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A STUDY OF THE HIGHER EXCITED STATES OF ^{10}Be FROM THE ^{9}Be(d, p)^{10}Be REACTION

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Abstract: The levels of ^{10}Be have been studied using the ^{9}Be(d, p)^{10}Be reaction and 17.3 MeV deuterons. The existence of levels at 10.57 and 11.76 MeV has been confirmed and widths of 150, 291 and 121 keV obtained for the levels at 9.27, 9.4 and 11.76 MeV. Angular distributions have been obtained for the ground state, 3.368, 5.958, 6.263, 7.371, 7.542 and 11.76 MeV levels and the results compared to DWBA calculations. The spectroscopic factors that were extracted were found to be appreciably less than those predicted by Cohen and Kurath. The effects of coupling in the channel involving the inelastic excitation of the 2.43 MeV state in ^{9}Be were found to be appreciable. Comparisons are drawn between the ^{9}Be(d, p)^{10}Be and ^{9}Be(p, π^+)^{10}Be reactions.

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NUCLEAR REACTIONS ^{9}Be(d, p)^{10}Be, $E = 17.3$ MeV; measured $\sigma(E_p, \theta)$. ^{10}Be deduced levels, L_n, S, Γ.

1. Introduction

Although a great deal of information has been obtained about the excited states of ^{10}Be from a variety of reactions [1]), a number of questions still remains, particularly concerning the particle unstable higher lying states. For example, there was evidence from a study [2]) of the ^{7}Li(^{7}Li, α)^{10}Be reaction for the existence of an unreported state at 11.9 MeV. Confirmation of its existence as well as a determination of its properties have been lacking. Similar questions exist concerning the levels at 9.27, 9.4 and 10.7 MeV. Recently, the results of an interesting experiment, that provided a different kind of information on the excited states of ^{10}Be, became available. Dahlgren *et al.* [3]) investigated the ^{9}Be(p, π^+)^{10}Be reaction with 185 MeV protons and an energy resolution of 0.55 MeV. They observed levels at 11.75±0.11, 9.31±0.24, 6.07±0.13 and 3.37±0.12 MeV which were populated very strongly, whereas a level at 7.39±0.13 MeV and the ground state were relatively weakly populated. Thus some confirmation for the existence of the level at 11.9 MeV was obtained. The groups at 9.31, 7.39 and 6.07 MeV are somewhat difficult to interpret because the rather broad energy resolution of the (p, π) experiment meant that more than one level in ^{10}Be could contribute.

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It thus appeared useful to obtain more precise information on some of the less well documented states in ^{10}Be and in particular to obtain data with an alternate reaction, such as ^{9}Be(d, p)^{10}Be, that could be of use in a direct comparison with the results of the (p, π^+) experiment.

The (d, p) reaction on ^{9}Be has been studied by several investigators [4-7]) but no information has been obtained until recently for any levels over 7.37 MeV using this reaction. Sonnemans [8]), in the process of studying multiparticle reactions induced by deuterons on ^{9}Be at 26.3 MeV, obtained angular distributions for the (d, p) reaction for the levels at 9.27+9.4 and 7.37+7.56 MeV as well as some of the lower excited states. A small peak was also seen at 11.8 MeV which became reasonably prominent at the backward angles but no angular distribution could be obtained.

In spite of difficulties generally encountered with the use of distorted wave calculations for the very light nuclei, useful information has been obtained for lower lying levels of ^{10}Be and some attempt has been made here to see what success can be achieved for higher levels that are particle unstable.

2. Experimental procedure

The 17.3 MeV deuteron beam used for the study of the ^{9}Be(d, p)^{10}Be reaction was produced by the University of Colorado 1.3 m sector focussing cyclotron. The measurements were carried out in a 91.5 cm diameter scattering chamber using Si(Li) detectors. The beam spot on the target was about 3 mm^2. After the beam passed through the target it was collected in a Faraday cup 1.5 m away.

