Excitation Curves for α Particles from B^{11} Bombarded with Protons

OLOF BECKMAN,* TORBEN HUUS, AND ČRTOMIR ZUPANČIČ†
Institute for Theoretical Physics, Copenhagen, Denmark

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The spectra of the α particles emitted from B^{11} under proton bombardment have been investigated by means of a 180° double-focusing magnetic spectrometer. In the range of bombarding energies from 0.3 Mev to 1.8 Mev, the α group leading to the first excited state of Be^8 exhibits the same resonances, at 0.67 Mev and 1.4 Mev, as does the proton capture process, whereas the α group leading to the ground state of Be^8 is resonant only for the higher energy. The approximate values for the cross sections at the maxima, are in the former case, 600 millibarns and 150 millibarns, respectively, and, in the latter, 6 millibarns. Spin and parity assignments of 2^- and 1^- for the two levels, respectively, are compatible with these results.

INTRODUCTION

RECENT investigations of the proton capture processes in B^{11} [1,2] have shown the existence of two new levels in C^{12} corresponding to proton bombarding energies of 0.675 Mev and 1.39 Mev. These resonances give a stronger yield and have a much greater width than the well-known resonance at 0.163 Mev. It is, therefore, most likely that they are excited by s-wave protons, although p-wave protons cannot definitely be excluded. The simplest assumptions fitting the results of these investigations would appear to be that the two levels have odd parity and spin 2 and 1, respectively.

This assignment can be tested by investigating the excitation curves for the $B^{11}(p, \alpha)Be^8$ process in the same range of proton energies. Such measurements have not been reported so far, but the spectrum of the α-particles has been investigated by several authors[3] at various proton energies. It consists of a sharp peak (α_0) at high energy, well separated from a broader peak (α_1), which is superimposed on a continuous background (α_{12}), extending down to low energies. The α_0 peak is due to α particles leaving the Be^8 nuclei in the ground state and corresponds to a Q value of 8.57 Mev. The α_1 peak is related to the first excited level in Be^8, which has an excitation energy of 2.95 Mev and a width of 1.20 Mev.[4] The α_{12} particles come from the break-up in flight of the Be^8 nuclei in this excited state. It is generally believed that the excited state of Be^8 is a 2^+ level and the ground state a 0^+ level. The assignment suggested for the C^{12} states, therefore, implies that the α_0 particles should not be resonant at the 0.67-Mev bombarding energy.

* On leave from the University of Uppsala, Uppsala, Sweden.
† On leave from J. Stefan Institute of Physics, Ljubljana, Yugoslavia.
1 T. Huus and R. B. Day, Phys. Rev. **85**, 761 (1952) and Phys. Rev. **91**, 597 (1953).
2 Cochran, Ryan, Givin, Kern, and Hahn, Phys. Rev. **87**, 672 (1952).
3 For references, see F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
4 Ward Whaling and C. W. Li, Phys. Rev. **81**, 661 (1951).

EXPERIMENTAL PROCEDURE

A 2-Mev electrostatic generator[5] equipped with a magnetic beam separator supplied a homogeneous, collimated beam of protons. Reaction products were analyzed with a 6-Mev double-focusing magnetic α spectrometer and detected with a large proportional counter. The spectrometer is of the design described by Snyder *et al.*,[6] except that the coils are wound around the pole shoes. The stabilized current in the coils was used as a measure of the α-particle energy, after careful cycling to avoid hysteresis effects. The scale was calibrated by using the known Q values of the α processes themselves, as well as by means of scattered protons.

The maximum field available in the spectrometer was not high enough for the detection of the α_0-particles at the higher proton energies. In the measurements of the ground-state transition, a 1.2-mg/cm^2 mica foil was, therefore, placed at the entrance to the spectrometer, whereby the particle energy for the α_0 group was decreased by about 650 kev. The foil was placed as close to the target as possible in order to avoid distortion of the lines because of scattering in the foil. The influence of the energy straggling in the foil, however, had to be taken into account. The straggling should be approximately independent of the α energy and correspond to a half-width of about 50 kev. The lower end of the spectrum was limited, in most of the measurements, by the cutoff at about 2.5 Mev of the 0.6-mg/cm^2 mica window of the proportional counter. A few measurements at lower energies were made with a scintillation counter, but unfortunately certain difficulties with background counts precluded precise determinations in this region. The general trend found for the α_{12} spectrum is nevertheless believed to be correct.

