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D State Effects in the $^{11}B(\vec{d}, n)^{12}C$ Reaction at 79 MeV

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Abstract

Vector analysing powers have been measured for the $^{11}B(\vec{d}, n)^{12}C$ reaction at 79 MeV for the 0·00, 4·44, 9·64, 12·71 and 15·11 MeV states of ^{12}C. The effects on DWBA calculations of exact finite range and the D state of the deuteron are investigated for this reaction. Compared with approximate finite range calculations, it is found that inclusion of exact finite range and D state in the calculations generally improves the agreement with the experimental data, for both the analysing powers and also the differential cross sections which have been previously reported for these five states.

1. Introduction

Deuteron D state effects on (d, p) and (p, d) reactions were first studied seriously by Johnson and Santos (1967) and by Delic and Robson (1970) and have since been the subject of many theoretical and experimental investigations (Johnson and Santos 1971; Ohnuma *et al.* 1980, 1981; Aoki *et al.* 1983). It now seems well established that although the deuteron D state can have quite significant effects on tensor analysing powers (Brown *et al.* 1971; Rohrig and Haeberli 1973; Knutson *et al.* 1975; Stephenson and Haeberli 1977), it has only relatively small effects on cross sections and vector analysing powers at lower energies (Bjorkholm *et al.* 1969; Delic and Robson 1970). At higher energies the D state contributions become more important and indeed dominate the S state at intermediate energies (Rost and Shepard 1975) and, therefore, it is interesting to investigate their effect on reactions such as $^{11}B(\vec{d}, n)^{12}C$ at 79 MeV, a beam energy between low and intermediate energy.

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In an earlier experiment at the Indiana University Cyclotron Facility (IUCF), unpolarised deuterons were used to obtain differential cross sections for five bound states in ^{12}C. The effects of deuteron breakup were investigated (Foot *et al.* 1985) using the adiabatic model of Johnson and Soper (1970). The analysis showed that this model was more successful than conventional DWBA calculations in reproducing the experimental results. It was then decided to use vector polarised deuterons at the same energy to determine whether this improvement was also reflected in the analysing powers, which we then measured in a subsequent experiment. Satisfactory fits to the analysing powers were obtained with adiabatic and with conventional calculations for the ground, 9·64, 12·71 and 15·11 MeV states in ^{12}C; however, there was marked disagreement in the case of the 4·44 MeV state even though it involved the same particle transfer as the 12·71 and 15·11 MeV states. The cause of this discrepancy was investigated (Foot *et al.* 1986) but so far remains unresolved. We present here an account of the experimental procedure and analysis. Exact finite range (EFR) calculations that include the deuteron D state are compared with S state EFR calculations and with calculations in approximate finite range to study the importance of both EFR and the D state at this energy.

2. Experimental Procedure

The experiment was performed with the beam swinger system (Goodman *et al.* 1979) at IUCF with the neutron spectra being obtained by time of flight. The differential cross sections and analysing powers were measured in separate experiments about two years apart. The experimental arrangement for both measurements was similar. Since the arrangement for the cross section measurements was described in detail by Foot *et al.* (1985), we note briefly here the similarities and differences between the two experiments.

Self-supporting targets of 97% isotopically enriched ^{11}B were used for both the cross sections and analysing power measurements, the thicknesses being 23·1 and 37·0 mg cm^{-2} respectively.

The emitted neutrons were detected for both experiments in large 10 cm thick, NE-102 plastic scintillators situated in three external detector stations at 0°, 24° and 45° with respect to the undeflected beam. The corresponding detector–target distances were 85·8, 89·1 and 62·8 m for the cross section measurements and 60·6, 61·0 and 61·6 m respectively for the analysing power measurements. The total areas for the detector arrays at each station were 1·55, 1·55 and 1·16 m^2 for the cross sections and 1·03, 1·55 and 2·32 m^2 for the analysing powers. The most important contributions to the overall neutron energy resolution are from the finite thicknesses of detectors and target. The resolutions were 300 keV for cross sections and 450 keV for analysing powers with the poorer resolution for the latter being due mainly to the shorter flight paths. The vector polarisation of the deuteron beam was sampled at 7·1 MeV between the two cyclotrons with the ^{3}He($\vec{\mathrm{d}}$, p)^{4}He reaction (Grüebler *et al.* 1971) and was typically $\pm 58\%$. The atomic-beam polarised-ion source was operated in 'fast spin-flip' mode; that is, the direction of the beam polarisation was reversed every 30 s.