A ΔE, E counter telescope consisting of a 97 μm thick ORTEC ΔE detector and a 3 mm thick E-detector fabricated in this laboratory was employed. Both detectors were cooled by circulating alcohol cooled by dry ice. A permanent magnet was placed in front of the telescope to prevent electrons from the target from entering the detector. The solid angle was 0.15 msr.

Particle identification was accomplished using a power-law identification circuit (ORTEC 423). The signal from the identification system was used to route the $E+\Delta E$ signal to 1024-channel sub-groups of a Nuclear Data 50/50 pulse height analyzer. Spectra for outgoing protons and deuterons were accumulated in this way at each scattering angle.

The basic cross-section data were taken with a self-supporting Be target that had an areal density of 2.60 mg/cm^2. In order to help evaluate the natural width of some of the higher lying states, data were also taken using a 285 μg/cm^2 target which was kindly supplied by R. H. Stokes of Los Alamos Scientific Laboratory. A pulse-height spectrum taken at 65° with the 285 μg/cm^2 target is shown in the upper panel of fig. 1. The energy resolution for the lower energy states was about 105 keV.

The number of counts in the various peaks was determined by fitting a skewed Gaussian function with a linear or exponential background to the region of interest in the spectrum. The statistical errors were generally less than 1 % except for the 11.76

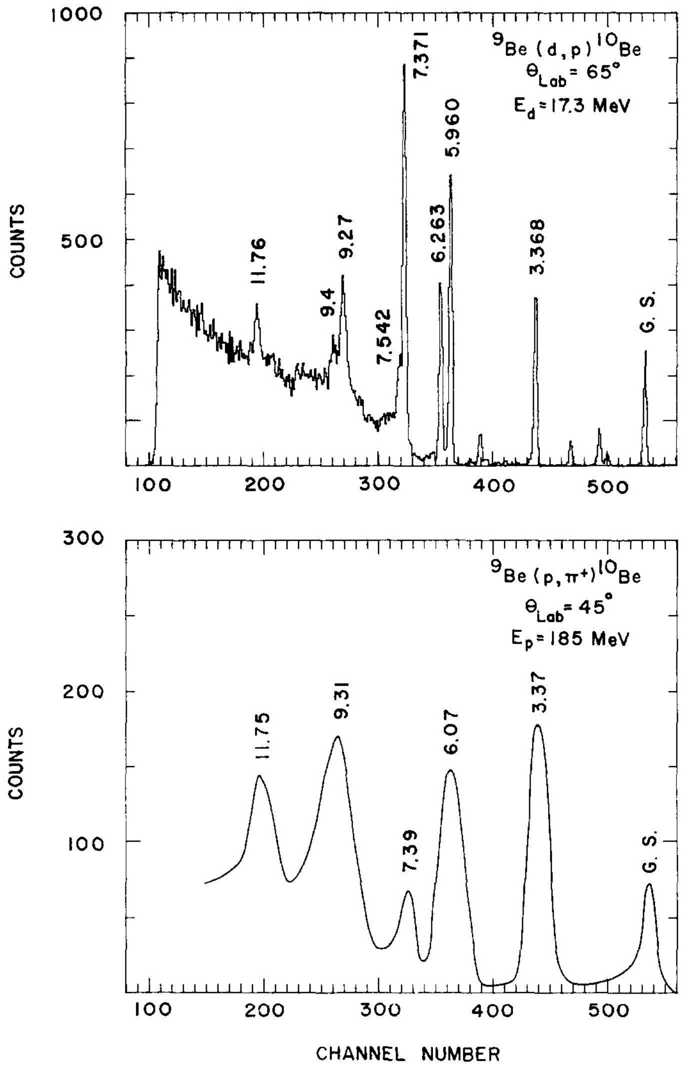

Fig. 1. In the upper panel an energy spectrum, taken at 65°, for the $^9Be(d, p)^{10}Be$ reaction is shown. The energies shown, except for the state at 11.76 MeV, are from a data compilation. In the lower panel an energy spectrum from the $^9Be(p, \pi^+)^{10}Be$ reaction at 185 MeV is shown. The data are those of Dahlgren *et al.* [3]) but have been replotted to conform with the $^9Be(d, p)^{10}Be$ energy scale.

