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STATES IN ^{12}C FROM RESONANT PROTON SCATTERING

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Résumé — Les sections efficaces différentielles de la diffusion élastique $^{11}\text{B}(p, p)$ ont été mesurées entre $E_p = 3,0$ et $5,2$ MeV. L'analyse effectuée au moyen du formalisme de la matrice R a permis de mettre en évidence quatre niveaux du carbone 12 à $E_x \approx 19$ MeV ($J^\pi = 4^-$), $19,20$ MeV ($J^\pi = 1^-$), $19,50$ MeV ($J^\pi = 2^-$) et $19,70$ MeV ($J^\pi = 1^+$). Leur caractère $T = 1$ est discuté.

Abstract. — The (p, p) elastic scattering cross-section on ^{11}B has been measured between $E_p = 3,0$ and $5,2$ MeV. Analysis with the R -matrix formalism establishes four levels in ^{12}C at $E_x \approx 19$ MeV ($J^\pi = 4^-$), $19,20$ MeV ($J^\pi = 1^-$), $19,50$ MeV ($J^\pi = 2^-$) and $19,70$ MeV ($J^\pi = 1^+$). Their possible $T = 1$ nature is discussed.

1. Introduction. — Analog states in ^{12}C of the seven first low-lying states in ^{12}B have previously been identified by comparing the reduced proton widths obtained in elastic scattering on ^{11}B and the reduced neutron widths deduced from the (d, p) , (d, n) and (n, n) reactions. However the elastic scattering data were not extended above $E_p = 3,5$ MeV [1]. Spin and parity assignments for many levels above $E_x = 18,5$ MeV in ^{12}C are uncertain or conflicting. In order to study these levels we measured the cross-section of the $^{11}\text{B}(p, p)^{11}\text{B}$ reaction between 3,0 and 5,2 MeV. The data have been analysed in the framework of the R -matrix formalism.

2. Experimental results. — Excitation curves for $^{11}\text{B}(p, p)^{11}\text{B}$ elastic scattering have been measured at eight angles ($\theta_{\text{lab}} = 40^\circ, 60^\circ, 75^\circ, 90^\circ, 120^\circ, 140^\circ, 160^\circ$ and 170°) up to 5,2 MeV at the 6 MeV Strasbourg Van de Graaff accelerator, by 15 to 25 keV steps using a $70 \mu\text{g}/\text{cm}^2$ self-supported ^{11}B target (95 % enrichment). The overall energy resolution was about 20 keV. The data have been normalized on the absolute cross-section measurement of Chanut [2], obtained with a diborane gas target. In the region of E_p from 3,0 to 3,5 MeV where the two measurements overlap, the data are in good agreement with previous works of Segel *et al.* [3], Tautfest *et al.* [4] and Symons *et al.* [5]. Figure 1 shows our results between 3 and 5 MeV at four angles. Statistical errors are smaller than the data points.

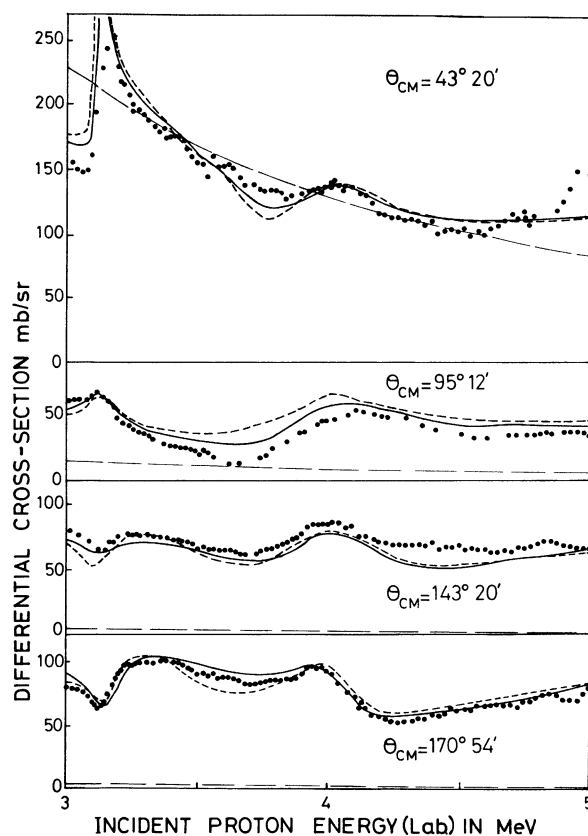


FIG. 1. — $^{11}\text{B}(p, p)$ differential cross-sections between $E_p = 3,0$ and $5,2$ MeV at four angles. Theoretical curves in dashed lines show Coulomb scattering; solid lines are the fits obtained with the parameters of table I, assuming a 4^- level at $E_x = 19,02$ MeV, and dotted lines show the fits assuming a 2^- level at $E_x = 18,94$ MeV.