The 10-mm aperture of the counter window gave an energy resolution of the spectrometer corresponding to a half-width of 1.3 percent. This large value was chosen in order to get an adequate intensity, especially in the case of the α_0 group. The solid angle of the

5 Broström, Huus, and Tangen, Phys. Rev. **71**, 661 (1947).
6 Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**. 852 (1950).

spectrometer was $2\times10^{-4}\times4\pi$ steradian, measured by means of the decrease in intensity when a limiting stop corresponding to a known solid angle was placed at the entrance to the spectrometer.

The angle between the beam of the bombarding protons and the direction of the particles observed in the spectrometer was about 97°, and the target was placed so that the surface made angles of 60° and 37°, respectively, with these two directions. For this position the target thickness corresponded to a half-width for the α_0 particles of about twice the spectrometer resolution used. The target was prepared in the isotope separator of the Institute[7] in order to have a pure and stable B^{11} target. The content of B^{11} atoms was determined by comparison with a B_2O_3 target, the thickness of which was found both from the width of the α_0 peak and from the proton scattering profile curve. The B^{11} target proved to be equivalent to a mixed layer of an equal number of B^{11} and Ag atoms on an Ag backing and of a thickness (perpendicular to the surface) of about 22 kev for 1-Mev protons.

RESULTS

The energy spectra of the α particles were obtained from the measured curves by means of the empirical energy-current relation. An example is shown in Fig. 1 for a proton energy of 0.700 Mev, where also the α_0-energy is low enough to be within the range of the spectrometer without use of the extra foil. The positions of the peaks of course agree with the known Q values used for the adjustment, but the agreement in the width of the α_1 peak with the value given by Whaling and Li gives an independent check on their result.

The excitation curves shown in Fig. 2 have been obtained from the measured spectra by calculating the areas of the peaks. In the case of the sharp α_0 lines,

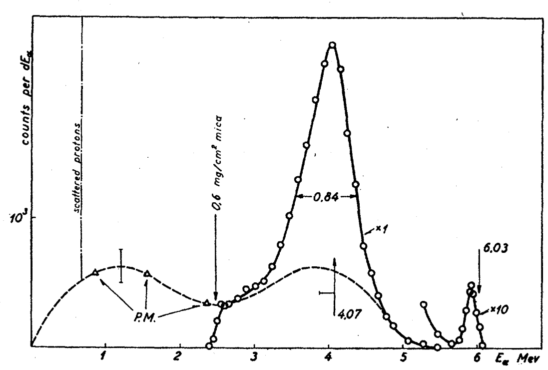

FIG. 1. Energy distribution of α particles from B^{11} bombarded with 0.700-Mev protons. The spectrum is not corrected for the finite experimental resolution. The points plotted as circles are obtained with a proportional counter as detector, whereas the triangle points (marked P.M.) at energies below the cutoff of the counter window correspond to a few less accurate measurements with a scintillation counter. The dashed curve indicates the spectrum assumed for the α particles from the break-up of Be^8. (See text.)

[7] We are grateful to Dr. J. Koch for supplying this target.

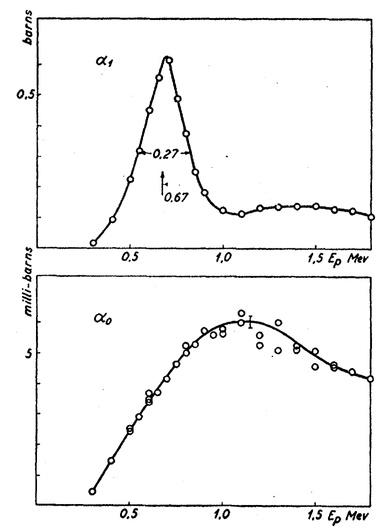

FIG. 2. Excitation curves for the process $B^{11}(p,\alpha)Be^8$ for proton energies in the range from 0.3 Mev to 1.8 Mev. α_1 corresponds to the case where Be^8 is left in the first excited state, whereas α_0 corresponds to the ground-state transition. The curves are not corrected for the influence of target thickness.

however, the areas are not calculated directly for each proton energy, because the accuracy of an individual measurement is limited by the accuracy in the field determination. Instead, the peak values have been used in combination with the average half-width of all the α_0 peaks multiplied by a correction factor, which varies smoothly with the proton energy in accordance with the dependence on the window-, straggling-, and target-widths.

