results, taken from Table 2 of Ref. 1 with the experimentally determined numbers. First let us consider the excitation of the two 1^+ states in ^{8}Li. Here the (6–16) 2BME model predicts the lower state to be strongly excited ($S=0.61$),

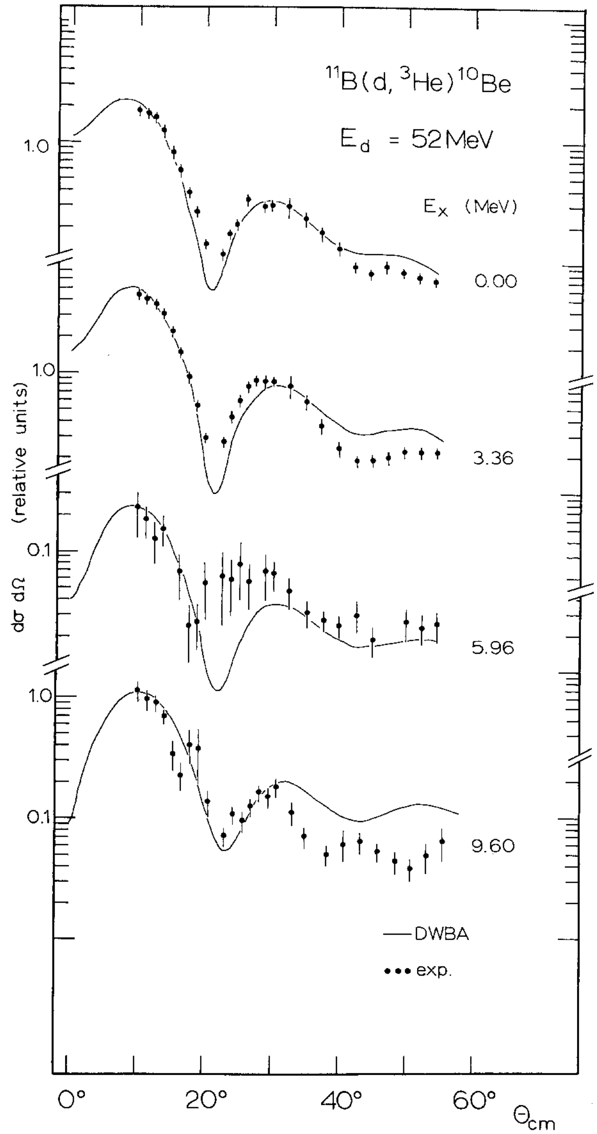

Fig. 6. Angular distributions from the ^{11}B(d, ^{3}He)^{10}Be reaction together with $1p_{3/2}$ DWBA curves

whereas the upper one contains only small strength ($S=0.08$). This is in exact agreement with the results of the (d, ^{3}He) experiment, where the lower 1^+ state is excited with $S=0.63$ and the upper one is not observed at all. In contrast, the (8–16) POT model gives just the opposite strength distribution for both states.

In the case of the three 2^+ states in ^{10}Be our results are again in favour of the (6–16) 2BME model. Especially the strength of the second 2^+ state is correctly described in contrast to the prediction of the (8–16) POT model which largely overestimates the spectroscopic factor.

In connection with the discussion of the shell model calculations we want to make some remarks concerning the excitation of the 11.3 MeV state in ^{9}Be and the new state at 9.6 MeV in ^{10}Be. Fig. 3 and in particular the high resolution spectrum of Ref. 6 show that the broad 11.3 MeV state contains an appreciable fraction of the pick-up strength. Now the shell model calculations predict a $7/2^-$ state with a large spectroscopic factor ($S=1.25$) nearly at the same energy. Therefore, it is tempting to identify the observed state with the predicted $7/2^-$ state. This assumption is compatible with the odd parity and the $l=1$ character of the angular distribution measured in the neutron pick-up reactions (compare the compilation of Ref. 2) leading to the probably analog state in ^{9}B at 11.75 MeV with spin $(7/2)^-$. The large peak width and the large spectroscopic factor which are observed both in proton and neutron pick-up reactions support the mirror relation between the 11.3 MeV state in ^{9}Be and the 11.75 MeV state in ^{9}B.

The new state of ^{10}Be at 9.6 MeV observed in the ^{11}B(d, ^{3}He)^{10}Be reaction does have positive parity due to the unique $l=1$ pick-up pattern of the measured angular distribution. The shell model calculation yields a 2^+ state at 9.16 MeV which should be strongly excited in the pick-up reaction, but contains nearly vanishing stripping strength. This could explain why the 9.6 MeV state had not been observed before, even though a great number of stripping experiments leading to mass 10 nuclei have been carried out in the past. The satisfactory agreement between theory and experiment concerning excitation energy and transition strength suggests a spin 2^+ for the new state.

Table 2. Comparison of spectroscopic factors with results of two different models [1]

Reaction	I^π	No. of state	(6–16) 2BME $S(p_{3/2}+p_{1/2})$	(8–16) POT $S(p_{3/2}+p_{1/2})$	exp. $S(p_{3/2})$
^{9}Be(d, ^{3}He)^{8}Li	1^+	1	0.31+0.30	0.08+0.12	0.63
	1^+	2	0.08+0.00	0.27+0.11	–
^{11}B(d, ^{3}He)^{10}Be	2^+	1	2.02	1.63	2.03
	2^+	2	0.14	0.71	0.13
	2^+	3	0.76	0.66	1.19

5. Conclusions

We have measured excitation energies and spectroscopic strengths for the reactions ^{9}Be(d, ^{3}He) and ^{10,11}B(d, ^{3}He). They are well described by the intermediate coupling shell model calculations of Cohen and Kurath [1]. Especially we have determined all spectroscopic factors for pick-up reactions which exhibit differences in the predictions of the two models used in Ref. 1. The spectroscopic factors for these five transitions to states in mass 8 and 10 nuclei are clearly in favour of the (6–16) 2BME model. This is in contrast to the result of Fick *et al.* [18] based on a ^{9}Be(d, p)^{10}Be experiment, where the probability to excite the first 2^+ state via $1p_{3/2}$ transfer proved to be in better agreement with predictions from the (8–16) POT model.

We have found a strongly excited pick-up state at 9.60 MeV in ^{10}Be. Its excitation energy and spectroscopic factor for pick-up have been correctly predicted by the shell model calculations of Ref. 1.

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