3. **Analysis.** — Analysis of the data was carried out using the R -matrix theory of Lane and Thomas [6]. The collision matrix is written in the one-level approximation where the energy dependence of the resonance parameters was evaluated explicitly. The level shift and the penetration factor were calculated at an interaction radius parameter $r_0 = 1.4$ fm. The boundary condition is chosen so that $B_l = -l$. The partial waves were limited to $l \leq 3$. The excitation curves exhibit two regions around 3.2 MeV and 4.0 MeV with strongly interfering resonances.

The experimental excitation curves $^{11}\text{B}(p, p)$ show the well-established $J^\pi = 2^+$ resonance at

$$E_x = 18.22 \text{ MeV} (E_p = 3.12 \text{ MeV})$$

and a large anomaly centered at $E_p \approx 3.35$ MeV. The study of theoretical curves for two levels indicates that this anomaly is due to excitation of a s - or d -wave resonance. The existence of a broad level ($\Gamma \approx 1$ MeV) in ^{12}C at the excitation of

$$E_x = 19.2 \text{ MeV} (E_p = 3.5 \text{ MeV})$$

has previously been reported [3]. The yield curve of the 2.125 MeV γ -ray from the $^{11}\text{B}(p, p'\gamma)$ reaction shows a broad structure centered at about $E_p = 3.35$ MeV [3, 7]. We measured the $^{11}\text{B}(p, p')^{11}\text{B}$ (2.125 MeV) angular distribution at this resonance energy and fitted it with Legendre polynomials (Fig. 2). This angular distribution is approximately of the form $(1 - 0.22 P_1)$ and can only be explained by the interference between levels of opposite parity. One of these levels is the 18.82 MeV ($J^\pi = 2^+$) which appears in the excitation curve of the $^{11}\text{B}(p, p'\gamma)$ reaction. Thus the broad level at $E_p = 3.5$ MeV has $J^\pi = 0^-, 1^-$ or 2^- , but only $J^\pi = 1^-$ is consistent with the result deduced from the $^{11}\text{B}(p, \gamma_0)$ reaction [3]. However it was found impossible to obtain a common satisfactory fit for the eight angles with these two levels only. Especially the observed increase of the yield at backward angles, just above the 3.12 MeV resonance, is not predicted

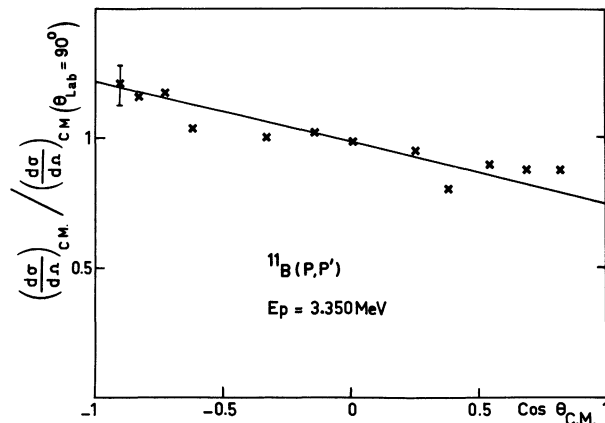


FIG. 2. — Relative angular distribution of $^{11}\text{B}(p, p)^{11}\text{B}^*$ (2.125 MeV) at $E_p = 3.350$ MeV. The solid line is the Legendre polynomial fit for $L = 1$.

by the theory. Thus it appears that there is another level near $E_p = 3.3$ MeV in ^{12}C contributing to the differential cross-section which was not taken into account previously. The analysis of the experimental data indicates d -wave proton formation, but does not allow an unambiguous choice between $J^\pi = 2^-$ and 4^- . A $0^-, 1^-$ or 3^- assignment to this level gives a much worse agreement than $J^\pi = 2^-$ or 4^- . Therefore we conclude to the existence of a 1^- level at $E_x = 19.2$ MeV with $\Gamma_p/\Gamma \approx 0.5$ and a $(2, 4)^-$ level at $E_x \approx 19$ MeV.

Two resonances, one of s -wave character at $E_p = 3.85$ MeV, the other of a p -wave character at $E_p = 4.1$ MeV contribute to the peak at $E_p \approx 4$ MeV. The first level has a width of about 400 keV due to $l=0$ and $l=2$ components with $J^\pi = 1^-$ or 2^- . The fact that the 3.85 MeV level is observed neither in the $^{11}\text{B}(p, \alpha_0)$ nor in the $^{11}\text{B}(p, p'\gamma)$ reaction indicates that a spin and a parity 2^- must be preferred. Furthermore the 2^- assignment for this level is suggested from the $^{12}\text{C}(p, p'\gamma)$ reaction [8]. This resonance is strongly excited in the $^{11}\text{B}(p, \alpha_1)$ reaction where the cross-sections show a large peak at $E_p \approx 3.7$ MeV. The second level ($\Gamma < 0.25$ MeV) results from a p - or f -wave. The fact that the 0^+ fit for this level does not reproduce all of the qualitative features of the differential cross sections rules out this choice. However it is necessary to introduce a state with a contribution of f -waves to explain the magnitude of the experimental cross sections at $\theta_{\text{lab}} = 120^\circ - 140^\circ$. This level is not excited in the other channels, except $^{11}\text{B}(p, n)$ which shows a weak resonance of similar width at this energy [9] leading to $\Gamma_p/\Gamma > 0.8$. This value favours a fit of the data with $J^\pi = 1^+$, excluding spins 2^+ and 3^+ which would give a too large cross-section.

