Inelastic Scattering of Protons by Aluminum and Carbon*

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The energy distributions of inelastically scattered protons from carbon and aluminum were found by range measurements with the detection taking place in photographic plates. The carbon distribution shows two levels in C^{12}, one at 4.8 and one at 10.1 Mev. There is also a third peak whose energy and intensity lead us to assign it to deuterons in which the C^{11} from the reaction $C^{12}(p,d)C^{11}$ is left in its ground state. The aluminum results show a continuum. An attempt is made to fit the distribution using a nuclear level density of from $W(E)=C\exp(AE^{\frac{1}{2}})$ as suggested by Weisskopf. The results fit fairly well at excitations above 15 Mev and not at all at excitations below that.

I. INTRODUCTION

WHEN a nuclear reaction is induced by monoenergetic incident particles the energy distribution of the emitted particles yields information about the excited states of the residual nucleus. When the separation of these states is larger than both their natural width and the minimum energy spread that the experiment can resolve, the emitted particles fall into discrete energy groups; see, for example, Fulbright and Bush.[1] When the level density is larger, the energy distribution appears continuous, but the shape of this continuum can yield information about the level density of the residual nucleus, as discussed by Feld[2] and Weisskopf.[3] Using photographic plates to detect the charged particles we have investigated the energy spectra of protons emitted from carbon and aluminum when bombarded by protons of 32 and 16 Mev from the Berkeley linear accelerator.

II. EXPERIMENTAL METHOD

A camera was constructed (Fig. 1) which allows eight plates to be exposed simultaneously each with its center at an angle of 96° with the beam axis and each plate set so that particles from the target enter it within 20° of grazing incidence. To cover the energy range desired, an absorber of either copper or aluminum was placed between the target and each plate. The absorbers were increased by steps of seven mils (48 mg/sq. cm) equivalent of aluminum which corresponds to 160μ of emulsion. Track lengths in the region from $15-200\mu$ were read on each plate (tracks less than 15 μ were considered unreliable) and so there was an overlap region of 25μ from plate to plate. This method requires that about 24 plates be read to cover the region 0–32 Mev. Reading track lengths of 200μ or less has two advantages: (a) It makes corrections for tracks scattering out of the emulsion negligible, and (b) it makes counting the tracks quite simple since they all fall well within one field of view of the microscope with a convenient magnification of 440. The tracks are measured by means of an eyepiece reticule calibrated against a Bausch and Lomb stage micrometer.

The absorbers were placed on an approximately spherical surface of radius 6.3 cm centered on the target. This insured that the effective thickness of the absorber for the scattered protons varied by less than 0.2 percent. All tracks read were at a polar angle of $96\pm4°$.

Ilford E-1, 100μ, plates were used. These plates are sufficiently insensitive to distinguish alpha-particles but not deuterons from protons. In order to minimize the number of tracks arising from recoil protons struck by neutrons incident on the plates, only those tracks coming from the direction of the target and starting at the top surface of the emulsion were read.

The background tracks were determined in two separate ways, with no target present and by using an absorber thick enough to cut out all scattered protons. In the high energy tail of the aluminum curve (Fig. 5) the background amounted to about 20 percent. In other regions of interest, it was much less than that.

III. RESULTS AND CONCLUSIONS

Carbon

A one-mil polystyrene target was used in two sets of runs, one at 16.3 Mev and one at 31.5 Mev. The experiment at the lower energy is essentially a duplication of work done by Fulbright and Bush[1] and provided a check on our method. The results are shown in Figs. 2–4. Figure 2 shows the distribution *vs.* range in the 31.5-Mev run as an example of the raw data taken from the plates. Each run shows two levels in C^{12}, the 16.3-Mev run at 4.8 and 10.2 Mev; the 31.6-Mev run at 4.7 and 10.1 Mev. Fulbright and Bush find three levels, at 9.7, 5.5, and 4.4 Mev, but their results were obtained at 162° and some of these levels probably have strong angular variations. Gibson[4] found levels at 4.47, 9.72, and, less certainly, at 7.7 Mev. The half-width at half-maximum is about 0.4 Mev for the 32-Mev run and about 0.5 Mev for the 16-Mev run. The half-width calculated from straggling, spread in polar angle, and target thickness is 0.3 Mev. The half-width in the

* This work was sponsored by the AEC.
[1] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).
[2] B. T. Feld, Phys. Rev. **75**, 1115 (1949).
[3] V. Weisskopf, Phys. Rev. **52**, 295 (1937).
[4] W. M. Gibson, Proc. Phys. Soc. **A62**, 586 (1949).