It is evident from the figure that the α_1 excitation curve shows both the broad resonances found also in the capture processes and at energies which are in very good agreement with these measurements. In the case of the α_0 excitation curve, it can be seen from the figure that this process is not resonant at 0.67 Mev but only at the higher energy. There is a clear shift downward of the peak of this resonance compared to the value of 1.39 Mev found for the capture process. This shift, apparently, cannot be due to penetration effects but might be explained by interference with higher-lying levels.

In order to find the absolute yields, the theoretical value for the dispersion of the spectrometer was used in the calculation of the total number of particles in each peak. This procedure is justified, since the spectrometer does, in fact, have the double-focusing properties expected, and the field, therefore, must decrease approximately as the reciprocal of the square root of the radius. As regards the absolute values of the cross sections, it must be borne in mind that, in the case of the α_1 peak, a large contribution of α_{12} particles must be expected. This correction is not easy to apply accurately, but if one assumes that the C^{12} levels in question are formed by s-wave protons, it is obvious that, in any direction in the laboratory system, there

TABLE I. Cross sections in millibarns for proton-induced processes in B^{11}. The values given are 4π times the differential cross sections at about 90°. E_{res} is the resonance energy of the protons in Mev.

E_{res}	0.163	0.67	$\simeq$1.4
$\sigma_{p\gamma_0}$	$\lesssim$0.006	$\lesssim$0.002	0.035
$\sigma_{p\gamma_1}$	0.15	0.048	0.018
$\sigma_{p\alpha_0}$	0.2[a]	$\lesssim$0.2	6
$\sigma_{p\alpha_1}$	10[a]	600	150

[a] See reference 8.

must be an equal number of the high and low energy component of the α_{12} pairs, i.e., the α_{12} spectra must be symmetrical around half the energy available, which is the 3-Mev excitation energy of the Be^8 level and the approximately 2-Mev kinetic energy of the Be^8 nuclei. For this reason, one should expect 50 percent of the α_{12} particles to be found in the energy region from about 2.5 Mev to 5 Mev and since the total number of α_{12} particles is twice that of the α_1 particles, it follows that only 50 percent of the particles found in this range are due to the α_1 process. This can only be the case if the α_{12} spectrum also has a peak at approximately 4 Mev, as indicated by the dashed curve in Fig. 1. This means that the low energy component of the α_{12} particles should also give a peak in the spectrum, approximately at 1 Mev. It was in order to check this point that the measurements with the photomultiplier were made. They were not in disagreement with the above considerations, and the cross sections for the α_1 process, therefore, are calculated by using only half the area of the peak between 2.5 Mev and 5 Mev. The values given are 4π times the differential cross section at 97°, both for the α_1 and the α_0 processes.

The cross sections found were expected to be correct within about 30 percent, but a measurement of the yield of protons scattered from a copper target gave a cross section nearly 50 percent smaller than that corresponding to the Rutherford scattering. It was made under the same conditions except for the use of an extra scaler, since the counting rate, even at a considerably lower current, was of the order of 10^3 counts per second. It is, however, not likely that the α-cross sections are a factor 2 too small, since the maximum found for the α_1 process in one case already is close to the highest value possible.

DISCUSSION

It is interesting to compare the measured cross sections for α emission with those for the resonance at 0.163 Mev[8–11] as well as with the capture cross sections for all three resonances.[1] This is done in Table I. Using these values and the approximate values for the total width Γ for the three levels, given in the second line of Table II, one obtains the estimates for the various partial widths Γ_x, given in the rest of the table, by means of the formula for the peak value of the resonance cross section

$$\sigma_{px}=\omega 4\pi\lambda\!\!\!^{-}_p{}^2\Gamma_{p0}\Gamma_x/\Gamma^2.$$

For the present purpose the value $\omega\simeq\frac{1}{2}$ can be used for the spin weight factor, and as the cross sections $\sigma_{p\alpha_1}$ for all three resonances are considerably larger than the other reaction cross sections, one has, approximately,

$$\sigma_{p\alpha_1}\simeq(1.3/E_{res})y(1-y)\text{barns}$$

and

$$\Gamma_x\simeq(\sigma_{px}/\sigma_{p\alpha_1})(1-y)\Gamma,$$

where $\Gamma_{p0}=y\Gamma$, $\Gamma_{\alpha_1}\simeq(1-y)\Gamma$, and E_{res} is expressed in Mev. There are, in general, two sets of solutions, corresponding to the cases where the main contribution to Γ comes from the proton width Γ_{p0} or from Γ_{α_1}.

