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A Study of the $^{11}B(\vec{d}, n)^{12}C$ Reaction with Polarized Deuterons at $\bar{E}_d = 900$ keV

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Abstract. The analysing power of the $^{11}B(\vec{d}, n)^{12}C$ reaction for the neutron group leaving the ^{12}C nucleus in the ground state has been measured at a mean deuteron energy of $\bar{E}_d = 900$ keV. An analysis of the results shows that the major contribution to the reaction at this energy comes from a $5/2^-$ state of the compound nucleus ^{13}C with s-waves in the entrance channel. It is shown that this is possibly the 19.7-MeV level in ^{13}C.

1. Introduction

A number of different experiments with the $d + {}^{11}B$ system [1, 2, 3, 4] performed with unpolarized deuterons indicates the presence of a resonance near the incident deuteron energy of 1.45 MeV (Fig. 1) [19]. The corresponding energy level in the com-

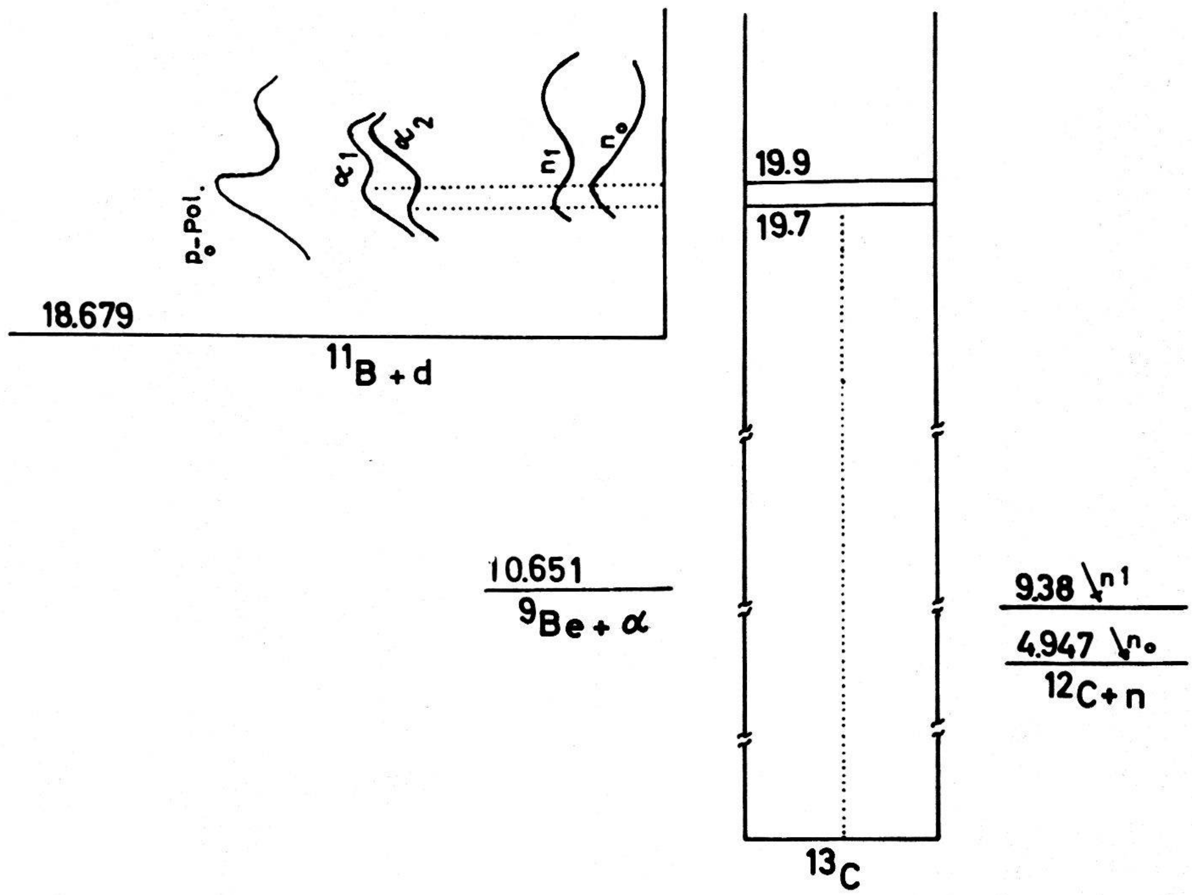

Figure 1
Level Scheme of ^{13}C.

pound nucleus ^{13}C lies at 19.9 MeV. Friedland and Verleger [4] analysing the excitation energy curves of several α-particle groups from the $^{11}B(d, \alpha)^9Be$ reaction pointed out the possibility of the existence of two overlapping levels separated by 200 keV near 20 MeV. The excitation curves for $^{11}B(d, n_0)^{12}C$ and $^{11}Be(d, n_1)^{12}C^*$ [1] seem to confirm this possibility. The neutron group leaving the ^{12}C nucleus in the ground state shows a broad maximum at the deuteron bombarding energy of 1.45 MeV whereas a maximum in the neutron group leaving the ^{12}C nucleus in the first exited state appears at 1.2 MeV.