MeV state. A monitor counter was present in the scattering chamber and provided a check on the normalization of the data. The absolute values of the cross sections have an uncertainty of about 15 %.

The energies of the higher lying states in ^{10}Be were based on a linear extrapolation from the known energies of the ground, 3.368 and 5.960 MeV levels.

3. Distorted wave calculations

In order to extract some information concerning the properties of the levels of ^{10}Be, theoretical calculations of the angular distributions were carried out using the computer code DWUCK [9]. The pertinent expression, in mb/sr, is for the predicted cross sections for the ^{9}Be(d, p)^{10}Be reaction

$$\sigma_{\text{exp}}(\theta) = 15.3\, C^2 S_{lj} \frac{2J_f+1}{2J_i+1} \frac{\sigma_{\text{DW}}(\theta)}{2J+1},$$

where $C^2 S_{lj}$ is the spectroscopic factor times the isospin coupling coefficient, J_f, J_i, and J are the total angular momentum of the initial and final states and the transferred neutron respectively and $\sigma_{\text{DW}}(\theta)$ is the DWUCK output in fm^2/sr. The optical model parameters used in the calculations are listed in table 1. The deuteron parameters were taken from the work of Satchler [10] where the optical model potential needed to describe elastic deuteron scattering from carbon at a variety of incident energies was investigated.

A variety of proton parameters were tried, most of which yielded an angular distribution that could adequately describe the data up to about 35°, but beyond this point the calculations in general provided smaller cross sections than the data. In fig. 2 the dashed curve for the ground state was calculated using a set of proton parameters from the work of Watson *et al.* [11]) where a rather extensive optical model analysis of nucleon scattering data from the 1p shell nuclei between 10 and 50 MeV was carried out. The actual parameters are listed in table 1 as set A. The potential had a standard Woods-Saxon form with the definition of the symbols given by Perey [12]. The difficulties with the calculations are obvious in that a too deep first minimum is predicted as well as generally too small a cross section at the higher angles. The optical model parameters suggested by Perey [12] (table 1, set B) from an analysis of proton elastic scattering data on a number of nuclei above aluminum gave similar results except that the first minimum is not as deep and the predicted cross sections at higher angles were larger. The predicted cross section at the first maximum increased by about 30 % in going from set A to set B.

The distorted wave calculations were carried out using the deuteron and set B proton parameters including a non-locality and finite range correction as indicated in table 1. The binding energy was assumed to be 50 keV for the states above 6.81 MeV of excitation.

The use of a single step direct reaction theory to calculate spectroscopic factors for the ^{9}Be(d, p)^{10}Be is subject to question not only because of the use of the optical model for this light nucleus but also because of the questionable applicability of the theory to cases such as that in question. Compound nuclear processes could be important, particularly for the higher excited states. Another complicating aspect is the need to include more than the direct channel in the calculation. Since the 2.43 MeV state of ^{9}Be can be strongly excited by inelastic deuteron scattering [8] one can

TABLE I

Optical-model and bound-state well parameters used in DWBA analysis

Particle	V_C (MeV)	r_{0r} (fm)	a_r (fm)	$4W_D$ (MeV)	r_{0I} (fm)	a_I (fm)	$V_{s.o.}$ (MeV)	r_{0s} (fm)	a_s (fm)	r_c (fm)	β [a]
deuteron	115	0.9	0.9	48.8	1.86	0.45	6.0	0.9	0.9	1.3	0.54
protons A	$48.7-9.3E$	[b]	0.57	$0.64E$	[b]	0.50	5.5	[b]	0.57	[b]	0.85
protons B	$59.4-0.55E$	1.25	0.65	27.48	1.25	0.47	7.5	1.25	0.65	1.25	0.85
neutron well		1.25	0.65				25 [c]	1.25	0.65		0.85

finite range parameter = 0.621

[a] Non-locality correction.

[b] All radius parameters were equal to $1.15-0.001E$.

[c] $\lambda = 25$ using the Thomas spin-orbit form.