3. Analysis

A typical time-of-flight spectrum of neutrons from the 79 MeV deuteron bombardment of ^{11}B is shown in Fig. 1. The analysis of the unpolarised data

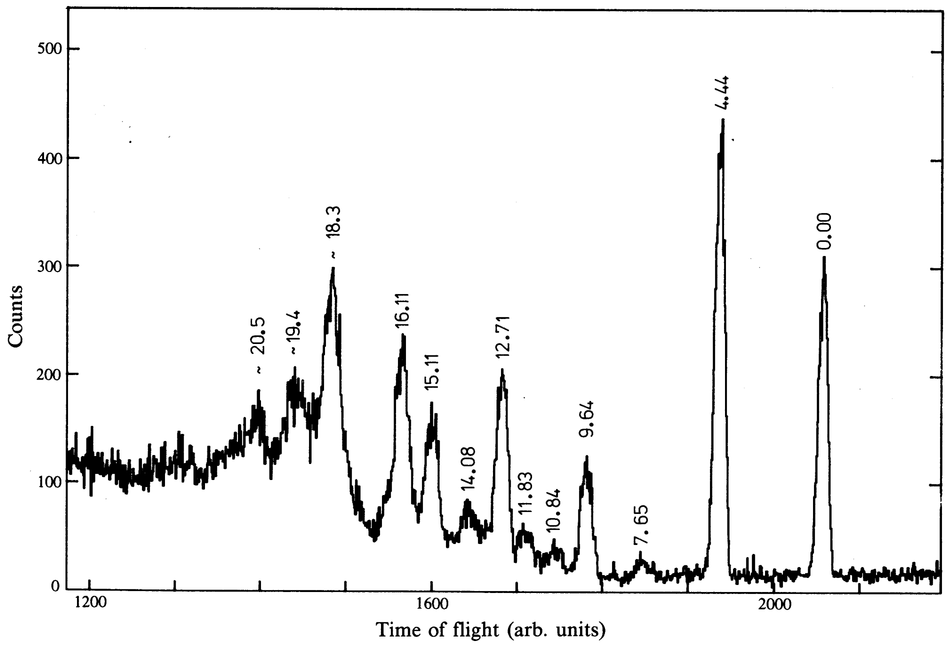

Fig. 1. Typical neutron time-of-flight spectra produced by 'spin-up' deuterons for the reaction $^{11}B(\vec{d},n)^{12}C$, with $E_d = 79$ MeV and $\theta_{lab} = 0°$. Neutron flight time increases to the left. The energies of the states are given in MeV.

to obtain the differential cross sections was described by Foot *et al.* (1985); similar procedures were used for extracting peak areas for the polarised data.

The differential cross sections and related analysing powers for five states in ^{12}C are shown in Figs $2a$ and $2b$ respectively. It is important to realise that the theoretical cross sections have been normalised to the third datum point. The data are compared with three DWBA calculations: (1) in approximate finite range using the local energy approximation, (2) in EFR with deuteron S state only and (3) in EFR with deuteron S and D wave contributions added coherently using the prescription of Delic and Robson (1970) with the Reid (1968) soft-core potential for the neutron–proton interaction. The computer codes DWUCK4 and DWUCK5 were used for the approximate and exact finite-range calculations respectively. In all calculations, non-locality effects were taken into account with the customary values of $\beta = 0{\cdot}54$ and $0{\cdot}85$ fm for deuterons and nucleons respectively. The optical-model parameters for the outgoing neutrons, at the appropriate energies were obtained for all calculations by interpolation from the proton values of Comfort and Karp (1980) with the Coulomb (slowing down) part of the proton potential being removed for the neutrons.

The choice of the deuteron optical-model parameters is less obvious and has been discussed by Foot *et al.* (1985), where it was observed that deuteron parameters constructed using the Johnson and Soper (JS) (1970) adiabatic model are quite successful in reproducing the cross section data.