In this work the attention has been concentrated on the ground state neutron group. From the measurements of the analysing power of the reaction $^{11}B(\vec{d}, n_0)^{12}C$ at $\bar{E}_d = 900$ keV we have determined the spin and parity of the level giving the major contribution at this energy.

2. Description of a Reaction with Polarized Deuterons

The differential cross section for a nuclear reaction with a beam of polarized deuterons and unpolarized target has been described by various authors [6–12] and can be written according to the Madison Convention [5] in the form:

$$\sigma(\vartheta) = \sigma_0(\vartheta) \left[1 + \frac{3}{2} p_y A_y(\vartheta) + \frac{1}{2} p_{zz} A_{zz}(\vartheta) + \frac{2}{3} p_{xz} A_{xz}(\vartheta) \right.$$
$$\left. + \frac{1}{6} (p_{xx} - p_{yy}) \big(A_{xx}(\vartheta) - A_{yy}(\vartheta)\big)\right] \tag{1}$$

where $\sigma_0(\vartheta)$ is the differential cross section for unpolarized deuterons. The cartesian coordinate system chosen here is right handed with the positive y-axis along $\boldsymbol{k}_d \times \boldsymbol{k}_n$ [12].

Using a quadruple arrangement of detectors as described in [9] and [12] the values of A_y and A_{ij} were obtained independently. The unpolarized relative cross section and the components of the analysing power of the reaction may be expanded in terms of Legendre Polynomials¹) as follows:

$$\sigma_0^n(\vartheta) = \sum_{n=0}^{n_{max}} a_0^n \, L_{n,0}(\cos\vartheta) \, ,$$

$$\sigma_0^n(\vartheta)\, A_y(\vartheta) = \sum_{n=1}^{n_{max}} a_y^n \, L_{n,1}(\cos\vartheta) \, ,$$

$$\sigma_0^n(\vartheta)\, A_{ij}(\vartheta) = \sum_{n \geqslant m}^{n_{max}} a_{ij}^n \, L_{n,m}(\cos\vartheta) \, , \quad ij = \begin{cases} zz \, , & m = 0 \\ xx - yy \, , & m = 2 \\ xz \, , & m = 1 \, . \end{cases} \tag{2}$$

$\sigma_0^n(\vartheta)$ is here normalized by $\sigma_{tot}/4\pi$ so that $a_0^0 = 1$.

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¹) In the notation of Jahnke-Emde: $L_{i,0}(\cos\vartheta) = P_i(\cos\vartheta)$; $L_{i,k}(\cos\vartheta) = P_i^k(\cos\vartheta)$.

The matrix elements of the reaction are contained in the expansion coefficients a^n such that:

$$a_0^n = \lambda\!\!\!^{-2} \sum_{\mu \geq \nu} \alpha_0^{n\mu\nu} \ \operatorname{Re}(R_\mu R_\nu^*) \,,$$

$$a_y^n = \lambda\!\!\!^{-2} \sum_{\mu \geq \nu} \alpha_y^{n\mu\nu} \ \operatorname{Im}(R_\mu R_\nu^*) \,,$$

$$a_{ij}^n = \lambda\!\!\!^{-2} \sum_{\mu \geq \nu} \alpha_{ij}^{n\mu\nu} \ \operatorname{Re}(R_\mu R_\nu^*) \,, \quad ij = \begin{cases} zz \\ xx - yy \,, \\ xz \end{cases}$$

where R_μ stands for the reaction matrix element $\langle l'_\mu S'_\mu J_\mu \mid R \mid l_\mu S_\mu J_\mu \rangle$ (l: orbital angular momentum, S: channel spin, J: total angular momentum). The unprimed quantities refer to the entrance channel. $\lambda\!\!\!^{-}$ is the reduced wavelength of the relative motion in the entrance channel.

A computer programme [13] is available which gives all the possible coefficients $\alpha_{ij}^{n\mu\nu}$ for a set of channels through which the reaction may succeed. For $l, l' \leqslant 3$ the reaction $^{11}B(d, n_0)^{12}C$ has 26 possible matrix elements (Table 1). The evaluation of the $\alpha_{ij}^{n\mu\nu}$ together with our data, shows that only 16 matrix elements (marked with an asterisk) are likely to occur as the resonance which means that the respective $\operatorname{Re}(R_\mu R_\mu^*) = |R_\mu|^2$ enters into the expansion; the others need to be considered only as interference terms $R_\mu \cdot R_\nu^*$ with the resonant element.