The best overall fits of the excitation functions at four angles from $E_p = 3.0$ to 5.0 MeV are shown by

TABLE I

Resonance parameters used in the analysis of elastic scattering of protons on ^{11}B for $3.0 < E_p < 5.2$ MeV. The interaction radius used in this analysis is $a = 4.51$ fm

J^π	E_{lab} (MeV)	E_x (MeV)	Γ_{CM} (MeV)	l	$(\gamma_p^2)_l$ (MeV) ^(a)	
					$S = 1$	$S = 2$
2^+	3.120	18.82	0.100 ± 0.010	(1)	—	0.070
4^-	3.300	19.02	0.700 ± 0.200	(2)	—	0.350
$(2^-)^{(b)}$	(3.250)	(18.94)	(0.500 ± 0.200)	{(0) (2)}	— (0.300)	(0.025) (0.300)
1^-	3.500	19.20	0.750 ± 0.200	{(0) (2)}	0.125 0.068	— 0.068
2^-	3.850	19.50	0.365 ± 0.050	{(0) (2)}	—	0.058 0.110
1^+	4.100	19.70	0.230 ± 0.030	{(1) (3)}	—	0.015 1.20

^(a) Calculated from $\Gamma_p = 2 V_l (\gamma_p^2)_l$, where V_l is the penetration factor.

^(b) An alternative solution for the second level is 2^- , which seems less satisfying than 4^- (see Fig. 1).

the solid curves in figure 1. The resonance parameters used to obtain this fit are given in table I. The well-known resonances outside the present energy range were also included. Hence contributions from the following resonances have been considered in the theoretical analysis : $E_p = 0.675(2^-)$, $1.4(1^-)$, $2.57(2^-)$, $2.62(3^-)$, $7.2(1^-)$ and $10.3(2^-)$ [1, 2, 10]. We have also examined the case of a state $J^\pi = 2^-$ at $E_x \approx 19.0$ MeV, but it was found to be quite impossible to get a satisfactory fit at each of the eight angles (Fig. 1, dashed curve). Particularly, predictions between 3.5 and 4 MeV are much too high at laboratory angles of 60° , 75° and 95° , and too low at 40° . Thus we conclude that there is a broad level in ^{12}C with $J^\pi = 4^-$ at $E_x \approx 19$ MeV.

4. Discussion. — In conclusion, the analysis of the elastic scattering cross-sections between 3 and 5 MeV supports the existence of ^{12}C levels with spins 2^+ , 4^- , 1^- , 2^- and 1^+ at $E_x = 18.82$, ≈ 19 , 19.2 , 19.5 and 19.7 MeV. The parameters of the 2^+ level are in good agreement with those of Segel *et al.* [3]. The 4^- , 1^- and 2^- levels have been suggested at similar energies but the corresponding parameters were not given [1].

It can of course not be deduced from this experiment whether observed resonances correspond to $T = 1$ states in ^{12}C . However, using the level parameters obtained from our analysis together with information from other reactions and comparison with ^{12}B levels

leads to some speculations on the possible $T = 1$ nature of these levels.

The 2^+ (18.82 MeV) level has been established previously as a $T = 1$ analog of the 3.76 MeV state in ^{12}B [1]. The 19.2 MeV state $J^\pi = 1^-$ is highly excited in the $^{11}\text{B}(p, \gamma_0)$ reaction. This fact and the small alpha particle width indicate an assignment $T = 1$ for this state, in agreement with the conclusion of Segel *et al.* [3]. The corresponding level $T = 1$ in ^{12}B is not well known, though the $^{11}\text{B}(n, n)$ elastic scattering data does not preclude of an additional broad 1^- state in ^{12}B between the 3.39 and 4.30 MeV states [11]. The 19.5 MeV state ($J^\pi = 2^-$) was suggested in inelastic electron scattering and was assigned $T = 1$ [12]. This state is a candidate for the analog of the 2^- , 4.37 MeV state in ^{12}B .

There is very little additional information on the 19.7 MeV level. Our spin assignment, $J^\pi = 1^+$, its width and Coulomb energy shift compared to other known $T = 1$ states in ^{12}C make it a good candidate for the analog of the 4.99 MeV level in ^{12}B . A similar comparison between the $J^\pi = 4^-$ levels in ^{12}B at 4.521 MeV and ^{12}C at ~ 19 MeV is highly questionable as the latter one is very broad and its energy is depressed by about 600 keV from its expected location.

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