The JS model provides an approximate method for simulating deuteron breakup effects in conventional DWBA codes by constructing deuteron optical-model parameters from those of protons and neutrons at half the deuteron energy. Thus,

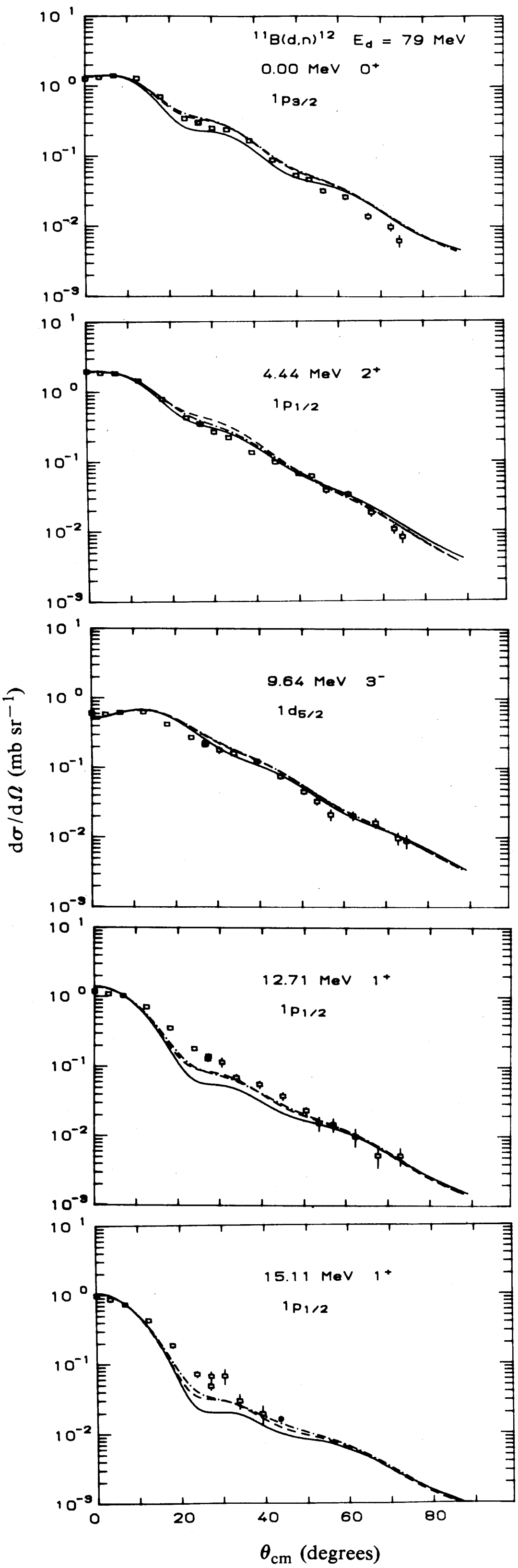

Fig. 2*a*. Experimental and calculated cross sections for the 0·00, 4·44, 9·64, 12·71 and 15·11 MeV states in ^{12}C. The solid, dashed and dot–dash curves correspond respectively to adiabatic calculations in approximate finite range, in EFR calculations with deuteron S state only and in EFR calculations with deuteron S and D state contributions added coherently.