Table 1
The reaction matrix elements of $^{11}B(d, n_0)^{12}C$ for $l, l' \leq 3$
$R_i \equiv \langle l'_i S'_i J_i \mid R \mid l_i S_i J_i \rangle$

i	l'	S'	J^π	l	S
1	1	1/2	3/2−	0	3/2*
2	1	1/2	1/2−	0	1/2
3	3	1/2	5/2−	0	5/2*
4	0	1/2	1/2+	1	1/2
5	2	1/2	3/2+	1	1/2
6	0	1/2	1/2+	1	3/2
7	2	1/2	3/2+	1	3/2
8	2	1/2	5/2+	1	3/2*
9	2	1/2	3/2+	1	5/2*
10	2	1/2	5/2+	1	5/2*
11	1	1/2	3/2−	2	1/2
12	3	1/2	5/2−	2	1/2
13	1	1/2	1/2−	2	3/2*
14	1	1/2	3/2−	2	3/2*
15	3	1/2	5/2−	2	3/2*
16	3	1/2	7/2−	2	3/2*
17	1	1/2	1/2−	2	5/2
18	1	1/2	3/2−	2	5/2*
19	3	1/2	5/2−	2	5/2*
20	3	1/2	7/2−	2	5/2*
21	2	1/2	5/2+	3	1/2
22	2	1/2	3/2+	3	3/2*
23	2	1/2	5/2+	3	3/2*
24	0	1/2	1/2+	3	5/2
25	2	1/2	3/2+	3	5/2*
26	2	1/2	5/2+	3	5/2*

The present work shows that the major contribution to the reaction $^{11}\mathrm{B}(\vec{d}, n_0)^{12}\mathrm{C}$ at $\bar{E}_d = 900$ keV comes from matrix element R_3 ($l = 0$). This is also what one should expect, since a resonance with higher l near this energy is less likely due to the centrifugal barrier.

3. Experimental Arrangement

3.1. *Target, detectors and discrimination*

The isotopically enriched ^{11}B-target on a Cu-backing[2]) had an average thickness of 550 μg/cm². This corresponds to an energy loss of 300 keV for 1000-keV deuterons. The deuteron energy referred to in this work is the mean energy in the target.

Plastic scintillators[3]) mounted on photomultipliers[4]) were used as neutron detectors. A typical pulse height spectrum of the recoil protons in the scintillation counters is shown in Figure 2. The edges marked with arrows are due to the first two neutron groups of the reaction $^{11}\mathrm{B}(d, n)^{12}\mathrm{C}$ of 9.3-MeV and 13.7-MeV lab energy.

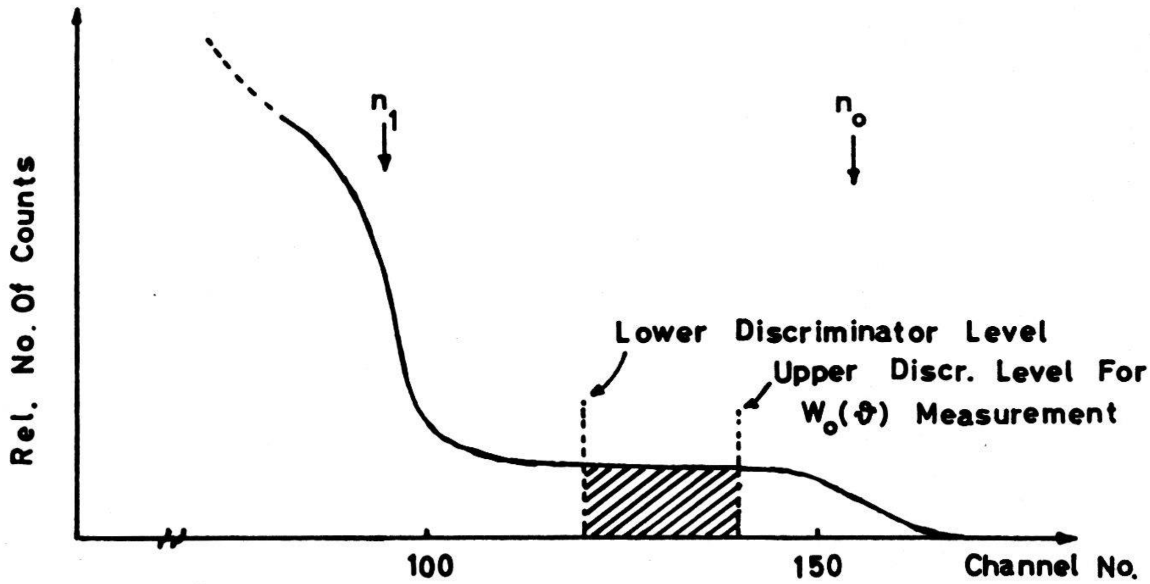

Figure 2
Pulse height spectrum of the recoil protons in the scintillation counter for neutrons of the $^{11}\mathrm{B}(d, n)^{12}\mathrm{C}$ reaction at $\bar{E}_d = 900$ keV.

Since the deuterons induce also the $^{11}\mathrm{B}(d, p)^{12}\mathrm{B}^*$ reaction the high energy β-particles with $E_{max} = 13.4$ MeV from $^{12}\mathrm{B}^*$ would appear superimposed on the pulse spectrum. Therefore 6 mm thick lead absorbers were placed in front of the plastic scintillators.

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2) Supplied by Atomic Energy Research Establishment, Harwell.

3) $1^1/_4'' \times 1^3/_8''$ (NE 102).