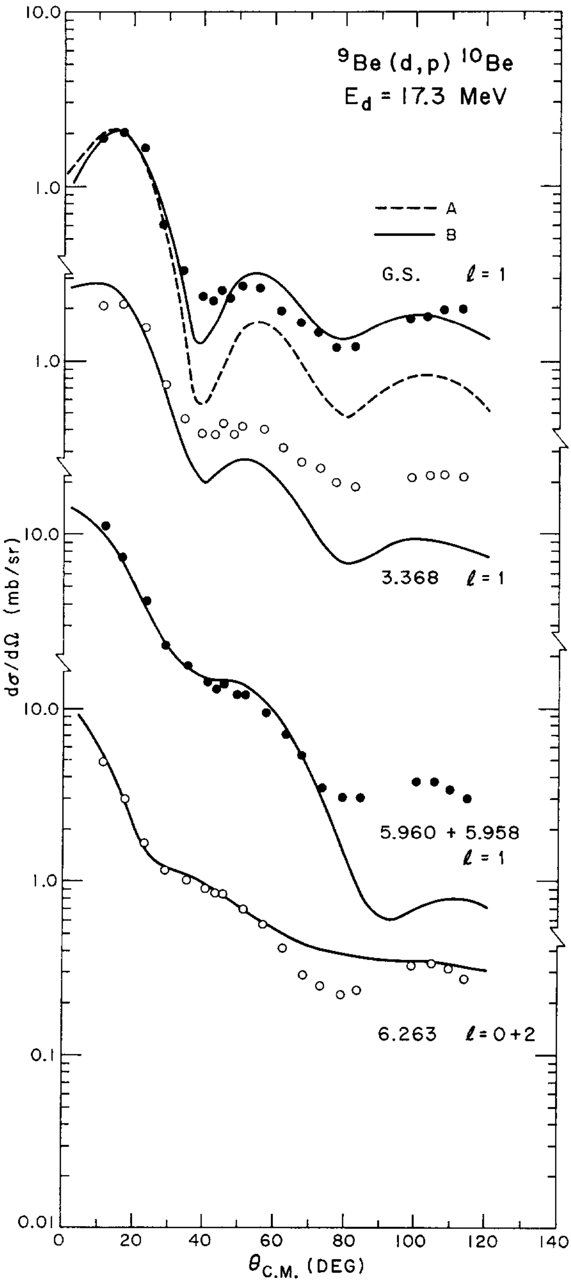

Fig. 2. Experimental angular distributions for $^9Be(d, p)^{10}Be$. The relative uncertainties in the cross sections are generally smaller than the data points. The results of the DWBA calculations are shown as solid lines for proton parameter set A and as dashed lines for parameter set B.

certainly expect coupled channels effects to be important. Later in this paper the effects of including coupled channels on the extraction of spectroscopic factors will be discussed.

4. The excited states of ^{10}Be

The spectrum taken at 65° shows most of the states of ^{10}Be up through 12 MeV. The small unlabeled peaks below 5.960 MeV behaved kinematically quite differently from the ^{10}Be peaks and are most likely due to oxygen on the target. The peak at 5.960 MeV is due to some combination of contributions from states known [1]) to be at 5.9583 MeV and 5.9599 MeV that have spins and parities of 2^+ and 1^- respectively. The state at 6.1793 MeV (0^+) is apparently not appreciably excited in the (d, p) reaction but the nearby state at 6.2633 MeV (2^-) is strongly excited. This is consistent with earlier (d, p) measurements [4, 6, 13]) using lower energy deuterons where the 6.18 MeV group was found to be extremely weak compared to the 6.26 MeV group. The known state at 7.371 MeV (3^-) is strongly excited while the nearby state at 7.542 (2^+) MeV has a cross section that is just about ten times smaller.

The states at 9.27 and 9.4 MeV are both considerably broader than the lower energy states. Unfortunately it was impossible at most angles to adequately separate the 9.27 and 9.4 MeV groups and hence angular distributions for the individual states could not be obtained. Although not shown in fig. 1, a state at 10.57 ± 0.03 MeV was seen quite clearly in three spectra and it could definitely be identified with ^{10}Be from its kinematic behavior. A state has previously been reported at 10.7 MeV from a study of the $^7Li(^7Li, \alpha)^{10}Be$ reaction [2]) and from a resonance in neutron scattering [ref. [14])] from ^{9}Be and it is likely that these are the same states.