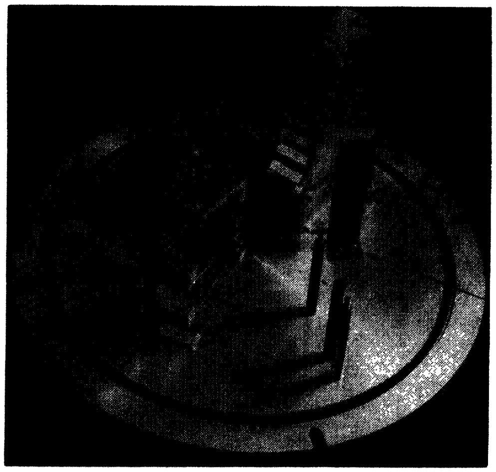

FIG. 1. General view of the construction of the camera.

16-Mev run is larger because of the energy spread introduced by stopping down the beam.

The third level shown in the 31.6-Mev run has two possible interpretations. It may be either deuterons or protons. Considered as deuterons going to the ground state of C^{11} it leads to a threshold of 16.7 Mev for the $C^{12}(p,d)C^{11}$ reactions. The threshold for the reaction calculated from the masses is 16.5 Mev. Considered as protons it leads to a level at 21.2 Mev in C^{12}. The low energy tracks could be associated with levels in C^{12} at excitations between 20–28 Mev or could be associated with protons arising from $C^{12}(p,np)C^{11}$ or $C^{12}(p,\alpha p)Be^8$ reactions.

The energy and the relative intensity of the third level in the 32-Mev run seem to indicate that it is composed of deuterons. From the threshold of the $C^{12}(p,pn)C^{11}$ reactions, Panofsky and Phillips[5] showed that deuterons are emitted at threshold and the intensity of the supposed deuterons in this experiment suggests that a substantial fraction of the C^{11} is due to deuteron emission even at 32 Mev. This is not surprising in view of the sparsity of levels in C^{12} and the high binding energy of a neutron to N^{13}, both of which mean that the processes competing with the deuteron emission are very much reduced.

The relative intensities of the excited states are of some interest. From the volume available in phase space, neglecting selection rules and statistical weights of the states of the excited nucleus, the ratio of the intensities should be simply the ratio of the energies of the emitted protons. The calculated and observed intensities are shown in Table I. The agreements between the calculated and observed results indicate that all of the reactions are equally allowed.

Aluminum

The target was one-mil aluminum foil and the bombarding energy 30.4 Mev. The distribution in Fig. 5 shows no levels except the elastic peak. Dicke and Marshall[6] have shown that there are levels in aluminum at 0.87, 2.03, 2.70, and 3.5 Mev. These could not be seen as separated levels, probably because the levels are too close to be resolved with the statistics available in this region. The elastic scattering is assumed to be due primarily to diffraction scattering since it is much more intense than the low lying excited levels. The experimental cross section for the elastic scattering is $\sigma(96°)=4.1\times10^{-27}$ sq. cm/sterad. The theoretical cross section, assuming only diffraction scattering, is given by[7]

$$\sigma(\theta)d\Omega=(\bar{\lambda}^2/4)\left|\sum_l(2l+1)(\beta_l-1)P_l(\theta)\right|^2d\Omega. \quad (1)$$

Here $1-|\beta_l|^2$ is the sticking probability of protons of angular momentum l. If one assumes a completely absorbing nucleus, $\beta_l=0$. If the sum is taken to $l_{max}=R/\bar{\lambda}$, approximately 5 in this case, where R = radius of aluminum nucleus, one finds $\sigma(\pi/2)=5.53\times10^{-27}$ sq. cm/sterad. This agreement is probably better than one should expect from the crude model used. However, it indicates that this explanation is not unreasonable.

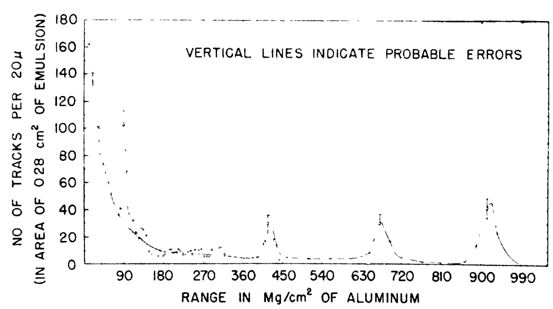

FIG. 2. Range distribution of charged particles from carbon bombarded with 31.5-Mev protons.