4) Philips 150 A.V.P.

The selection of the neutron group n_0, leaving the ^{12}C nucleus in the ground state, is relatively easy. As the energy difference between the first two groups of neutrons is rather large (4 MeV) and the cross section for $^{11}B(d,n_1)^{12}C^*$ is about three times bigger than that for $^{11}B(d,n_0)^{12}C$ [1, 2], the edges corresponding to the two groups appear very well separated in the spectrum of the recoil protons in the plastic scintillators. The lower discriminator level is chosen such that no contribution from the n_1-group is registered.

For the measurement of the n_0-angular distribution with unpolarized deuterons only the horizontal part of the spectrum (shaded area in Figure 2) was used. The upper and lower discriminator levels being constant, the area of the shaded part is a measure of the relative angular distribution. The measurements have been corrected for the variations in the (n, p) cross section and those of the solid angle with the reaction angle ϑ.

3.2. *The source of polarized deuterons and the determination of the analysing power*

The source of polarized deuterons used in this experiment has been described by Grunder et al. [11]. For the measurement of the beam polarization we used the $T(d,n)^4He$ reaction at the 107-keV resonance as analyser. The analysing power of the reaction was determined in basically the same way as described by Petitjean et al. [9] and Neff et al. [12].

4. Experimental Results

The angular distribution $\sigma_0^n(\vartheta)$ of the ground state neutrons from the $^{11}B(d,n)^{12}C$ reaction induced by unpolarized deuterons has been observed and is presented in Table 2 and Figure 3. All angles are center-of-mass angles. Our results agree very well with the angular distribution measured by Siemssen et al. [15] at 1.09 MeV deuteron energy.

Table 2
Analysing power of the $^{11}B(\vec{d},n_0)^{12}C$ reaction at $\bar{E}_d = 900$ keV.

$\vartheta_{c.m.}$	$\sigma_0^n(\vartheta)$	$A_y(\vartheta)$	$A_{zz}(\vartheta)$	$A_{xx}(\vartheta)-A_{yy}(\vartheta)$	$A_{xz}(\vartheta)$
0.0	1.467±0.037	0	−1.008±0.054	0	0
10.3	1.478±0.038				
20.6	1.416±0.036				
30.8	1.342±0.035	−0.050±0.005	−0.673±0.022	−0.340±0.013	−0.701±0.011
41.0	1.259±0.033	−0.060±0.011	−0.235±0.057	−0.667±0.021	
51.2	1.182±0.032	−0.055±0.008	0.047±0.041	−0.850±0.019	−0.800±0.002
61.4	1.106±0.030	−0.056±0.004	0.340±0.032	−1.131±0.012	−0.659±0.034
71.5	1.010±0.028	−0.063±0.007	0.583±0.081	−1.196±0.049	−0.438±0.004
81.6	0.982±0.028	−0.060±0.007	0.645±0.031	−1.262±0.027	−0.135±0.031
91.6	1.054±0.030	−0.056±0.006	0.620±0.037	−1.194±0.031	0.141±0.019
101.6	1.057±0.031	−0.042±0.008	0.565±0.031	−1.065±0.022	0.364±0.022
111.5	0.983±0.029	−0.045±0.004	0.374±0.025	−0.862±0.012	0.518±0.013
121.4	0.914±0.028	−0.037±0.013	0.211±0.051	−0.671±0.027	0.650±0.011
131.2	0.778±0.025	0.029±0.006	−0.037±0.043	−0.496±0.035	0.650±0.004
141.0	0.689±0.023	0.030±0.009	−0.212±0.030	−0.288±0.021	0.614±0.003
150.8	0.604±0.020	0.008±0.006	−0.495±0.025	−0.144±0.030	0.473±0.018