A state at 11.76 MeV is clearly seen in fig. 1 and it is probably the same as the state at 11.9 MeV seen in the $^7Li(^7Li, \alpha)^{10}Be$ and the state at 11.75 MeV from the (p, π^+) reaction [3]). Unfortunately, due to the large background from the breakup of the deuteron, cross-section determinations for angles below 30° could not be made. In fig. 3 is shown the energy of the state determined at various angles. The energy was determined to be 11.76 ± 0.02 MeV from these data with the indicated error based solely on an rms deviation from the mean. In order to provide convincing information that the state behaved correctly kinematically, lines are indicated in fig. 3 for the expected energy shift if the final nucleus had a mass one unit either way from 10. There would appear to be no doubt as to the correct assignment. The spectra at 55°, 60° and 65° suggested the presence of another broad state at 13.6 MeV with a width of about 700 keV. However, because of the large background present (largely from the breakup of the deuteron), it is impossible to draw definite conclusions concerning the reality of this state from the present data.

Information was extracted from the various spectra concerning the widths of the states at 9.27, 9.4 and 11.76 MeV using data taken with the thinner target. The instrumental width taken from the ground and first excited state was about 102 keV while the strong 7.37 MeV state had a width of 119 keV. Correcting the 7.37 MeV

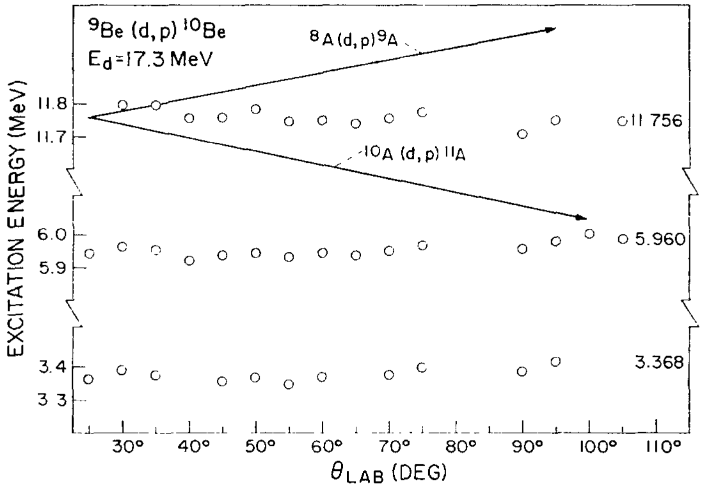

Fig. 3. The measured excitation energy as a function of scattering angle for several states in ^{10}Be. The solid lines indicate the expected kinematic behavior for a target one mass unit removed from 10.

width for the natural width of the state gives an instrumental width of 118 keV and this was the instrumental width assumed for the higher lying states since the energy resolution became greater at higher excitation energies. Natural widths of 150 ± 20, 291 ± 20 and 121 ± 10 keV were calculated for the states at 9.27, 9.4 and 11.76 MeV, respectively. Estimates have been made from neutron scattering data [15]) that the width of the 9.27 MeV state was about 100 keV and that of the 9.4 MeV state was 400 keV. Sonnemans [8]) determined the widths of the 9.24 MeV and 11.8 MeV states to be 700 keV and 500 keV respectively. Both of these widths are considerably larger than the values from the present work. In the case of the 9.24 MeV level Sonnemans feels that the 9.4 MeV state could have contributed to the width obtained.