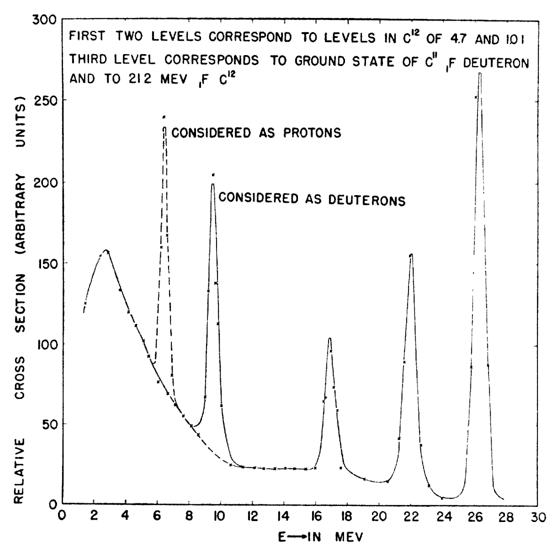

FIG. 3. Energy distribution of protons from carbon bombarded with 31.5-Mev protons.

[5] W. K. H. Panofsky and R. Phillips, Phys. Rev. 74, 1732 (1948).

[6] R. H. Dicke and J. Marshall, Jr., Phys. Rev. 63, 86 (1943).

[7] H. A. Bethe, Phys. Rev. 57, 1125 (1940).

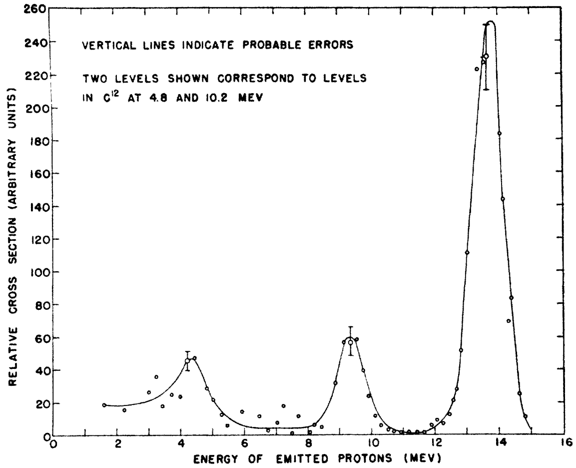

FIG. 4. Energy distribution of protons from C^{12} bombarded with 16.3-Mev protons.

By assuming a statistical model for the nucleus, one can use the data to calculate the variation of level density with energy. At excitations of about 30 Mev it seems likely that even as light an element as aluminum can be treated by these methods. The energy distribution of the emitted protons can be shown to be given by[3]

$$I(\epsilon)d\epsilon = K\epsilon\omega_R(E)\sigma_c(\epsilon)d\epsilon, \tag{2}$$

where $I(\epsilon)$ is the number of protons of energy ϵ emitted per unit time; $\omega_R(E)$ is the density of levels of the residual nucleus at excitation E; $\sigma_c(\epsilon)$ is the capture cross section for protons of energy ϵ; and K is the constant independent of energy. In all calculations $\sigma_c(\epsilon)$ was taken as $\pi R^2 P(\epsilon)$. Here $P(\epsilon)$ is probability of a proton of energy ϵ penetrating the Coulomb barrier.

Weisskopf[3] gives $W_R(E) = B\exp(AE^{\frac{1}{2}})$. Here $E = 29.4 - \epsilon$, where 29.4 is energy of the protons in the center-of-mass system. Thus, by plotting $\ln[I(\epsilon)/\epsilon]$ *vs.* $(29.4-\epsilon)^{\frac{1}{2}}$, one gets the constant A as the slope of the curve. However, this neglects the fact that not all the protons measured come from the $Al^{27}(p,p)Al^{27*}$ reaction. They may also come from multiple reactions such as $Al^{27}(p,np)Al^{26*}$ or $Al^{27}(p,2p)Mg^{26*}$. From an analysis of the binding energies involved one can estimate that about half of all the protons arise from multiple reactions and that the energy distribution of the second proton would be about the same whether it follows a neutron or a proton. One can find the energy distribution of these protons as follows.[8] Let the distribution of second protons be given by

$$I(\epsilon')d\epsilon' = K\epsilon' \exp[A(E'-\epsilon')^{\frac{1}{2}}]\sigma_c(\epsilon')d\epsilon'.$$

$E' = 29.4 - E_b - \epsilon$, where E_b = binding energy of proton to Al^{27}. $E' - \epsilon'$ is the excitation of Mg^{26} after emission of second proton. This must now be multiplied by the probability of the first proton being emitted with energy ϵ and integrated over all ϵ for which ϵ' is possible. Thus:

$$I(\epsilon')d\epsilon' = K\epsilon'\sigma_c(\epsilon')\int_0^{29.4-E_b-\epsilon'} \epsilon\sigma_c(\epsilon) \times \exp A[(29.3-E_b-\epsilon'-\epsilon)^{\frac{1}{2}} + (29.3-\epsilon)^{\frac{1}{2}}]d\epsilon.$$