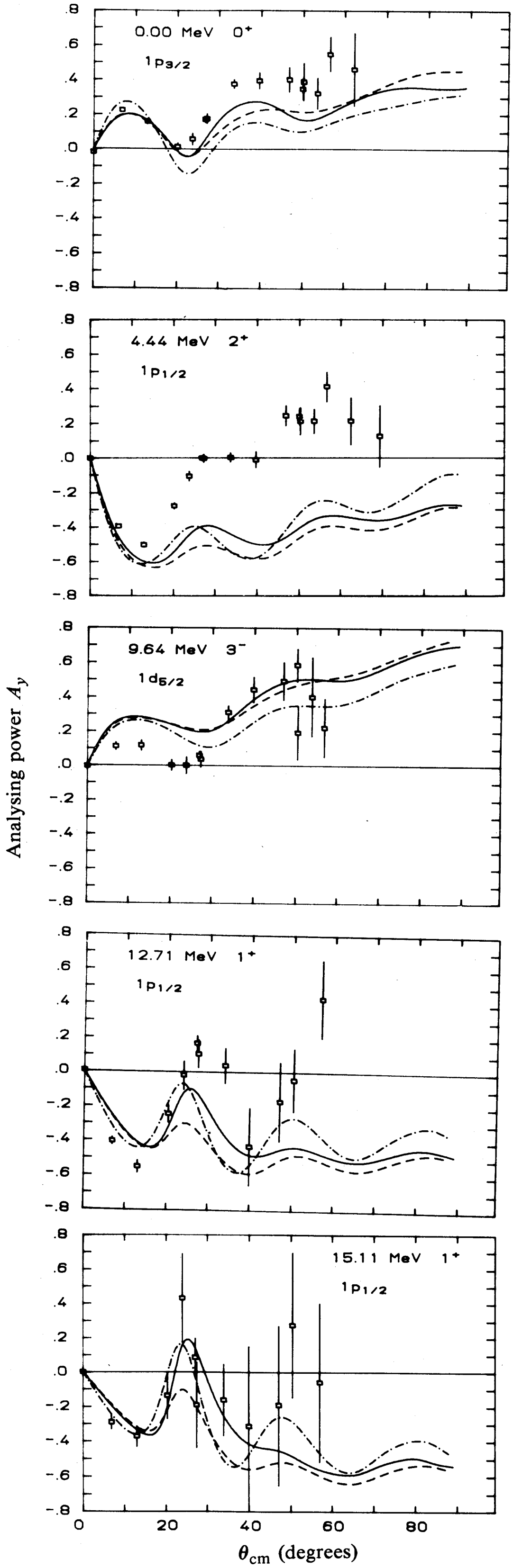

Fig. 2*b*. Experimental and calculated analysing powers for the 0·00, 4·44, 9·64, 12·71 and 15·11 MeV states in ^{12}C (see caption to Fig. 2*a*).

the current calculations require 40 MeV nucleon optical-model parameters but unfortunately none are available and global parametrisations tend to be unsuccessful for light targets. The differential cross sections, however, are reproduced reasonably well by adiabatic calculations with the 30 MeV proton parameters of Karban *et al.* (1969) and also with the 40 MeV ^{12}C parameters of Comfort and Karp (1980). The resulting deuteron parameters are given as sets A and B in Table 1.

Table 1. Deuteron optical-model parameters

Set A: Adiabatic deuteron parameters constructed using Karban *et al.* (1969) ^{11}B proton parameters.

Set B: Adiabatic deuteron parameters constructed using Comfort and Karp (1980) ^{12}C proton parameters.

All optical-model parameters have been converted to the form of the potential $V(r)$ in DWUCK4 where

$$V(r) = V_R f(r, r_R, a_R) + \mathrm{i}\, V_I f(r, r_I, a_I) + \mathrm{i}\, V_I' a_I' \frac{\mathrm{d}f}{\mathrm{d}r}(r, r_I', a_I') - V_{so} \frac{1}{r} \frac{\mathrm{d}f}{\mathrm{d}r}(r, r_{so}, a_{so})\, L.S + V_C(r),$$

and where the Woods–Saxon well is given by $f(r, r_i, a_i) = [1 + \exp\{(r - r_i A^{1/3})/a_i\}]^{-1}$

Parameter set	V_R (MeV)	r_R (fm)	a_R (fm)	V_I (MeV)	r_I (fm)	a_I (fm)	
A	$-86\cdot3$	$1\cdot09$	$0\cdot627$	$0\cdot00$	$0\cdot00$	$0\cdot00$	
B	$-74\cdot8$	$1\cdot20$	$0\cdot646$	$-12\cdot3$	$1\cdot40$	$0\cdot720$	
Parameter set	V_I' (MeV)	r_I' (fm)	a_I' (fm)	V_{so} (MeV fm^2)	r_{so} (fm)	a_{so} (fm)	r_C (fm)
A	$26\cdot2$	$1\cdot30$	$1\cdot03$	$-15\cdot6$	$0\cdot980$	$0\cdot570$	$1\cdot3$
B	$0\cdot00$	$0\cdot00$	$0\cdot00$	$-10\cdot8$	$0\cdot994$	$0\cdot641$	$1\cdot3$

It was observed (Foot *et al.* 1986) that reasonable fits to the analysing powers for all the ^{12}C states, with the exception of the $4\cdot44$ MeV state, were obtained with set B while set A generally resulted in poorer fits especially to the ground state. It was noted that the magnitude of V_{so} in set A is unusually large compared with other deuteron potentials studied by Foot *et al.* (1985). Also it was found that replacing the spin–orbit parameters in A with those of set B resulted in satisfactory fits to all analysing powers studied, with the exception of the $4\cdot44$ MeV state, and to all cross sections. All the theoretical curves in Fig. 2 were obtained in this way. The substitution can be justified by the observation that when the same substitution is made to the original ^{11}B potential (Karban *et al.* 1969) with the ^{12}C spin–orbit parameters of Comfort and Karp (1980) interpolated to 30 MeV, experimental ^{11}B elastic cross sections and analysing powers are reproduced almost as well as with the published Karban parameters.