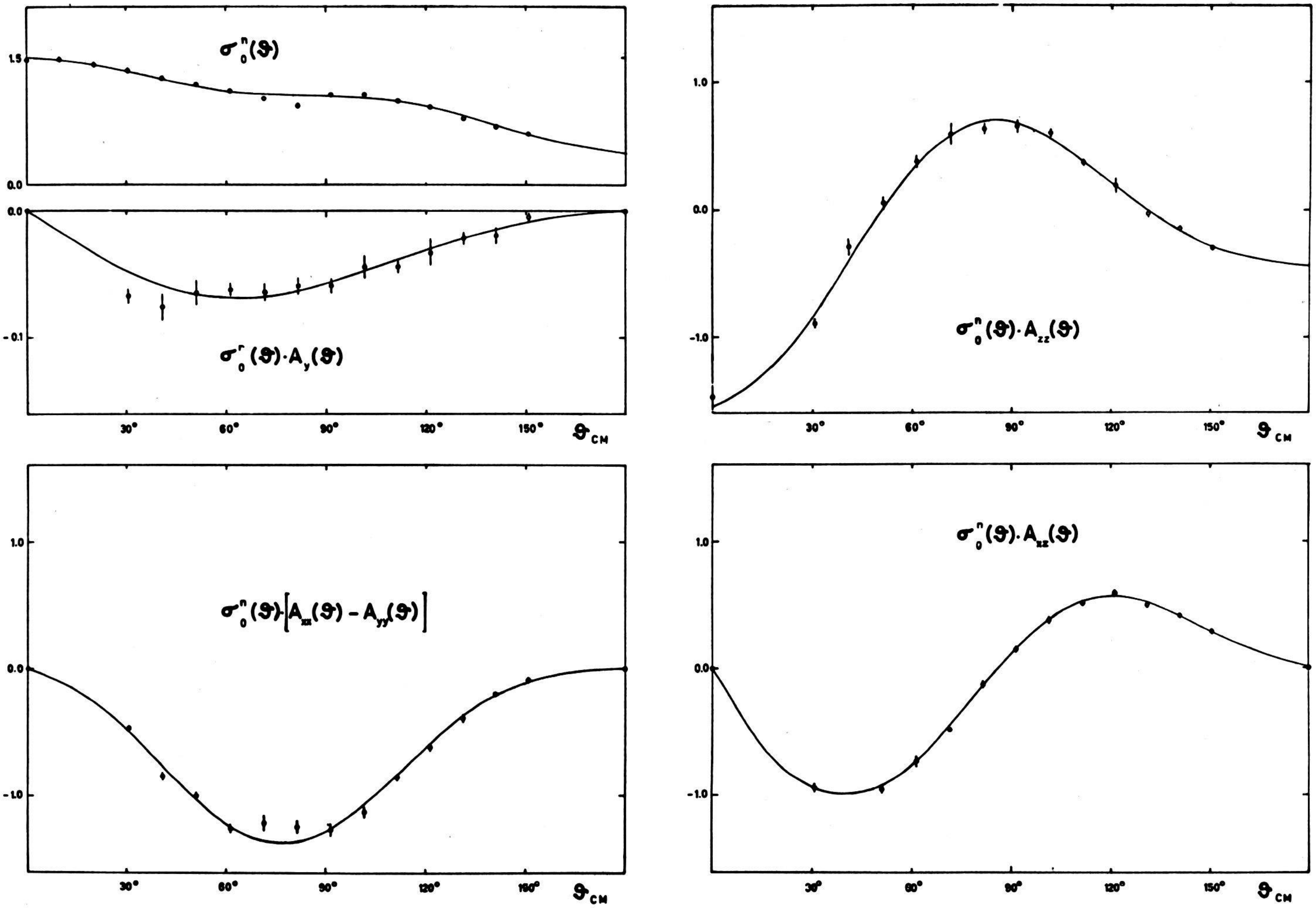

Figure 3
Analysing power of $^{11}B(\vec{d}, n_0)^{12}C$ at $\bar{E}_d = 900$ keV multiplied by $\sigma_0^n(\vartheta)$ plotted as a function of the reaction angle $\vartheta_{c.m.}$

As described by Neff et al [12], the components of the deuteron polarization have been deduced from p^*_{zz}. This is the maximum value of the tensor component p_{zz} of the deuteron polarization observed in a coordinate system, the z-axis of which is the symmetry axis of the polarization state. p^*_{zz} was directly measured with the $T(d,n)^4He$ reaction and varied between 0.47 and 0.68, depending upon the operation conditions of the source.

In order to determine the analysing power of the $^{11}B(\vec{d},n)^{12}C$ reaction according to equation (1) we observed the ratio $\sigma(\vartheta)/\sigma_0(\vartheta)$ which is equal to the ratio of the neutron counting rates with polarized and unpolarized deuteron beams. The components $A_y(\vartheta)$, $A_{zz}(\vartheta)$, $A_{xx}(\vartheta) - A_{yy}(\vartheta)$ and $A_{xz}(\vartheta)$ multiplied by $\sigma^n_0(\vartheta)$ are given in Table 2 and plotted in Figure 3 as a function of $\vartheta_{c.m.}$. The curves in Figure 3 represent the respective fits obtained by Legendre Polynomial expansions. The series were terminated where the errors were larger than or of the same order of magnitude as the respective effects. The expansion coefficients of the analysing powers are collected in Table 3.

Table 3
Coefficients of Legendre Polynomials expansions of the analysing power components of $^{11}B(\vec{d},n_0)^{12}C$ at $\bar{E}_d$ = 900 keV.