5. The ^{9}Be(d, p)^{10}Be angular distributions

The experimental angular distributions are shown in figs. 2, 4 and 5. Using the parameters described earlier the distorted wave calculations were carried out and are shown as the solid lines. For the ground state and first excited state the data are remarkably well described by the theoretical angular distributions which were calculated assuming an l-value of 1, i.e. stripping into $1p_{\frac{3}{2}}$ and $1p_{\frac{1}{2}}$ orbitals. The 1p spectroscopic factors have been calculated by Cohen and Kurath [16]) using an effective interaction. They predict that the ground-state transition should be 100 % $1p_{\frac{3}{2}}$ and the first excited state 17 % $1p_{\frac{1}{2}}$ (83 % $1p_{\frac{3}{2}}$). The experimental spectroscopic factors were calculated under these assumptions and the results are shown in table 2 along with the theoretical values [16]). The ratios of the experimental to theoretical spec-

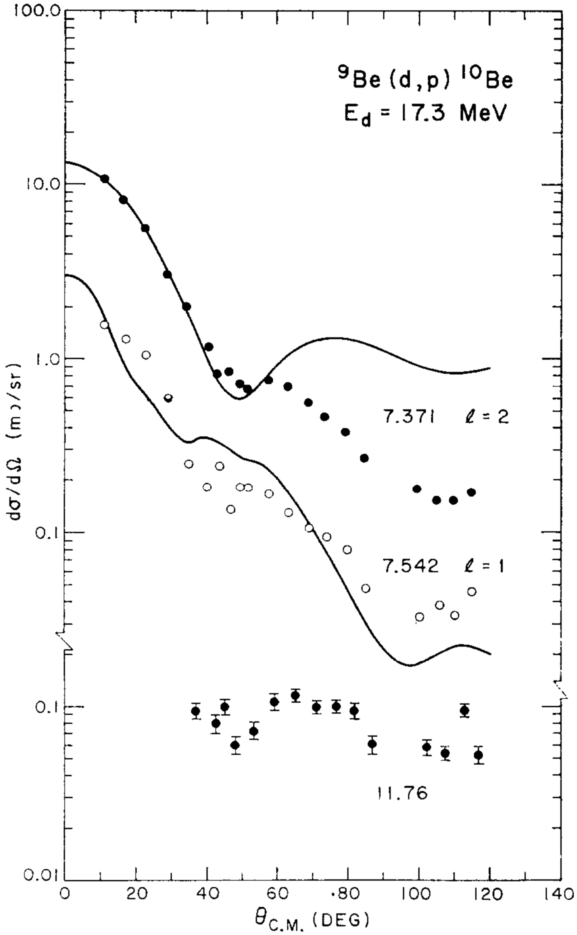

Fig. 4. Experimental angular distributions for the higher excited states of ^{10}Be. The solid lines are the results of DWBA calculations.

troscopic factors are 0.51 and 0.62 for the ground and first excited states. Cohen and Kurath also computed the spectroscopic factors using a different interaction (2 BME) and this yielded a value of 0.194 (65 % $p_{\frac{1}{2}}$) for the first excited state, which is rather close agreement with the experimental value of 0.165 based on 65 % $p_{\frac{1}{2}}$. Also shown in table 2 are values for the spectroscopic factors obtained by Schiffer *et al.* [5]) based on the data of Schmidt-Rohr *et al.* [4]). Both sets of experimental spectroscopic factors fall appreciably below the theoretical values for reasons that are not obvious.

The experimental angular distributions for the higher lying states are more difficult to interpret because there are some unresolved doublets and in some cases several l-values can be expected to contribute to the angular distribution for a particular state.

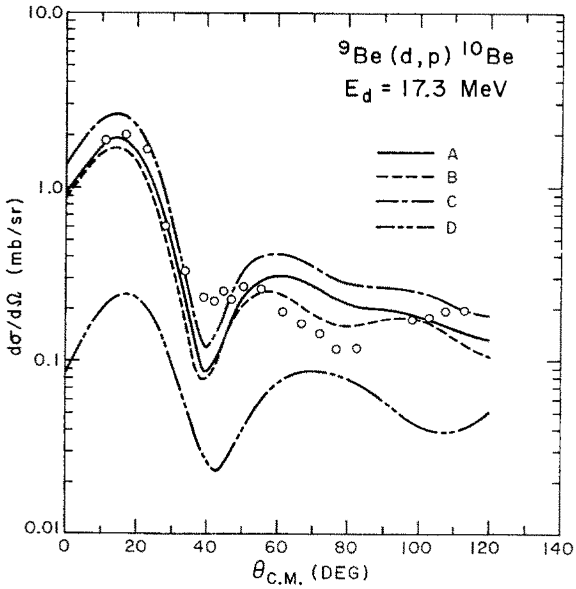

Fig. 5. Comparison of experimental angular distributions for the ground state with various coupled channel calculations as detailed in the text.