The bound proton form factors were obtained, for all calculations by the separation energy method with the standard geometry parameters ($r_0 = 1\cdot25$ fm and $a = 0\cdot65$ fm).

4. Results and Conclusions

There are several general observations that can be made from Fig. 2. The full EFR calculation with D state differs significantly for analysing power from both approximate finite range and EFR calculations with S state only. This difference is less apparent in the normalised cross sections and both EFR calculations tend to yield similar results. The corresponding spectroscopic factors are compared with each other and with those of Cohen and Kurath (1967) in Table 2. For the ground and first excited states the spectroscopic factors for the full EFR calculations are closer to the Cohen and Kurath values than those obtained with approximate finite range calculations. The situation is reversed, however, for the higher excited states.

The use of full EFR results is an improvement over approximate finite range in reproducing the experimental differential cross section shapes for states at higher excitation. The calculated analysing powers for those more highly excited states also reflect this improvement. However, the use of EFR with D state worsens the fit to

Table 2. ^{12}C absolute spectroscopic factors

The deuteron optical-model parameters used are those of set A except the spin–orbit parameters which are those of set B in Table 1

E_x (MeV)	J^π, T	l_j transfer	S^A	S^B	S^C	S^D
0·00	$0^+,0$	$p_{3/2}$	5·0	6·2	5·5	5·7
4·44	$2^+,0$	$p_{1/2}$	1·1	1·4	1·2	1·1
9·64	$3^-,0$	$d_{5/2}$	0·22	0·26	0·24	—
12·71	$1^+,0$	$p_{1/2}$	1·2	1·4	1·3	0·79
15·11	$1^+,1$	$p_{1/2}$	0·98	1·1	1·1	0·83

^{A} Approximate finite range DWUCK4 calculation.
^{B} Exact finite range DWUCK5 calculation (S state only).
^{C} Exact finite range DWUCK5 calculation (coherent S and D states).
^{D} Cohen and Kurath (1967) prediction.

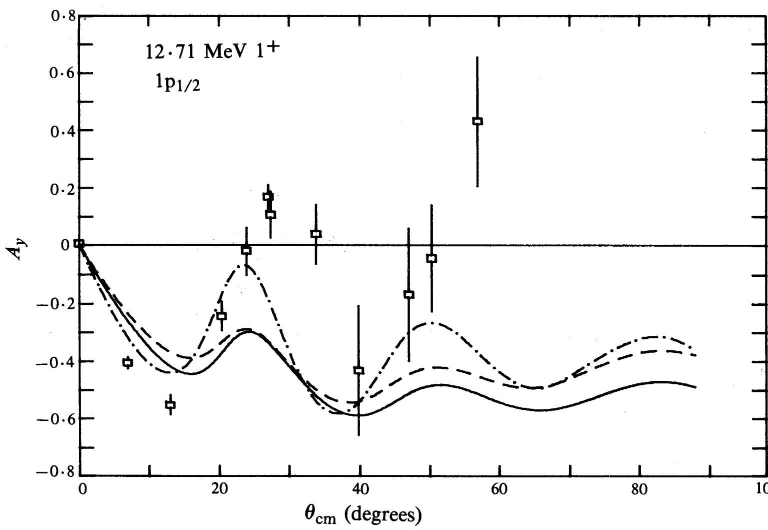

Fig. 3. Experimental and calculated analysing powers for the 12·71 MeV state in ^{12}C. The solid, dashed, and dot–dash curves correspond respectively to EFR calculations with S state only, S and D states added incoherently, and S and D states added coherently.

the ground state analysing power data. It is also clear from Fig. 2*b* that there is severe disagreement between the data and any calculation for the 4·44 MeV analysing powers. This discrepancy was discussed at some length by Foot *et al.* (1986), but has yet to be resolved.

It is interesting to note that the effect of the D state on the cross sections is due almost entirely to simply its presence rather than interference between the S and D state amplitudes, while the effects on the analysing powers are predominantly due to interference. This result is illustrated for the 12·71 MeV state in Fig. 3, where a comparison is made of EFR calculations with S state only, with S and D added incoherently, and with S and D added coherently. (Interference effects are 'turned off' in an incoherent sum.)

5. Summary

The effects of including both exact finite range and deuteron D state on the cross sections and analysing powers for the $^{11}B(\vec{d},n)^{12}C$ reaction at 79 MeV have been investigated. It was found that these effects, although not large, are significant and in most cases, their inclusion improves the agreement between calculation and experimental data.

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