In the case of the resonance at 0.163 Mev, one gets the two solutions $y\simeq1$ and $y\simeq10^{-3}$. The first possibility, however, can be excluded, as the values for the reduced proton width which would correspond to $\Gamma_{p0}=5$ kev for angular momenta of $l\geq1$ are considerably higher than the theoretical upper limit of $\gamma_{max}\simeq3\hbar^2/2M_0R^2$, and it is known [see (3)] that the level is not formed by s waves, because the reaction products are anisotropically distributed. Taking $y=10^{-3}$, one obtains the values for the partial widths listed in the second column of Table II. If the level is a 2^+ state [see (3)], the strongest transitions should be of the type indicated in the table in the corresponding parentheses. The theoretical estimates[12] for single particle γ-ray transition probabilities agree reasonably well with the experimental radiation widths for the transitions in question. The relative smallness of the α widths as well as the large ratio between Γ_{α_1} and Γ_{α_0} cannot be accounted for theoretically in terms of the listed wave types by the penetration factors alone, since these at the energies involved are of the order unity for s-, p-, and d-wave α particles. This difficulty was pointed out at an early date by Oppenheimer and Serber,[13] who brought

TABLE II. Estimates of the partial widths for proton induced processes in B^{11}. Spin and parity assignments and the corresponding type of transitions are indicated in parentheses.

E_{res}	[a] 0.163	(2^+)	0.67	(2^-)	[b] $\simeq$1.4	(1^-)
Γ	5 kev		0.3 Mev		$\simeq$1 Mev	
Γ_{γ_0}	$\lesssim$3 ev	$(E2)$	$\lesssim$0.5 ev	$(M2)$	40 ev	$(E1)$
Γ_{γ_1}	70 ev	$(M1)$	15 ev	$(E1)$	20 ev	$(E1)$
Γ_{α_0}	100 ev	(d)	$\lesssim$50 ev	(no)	7 kev	(p)
Γ_{α_1}	5 kev	(s,d)	150 kev	(p,f)	200 kev	(p,f)
Γ_{p0}	5 ev	(p)	150 kev	(s)	1 Mev	(s)

[a] $\Gamma_{p_0}:\Gamma\simeq10^{-3}$ or 1; the former value is used.
[b] $\Gamma_{p_0}:\Gamma\simeq0.2$ or 0.8; the latter value is used.

[8] The α-particles from this sharp resonance were barely detectable with the present experimental setup. Estimates for the cross sections can be obtained by comparing the information in references 9–11.

[9] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. (London) **154**, 261 (1936).

[10] Williams, Wells, Tate, and Hill, Phys. Rev. **51**, 434 (1937).

[11] R. B. Bowersox, Phys. Rev. **55**, 323 (1939).

[12] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[13] J. R. Oppenheimer and R. Serber, Phys. Rev. **53**, 636 (1938).

forward the suggestion that an isotopic spin selection rule is involved. It is, in fact, just in this region of C^{12}, from 15.5 Mev and up, that the first states of isotopic spin $T=1$ are expected, and it appears not impossible that the present level, at 16.11 Mev in C^{12}, corresponds to the first excited state, at 0.947 Mev, of B^{12}. The α width would than be expected to be rather small and to depend critically on the purity of the initial and final states. Finally, it should be noted that the value given for the proton width, with the assignment used, is about 50 times smaller than corresponding to $\gamma_{\max}$.

For the resonance at 0.67 Mev, there is no ambiguity in the estimate of the partial widths, since the cross section $\sigma_{p\alpha_1}$ is close to the maximum value possible ($y=\frac{1}{2}$), but as the maximum is rather insensitive to y, there is an extra uncertainty in the values given here. The value of Γ_{p0} is, however, so large that the corresponding reduced width is equal to $\gamma_{\max}$ already for p-wave protons, so that it can be concluded that the level is formed by waves with $l\leq 1$, and thus most likely due to s-wave protons. If this is the case, it follows that the state must have odd parity and spin 1 or 2. The absence of α_0 and γ_0 transitions to the respective ground states (both 0^+) can then readily be explained by the assignment 2^-. This means that the γ_1 transition to the 2^+ state at 4.4 Mev in C^{12} should be predominantly of the electric dipole type. The value given for $\Gamma_{\gamma 1}$ in the table is of the same order as found for such transitions in other light nuclei. This would indicate an isotopic spin $T=1$ for the state, considering the forbiddenness of $T=0\rightarrow T=0$ transitions for $E1$ radiation and the assumed value $T=0$ for the first excited level in C^{12}. $T=1$ would also account for the relatively small value of $\Gamma_{\alpha 1}$ as compared to, for instance, the 1.2-Mev α width of the Be^8 level.