$\sigma^n_0(\vartheta)$	a^0_0	= 1
	a^1_0	= 0.355 ± 0.013
	a^2_0	= −0.052 ± 0.018
	a^3_0	= 0.196 ± 0.022
$A_{xx-yy}(\vartheta)$	a^2_{xx-yy}	= −0.414 ± 0.008
	a^3_{xx-yy}	= −0.052 ± 0.003
	a^4_{xx-yy}	= 0.004 ± 0.002
$A_y(\vartheta)$	a^1_y	= −0.058 ± 0.002
	a^2_y	= −0.015 ± 0.002
$A_{zz}(\vartheta)$	a^0_{zz}	= 0.120 ± 0.012
	a^1_{zz}	= −0.208 ± 0.019
	a^2_{zz}	= −1.111 ± 0.027
	a^3_{zz}	= −0.354 ± 0.034
$A_{xz}(\vartheta)$	a^1_{xz}	= −0.074 ± 0.007
	a^2_{xz}	= −0.498 ± 0.005
	a^3_{xz}	= −0.131 ± 0.005
	a^4_{xz}	= 0.013 ± 0.003

The errors shown in Table 2 and 3 are solely statistical. The actual uncertainties are considerably larger, because the variations in the beam quality during the measurements are not considered. Another uncertainty of the analysing power comes from the fact that the beam polarization was determined using the $T(\vec{d},n)^4He$ reaction at the 107-keV resonance as an analyser. It was assumed that the reaction is induced by s-waves only and proceeds through the $3/2^+$ compound state exclusively. In the light of the recent measurements of McIntyre and Haeberli [16], Ohlsen et al. [14], and those of Grunder et al. [11] these assumptions do not seem to be quite correct. The analysing power of the calibration reaction is somewhat smaller and therefore the deduced polarization larger than anticipated. For a correction of this error more data on the $T(d,n)^4He$ reaction are desirable.

Table 4

Coefficients $\alpha_{ij}^{n3\nu}$ for the reaction ${}^{11}\mathrm{B}(\vec{d},n){}^{12}\mathrm{C}$ with $l, l' \leqq 3$ (The space is left blank if the coefficient is zero).

	$n = 0$		$n = 1$				$n = 2$					$n = 3$				
ν	$\alpha_0^{03\nu}$	$\alpha_{zz}^{03\nu}$	$\alpha_0^{13\nu}$	$\alpha_y^{13\nu}$	$\alpha_{zz}^{13\nu}$	$\alpha_{xz}^{13\nu}$	$\alpha_0^{23\nu}$	$\alpha_y^{23\nu}$	$\alpha_{zz}^{23\nu}$	$\alpha_{xx-yy}^{23\nu}$	$\alpha_{xz}^{23\nu}$	$\alpha_0^{33\nu}$	$\alpha_y^{33\nu}$	$\alpha_{zz}^{33\nu}$	$\alpha_{xx-yy}^{33\nu}$	$\alpha_{xz}^{33\nu}$
1									−0,122	−0,061	−0,061					
2									0.194	0.097	0.097					
3	0.125								−0.100	−0.050	−0.050					
4														0.194	0.032	0.065
5					0.232	0.174								0.155	0.026	0.052
6														0.087	0.014	0.029
7				0.083	−0.230	−0.173								0.175	0.029	0.058
8				−0.034	−0.040	−0.030								−0.161	−0.027	−0.054
9			−0.224	−0.156	0.125	0.094								0.054	0.009	0.018
10			0.073	0.015	0.047	0.035								−0.105	−0.018	−0.035
11									0.055	−0.028	0.014					
12		0.194							0.221	−0.111	0.055					
13								−0.014	0.087	−0.043	0.022					
14								0.020	−0.087	0.044	−0.022					
15		−0.229						0.066	−0.094	0.047	−0.023					
16								−0.031	−0.079	0,040	−0.020					
17							0.144	0.067	−0.115	0.058	−0.029					
18							−0.109	−0.040	0.031	−0.016	0.008					
19		0.187					−0.267	−0.054	−0.076	0.038	−0.019					
20							0.126	−0.004	0.061	−0.031	0.015					
21					0.017	−0.008								0.103	−0.026	0.013
22					0.033	−0.016							−0.018	0.131	−0.033	0.016
23					−0.038	0.019							0.027	−0.124	0.031	−0.016
24												0.144	0.048	−0.115	0.029	−0.014
25					−0.066	0.033						0.183	0.052	−0.080	0.020	−0.010
26					0.042	−0.021						−0.183	−0.037	−0.005	0.001	−0.001

Table 5

Expansion coefficients for the analysing power of $^{11}B(\vec{d}, n)^{12}C$ calculated for a s-wave $5/2^-$ resonance in interference with a $3/2^+$ state ($l = 1, 3$) and a $5/2^-$ state ($l = 2$)

$U_i \equiv \lambda\!\!\!^{-2}\,\mathrm{Re}(R_3 R_i^*)$, $V_i \equiv \lambda\!\!\!^{-2}\,\mathrm{Im}(R_3 R_i^*)$