TABLE 2
Spectroscopic factors

Level energy	J^π	l_n	S_{lj} [a])	S_{lj} [b])	Theo. S_{lj} [c])	Percent $1p_{\frac{3}{2}}$ [c])
g.s.	0^+	1	0.94 (pot. A) 1.21 (pot. B)	1.67	2.357	100
3.368	2^+	1	0.17	0.24	0.274	17
5.958	2^+	1	0.54		0.421	47
6.263	2^-	0, 2				
7.371	3^-	2	0.36			
7.542	2^+	1	0.20			

[a]) Present work. [b]) Ref. [4]). [c]) Ref. [15]).

Of the two states at 5.958 (2^+) and 5.960 (1^-) MeV, it is assumed here that the former is predominantly excited with the (d, p) reaction. Cohen and Kurath [16]) in fact predict a 2^+ state at about 5.8 MeV with a spectroscopic factor of 0.421 (47 % $1p_{\frac{3}{2}}$). This is to be compared to the experimental value of 0.506 obtained assuming the above fraction of $1p_{\frac{3}{2}}$.

The angular distribution for the 6.263 MeV (2^-) state could involve some combination of $l = 0$ and $l = 2$ and the solid line shown in fig. 2 for that state involves combining 80 % of the theoretical $l = 0$ strength with 20 % of the theoretical $l = 2$ strength to achieve some reasonable description of the data. There is no theoretical value to compare with the experimental value, but the measured value does not seem unreasonable.

The 7.371 MeV state is known to have a spin and parity of 3^- and a pure $l = 2$ theoretical angular distribution describes the data reasonably well to 45° and then there is a wide divergence. The 7.542 MeV (2^+) state is described remarkably well by an $l = 1$ transition considering the approximate nature of the calculations for the unbound states. Cohen and Kurath [16]) do not predict a 2^+ state in this region and it thus is not clear what the theoretical spectroscopic factor is.

The angular distribution for the 11.76 MeV state suffers from our inability to extract cross sections at the smaller angles. It is unfortunate that at the higher excitation energies that $l = 1$ and $l = 2$ experimental angular distributions appear to be so similar that a choice is difficult. There is perhaps some reason to favor a $l = 2$ assignment from the point of view of the distorted wave calculations but this is not felt to be a reliable basis for an assignment at these high excitation energies.

The distorted wave calculations described so far assume a simple one-step stripping processes. As mentioned earlier the 2.43 MeV ($\frac{5}{2}^-$) state of ^9Be is very strongly excited in both inelastic proton [17]) and deuteron [8]) scattering. The two states involved are thought to be the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of a $K = \frac{3}{2}$ ground-state rotational band. Values of 1.1 and 1.4±0.3 were obtained in the case of protons and deuterons, respectively, for the nuclear quadrupole deformation parameter, β. It is thus possible that, in addition to the direct process, a channel involving the inelastic excitation of the $\frac{5}{2}^-$ level in ^9Be and then proton emission to the various levels of ^{10}Be could have important effects when coupled. In order to investigate these coupled channel effects preliminary calculations were carried out for the $^9Be(d, p)^{10}Be$ reaction using the computer code CHUCK [9]). The excitation of states other than the $\frac{5}{2}^-$ state in ^9Be was neglected. The optical potentials for the deuterons and protons were taken to be the same as those used in the distorted wave calculations with the exception that the spin-orbit potential for the deuteron was taken to be zero to simplify the calculations. This simplification is expected to have little effect on the results.