Also for the third resonance, $\sigma_{p\alpha_1}$ is comparatively close to the highest value possible, although the two sets of solutions appear to be somewhat more different than in the previous case. For this reason and because of the higher proton energy, the above argument for $l\leq 1$ is less definite here. Assuming s waves for the protons also in the present case, it follows that the level must be a 1^- state, because of the occurrence of the α_0 transition. This assignment is supported by the results of measurements on the angular distributions of the α_0 particles in the region of the resonance at 0.163 Mev,[14] which are explained in terms of interferences with a broad 1^- level at higher energies. For the calculation of the values of the partial widths listed in the last column of Table II the solution $y=0.8$ has been chosen rather than $y=0.2$, because it gives widths more similar to those of the same transitions for the previous level. As in the case of that level, the strong $E1$ transitions indicate $T=1$, which also helps explain the relatively small α widths.

The shape of the α_{12} spectra might constitute a possible difficulty in ascribing the formation of the two broad states to s-wave protons. With the above assignments, the d_{12} spectra corresponding to p-wave α_1 particles should show a maximum at about 2.5 Mev for the 2^- level and two maxima at about 0 Mev and 5 Mev for the 1^- level. The measurements indicate shapes of the spectra which are similar for both resonances and lie between these two limits, but it appears, nevertheless, possible to account for this discrepancy by a suitable contribution of f-wave α_1 particles. The amplitudes of the f waves are, however, diminished by the penetration factor, which for $l=3$ and $E_\alpha\simeq 4$ Mev depends strongly on the value used for the nuclear radius, and the point is therefore left open.

It is of interest to note that the cross-section measurements can also be explained if the resonance at 0.67 Mev corresponded to a 3^+ state formed by p-wave protons. It would, therefore, be of importance to measure the angular distribution of the α_1-particles at this energy. Also measurements of the scattered protons from all the three resonances might be useful in order to check the estimates made here for the proton widths, which, in view of the inaccuracy of the cross-section values, are rather uncertain.

We are very grateful to Mr. A. P. French and Mr. G. A. Dissanaike from the Cavendish Laboratory for informing us about the results of experiments they have recently made on much the same lines as the present investigation. Compared with our results, the main differences are as follows: They find the second resonance at 0.64 Mev by direct comparison with the fluorine resonance at 0.669 Mev and suggest that the discrepancy with the resonance energy here reported might be due to our use of targets prepared by bombardment in the isotope separator. This might be true, although the way in which the boron ions penetrate into the silver target is believed more to resemble a diffusion process and the concentration of boron atoms, thus, to be highest at the surface.§ For the resonance at 0.163 Mev, they have made indirect estimates of $\sigma_{p\alpha_0}$ and $\sigma_{p\alpha_1}$, which are factors of 6 and 2.5, respectively, larger than the values listed in Table II.|| For the two broad resonances their α-emission cross-section estimates are about three times smaller than ours. This emphasizes the uncertainty in the determination of the absolute values.

In conclusion, we want to express our thanks to Professor Niels Bohr for working facilities and constant interest. We are also indebted to Professor Thomas Lauritsen whose visit to the Institute as Fulbright Lecturer has been a source of great stimulation to us. One of us (O.B.) wishes to acknowledge a grant from the Swedish Atomic Committee and another (Č.Z.) a grant from the Rask-Oersted Foundation.

[14] Thomson, Cohen, French, and Hutchinson, Proc. Phys. Soc. (London) **A65**, 745 (1952).

§ *Note added in proof:*—Paul and Clarke (Washington meeting, 1953) have found this α resonance at a proton energy of 0.68 Mev.

|| *Note added in proof:*—In a private communication, Whaling gives estimates which are even larger than those given by French.