$$
\begin{aligned}
a_0^0 &= 0.125\ U_3 \\
a_{zz}^0 &= 0.194\ U_{12} - 0.229\ U_{15} + 0.187\ U_{19} \\[4pt]
a_0^1 &= -\ 0.224\ U_9 \\
a_y^1 &= 0.083\ V_7 - 0.156\ V_9 \\
a_{zz}^1 &= 0.232\ U_5 - 0.230\ U_7 + 0.125\ U_9 + 0.033\ U_{22} - 0.066\ U_{25} \\
a_{xz}^1 &= 0.174\ U_5 - 0.173\ U_7 + 0.094\ U_9 - 0.016\ U_{22} + 0.033\ U_{25} \\[4pt]
a_0^2 &= -\ 0.267\ U_{19} \\
a_y^2 &= 0.066\ V_{15} - 0.054\ V_{19} \\
a_{zz}^2 &= -\ 0.122\ U_1 + 0.194\ U_2 - 0.100\ U_3 + 0.221\ U_{12} - 0.094\ U_{15} - 0.076\ U_{19} \\
a_{xz}^2 &= -\ 0.061\ U_1 + 0.097\ U_2 - 0.050\ U_3 + 0.055\ U_{12} - 0.023\ U_{15} - 0.019\ U_{19} \\
a_{xx-yy}^2 &= -\ 0.061\ U_1 + 0.097\ U_2 - 0.050\ U_3 - 0.111\ U_{12} + 0.047\ U_{15} + 0.038\ U_{19} \\[4pt]
a_0^3 &= 0.183\ U_{25} \\
a_y^3 &= -\ 0.018\ V_{22} + 0.052\ V_{25} \\
a_{zz}^3 &= 0.155\ U_5 + 0.175\ U_7 + 0.054\ U_9 + 0.131\ U_{22} - 0.080\ U_{25} \\
a_{xz}^3 &= 0.052\ U_5 + 0.058\ U_7 + 0.018\ U_9 + 0.016\ U_{22} - 0.010\ U_{25} \\
a_{xx-yy}^3 &= 0.026\ U_5 + 0.029\ U_7 + 0.009\ U_9 - 0.033\ U_{22} + 0.020\ U_{25}
\end{aligned}
$$

Table 6

Expansion coefficients for the analysing power of $^{11}B(\vec{d}, n)^{12}C$ calculated for a s-wave $5/2^-$ resonance in interference with a $5/2^+$ state ($l = 1, 3$) and a $5/2^-$ state ($l = 2$)

$U_i \equiv \lambda\!\!\!^{-2}\,\mathrm{Re}(R_3 R_i^*)$, $V_i \equiv \lambda\!\!\!^{-2}\,\mathrm{Im}(R_3 R_i^*)$

$$
\begin{aligned}
a_0^0 &= 0.125\ U_3 \\
a_{zz}^0 &= 0.194\ U_{12} - 0.229\ U_{15} + 0.187\ U_{19} \\[4pt]
a_0^1 &= 0.073\ U_{10} \\
a_y^1 &= -\ 0.034\ V_8 + 0.015\ V_{10} \\
a_{zz}^1 &= -\ 0.040\ U_8 + 0.047\ U_{10} - 0.038\ U_{23} + 0.042\ U_{26} \\
a_{xz}^1 &= -\ 0.030\ U_8 + 0.035\ U_{10} + 0.019\ U_{23} - 0.021\ U_{26} \\[4pt]
a_0^2 &= -\ 0.267\ U_{19} \\
a_y^2 &= 0.066\ V_{15} - 0.054\ V_{19} \\
a_{zz}^2 &= -\ 0.122\ U_1 + 0.194\ U_2 - 0.100\ U_3 + 0.221\ U_{12} - 0.094\ U_{15} - 0.076\ U_{19} \\
a_{xz}^2 &= -\ 0.061\ U_1 + 0.097\ U_2 - 0.050\ U_3 + 0.055\ U_{12} - 0.023\ U_{15} - 0.019\ U_{19} \\
a_{xx-yy}^2 &= -\ 0.061\ U_1 + 0.097\ U_2 - 0.050\ U_3 - 0.111\ U_{12} + 0.047\ U_{15} + 0.038\ U_{19} \\[4pt]
a_0^3 &= -\ 0.183\ U_{26} \\
a_y^3 &= 0.027\ V_{23} - 0.037\ V_{26} \\
a_{zz}^3 &= -\ 0.161\ U_8 - 0.105\ U_{10} - 0.124\ U_{23} - 0.005\ U_{26} \\
a_{xz}^3 &= -\ 0.054\ U_8 - 0.035\ U_{10} - 0.016\ U_{23} - 0.001\ U_{26} \\
a_{xx-yy}^3 &= -\ 0.027\ U_8 - 0.018\ U_{10} + 0.031\ U_{23} + 0.001\ U_{26}
\end{aligned}
$$

5. Discussion

The values of the coefficients in Table 3 show that the major contribution to the tensor components of the analysing power comes from the Legendre Polynomials having the degree $n = 2$. This suggests [6] the presence of an s-wave resonance in the neighbourhood of the energy at which we performed our experiment. As the ^{11}B-nucleus has a spin $3/2^-$ in the ground state, the energy level in ^{13}C corresponding to the resonance should therefore also have a negative parity. Out of the three possible matrix elements with $l = 0$ of the incoming particles (Table 1) we can exclude the one with $J^\pi = 1/2^-$ as the resonant element, because an s-wave resonance with $J = 1/2$ would result in vanishing components of the analysing power. Our calculations of the coefficients $\alpha_{ij}^{n\mu\nu}$ using an s-wave resonance corresponding to a $3/2^-$ level show that the expansions of $A_{ij}(\vartheta)$ would have positive coefficients of the Legendre Polynomials $L_{2n}(\cos\vartheta)$. The element R_1 ($l = 0$, $J^\pi = 3/2^-$) may thus be dropped since the corresponding components of the analysing power would have signs opposite to the observed ones. Therefore, the resonance must come from a $5/2^-$ level in ^{13}C. In the previous calculations a sign error led to the wrong conclusion [17].