The spectroscopic factors for both single-particle transfers were set equal to one while the value of β_2 for the excitation of the 2.43 MeV state was set at 0.6. This deformation was intentionally put lower than the values quoted (1.4 to 1.1) because CHUCK does the calculation for all orders of β while the usual DWBA calculation, in the process of extracting a value for β from the inelastic data, does it only to first order in β. The differential cross section predicted by the coupled channels calculation for the ground state of ^{10}Be is shown in fig. 5 as curve A along with the experimental results. The calculations were not renormalized to the data. While the magnitude of the calculations is very good the shape of the angular distribution is not quite as good as the single step calculations.

To get some further insight into the effects of coupled channels the spectroscopic factor for stripping from the 2.43 MeV level, which was originally rather arbitrarily set to one, was reduced to 0.3. The results are shown in fig. 5 as the dashed curve (B). The magnitude at the first maximum is reduced by about 10 % but the slope of the angular distribution beyond that describes the data more closely than previously. In contrast to this, if the ground-state spectroscopic factor is reduced to 0.3, the entire angular distribution is reduced by about 85 %. This result is shown as curve D. If the spectroscopic factor for the ground-state channel is set equal to 1.2, that is the value from the single-step calculation, and the other channel is kept at 1.0, the results shown in curve C are obtained. The result rather badly overpredicts the cross section. It is clear that the spectroscopic factor obtained by the usual DWBA methods in the case of $^{9}Be(d, p_0)^{10}Be$ is overestimated because of the neglect of inelastic channels.

A more complete coupled channels calculation that included additional excited states in ^{9}Be, further investigation of the spectroscopic factors, and effects of the optical model parameters was felt to be beyond the scope of the present study.

6. Summary

Additional information on the higher lying states of ^{10}Be has been sought through the use of the (d, p) reaction. Confirmation of the existence of states at 10.57 and 11.76 MeV has been obtained and the natural widths of the levels at 9.27, 9.4 and 11.76 MeV were extracted from the data. The experimental angular distributions were reasonably well described by distorted wave calculations assuming the known spins and parities but the spectroscopic factors which were obtained were generally lower than theoretical values by as much as a factor of two. The effects of coupled channels was investigated in a limited way and a further reduction of the spectroscopic factors would appear to be called for.

A π^+ spectrum from the $^{9}Be(p, \pi^+)^{10}Be$ reaction taken at 45° and 185 MeV bombarding energy is shown in the lower half of fig. 1. The data of Dahlgren *et al.* [3]) have been replotted on the same energy scale as the $^{9}Be(d, p)^{10}Be$ spectrum to bring out any similarities. The major differences appear to be the relatively weak population of the state at 7.37 and the relatively strong excitation of the states at 9.27, 9.4 and 11.76 MeV. The character of the 7.37 MeV (3^-) state is not known except that there must be some 1d component, but it is not obvious why the (d, p) prefers populating the level relative to the (p, π^+) reaction. One might expect, on the basis of the one-nucleon model [18, 19]) where a pion is emitted by the incoming proton and the neutron is captured into a vacant orbital, that there would be a more exact correspondence between the (d, p) and (p, π^+) data. There is, however, a greater angular momentum mismatch in the case of the (p, π^+) reaction which might be a reason for that reaction to preferentially populate the higher angular momentum states. That does not appear to agree with the present observations.

A similar set of data is available for the $^{12}C(d, p)^{13}C$ reaction at 17.3 MeV bombarding energy [20]) and the $^{12}C(p, \pi^+)^{13}C$ reaction [21]). Here again the spectra show some striking similarities but there are interesting differences particularly for the higher lying states. For example, the rather broad 8.25 MeV ($\frac{3}{2}^+$) level is not appreciably excited in the (p, π^+) reaction whereas it is quite strong in the (d, p) reaction. The 10.75 MeV ($\frac{7}{2}^-$) state is similarly weakly excited in the (p, π^+) reaction relative to the (d, p) reaction.

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Note added in proof: The thickness of the thin target which was used to provide the absolute normalization of the data has been determined to be 245 μg/cm^2 rather than the 280 μg/cm^2 quoted. Thus the absolute cross sections and spectroscopic factors should be multiplied by a factor of 1.11. This correction does not change any of the conclusions reached.

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