Besides the main s-wave contribution p- and d-waves also participate in the reaction. This is indicated by the presence of the coefficients a_0^n with $n > 0$ in the $\sigma_0^n(\vartheta)$-angular distribution (Table 3). Taking the matrix element R_3 of Table 1 ($l = 0$, $J^\pi = 5/2^-$) as resonant and assuming that all others are small and therefore appear only in interference with R_3, we have calculated the coefficients $\alpha_{ij}^{n3\nu}$. These values, given in Table 4, show that in order to explain the presence of a_0^3 one must include also $l = 3$ in the incoming channel. Moreover the coefficients a_{ij}^1 and a_{ij}^3 appear only by interference of the $5/2^-$ state with a state of even parity ($3/2^+$ or $5/2^+$ for $l, l' \leqslant 3$).

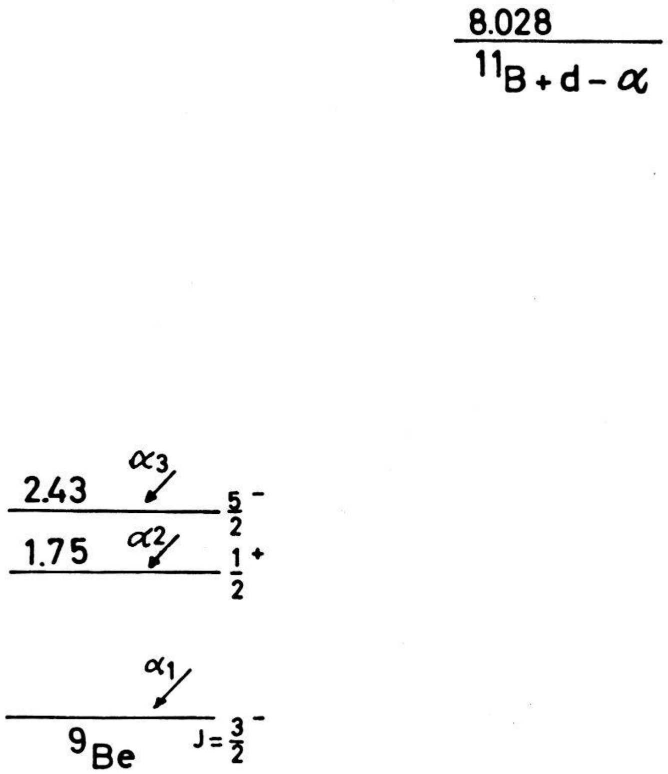

Figure 4
Level Scheme of ^{9}Be

By substituting the values of the coefficients α_0^n and α_{ij}^n in equation (3) one obtains a set of equations relating the expansion coefficients of the A_{ij} with the resonant matrix element R_3 and the terms of interference between R_3 and one of the following elements: R_{12}, R_{15}, R_{19} ($l = 2$, $J^\pi = 5/2^-$) and $R_5, R_7, R_9, R_{22}, R_{25}$ ($l = 1, 3$; $J^\pi = 3/2^+$) in Table 5, or R_{12}, R_{15}, R_{19} and R_8, R_{10}, R_{23}, R_{26} ($l = 1, 3$; $J^\pi = 5/2^+$) in Table 6. Since the equations both in Table 5 and Table 6 show the same linear relations (4) and (5), which are fulfilled fairly well by the experimental values, it has not been possible to identify the interfering level in the approximation used here.

$$3\, a_{zz}^2 - 8\, a_{xz}^2 + 2\, a_{xx-yy}^2 = 0\,, \tag{4}$$

$$a_{zz}^3 - 4\, a_{xz}^3 + 2\, a_{xx-yy}^3 = 0\,. \tag{5}$$

As our experiment was performed just below the two resonances observed in $^{11}B(d,\alpha)^9Be$ and $^{11}B(d,n)^{12}C$ at 1.2 MeV and 1.4 MeV [3, 5], it is justified to assume that one of the two corresponding levels in ^{13}C (19.7 MeV, 19.9 MeV) has $J^\pi = 5/2^-$. The relatively higher contribution from the 19.7 MeV level to the α_3-group of $^{11}B(d,\alpha)^9Be$ may be easily understood, if this level is taken as $5/2^-$. Such a transition would require an orbital angular momentum $l = 0$ for the outgoing α-particles, whereas a transition from a $5/2^-$ state of ^{13}C to the ground state of ^9Be $(3/2^-)$ or to the first excited state $(1/2^+)$ would require $l = 2$ and 3 respectively [18] (Fig. 4).

A positive identification of these levels is expected if this reaction is studied at higher energies.

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