This integral was evaluated numerically as a function of ϵ' for $A = 3.0(\text{Mev})^{-\frac{1}{2}}$ and $A = 3.6(\text{Mev})^{-\frac{1}{2}}$ and the resulting distribution normalized so that it contained half the total number of protons. This was then added to the distribution expected for the first proton assuming the same value of A. The smooth curve (Fig. 5) is calculated for $A = 3.6$ and the dashed curve for $A = 3.0$.[9] There seems to be a qualitative agreement between the experimental and calculated distributions for energies below 12 Mev. This corresponds to an excitation of the aluminum of about 15 Mev. Thus, the evidence seems to be that at excitations above 15 Mev the density of levels increases quite rapidly and possibly exponentially. The much slower decrease of the experi-

TABLE I. Ratio of intensities.

	16-Mev run Observed	16-Mev run Calculated	32-Mev run Observed	32-Mev run Calculated
Ratio of intensity of first excited state to second excited state	2.2	2.1	1.6	1.2
	Observed	Assuming deuteron Calculated[a] A	B	Assuming proton Calculated
Ratio of intensity of first excited state to third level in 32-Mev run	1.4	1.25	0.8	4.2

[a] Case "*A*" neglects the statistical weight of the deuteron. Case "*B*" ascribes a statistical weight of 3/2 relative to that of proton. One cannot decide which is correct without knowing the angular momentum of the original excited state of C^{12}. It is likely that many states with different angular momenta are excited.

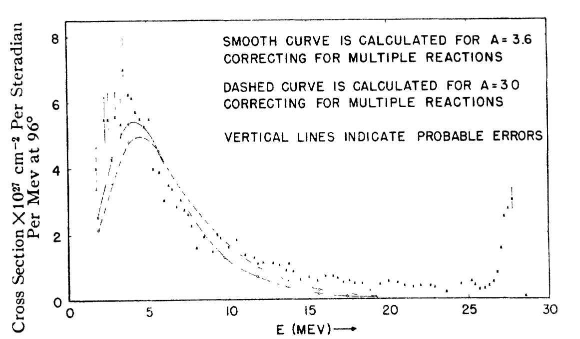

FIG. 5. Energy distribution of protons from aluminum bombarded with 30.4-Mev protons.

[8] The calculation is done for the $Al^{27}(p,2p)Mg^{26*}$ reaction. As stated in text, there would be no substantial difference if it were done for the $Al^{27}(p,np)Al^{26*}$ reaction.

[9] The value of A calculated directly from the raw data is 3.8 $\text{Mev}^{-\frac{1}{2}}$. It is seen that the correction for the protons from multiple reactions does not change the value of A very much. This is because the distribution of these protons is not greatly different from the distribution of the first protons.

mental curve than the calculated one above 12 Mev indicates that for excitations less than 15 Mev the level density changes much more slowly than the exponential form chosen in the calculations. Weisskopf[3] estimates $A=3.1$ for light nuclei. Bethe[10] gives $A\cong(M/2.2)^{\frac{1}{2}}$, or $A=3.5$ Mev$^{-\frac{1}{2}}$ for Al, where $M=$mass number.

One can estimate the absolute level density at any excitation from Eq. (2), by using relative values of $I(\epsilon)$ and assuming a value of $\omega(E)$ at some energy. Using the known levels[6] to get the average density for the first few Mev, one arrives at a level distance of 10 kv at 20 Mev. This level distance is considerably larger than one would obtain from the statistical models of the nucleus which are used by Weisskopf and Bethe.

[10] H. A. Bethe, Phys. Rev. **50**, 332 (1936).

ACKNOWLEDGMENTS

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On the Nuclear Spin of B^{10} *

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From measurements on the fine structure of the $J=0\rightarrow1$ rotational transition of $H_3B^{10}CO$ near 17,960 Mc/sec. we are able to establish that the spin of B^{10} is 3 as had previously been reported by Gordy, Ring, and Burg. A quadrupole coupling constant of 3.44 ± 0.1 has also been determined for this molecule. A brief description of our spectroscope is included.

INTRODUCTION

It has been reported by Gordy, Ring, and Burg[1] that the spin of B^{10} is 3 and is not 1 as had been assumed for theoretical reasons. They deduced this spin value from observation of quadrupole fine structure in the $J=1\rightarrow2$ microwave transition of borine carbonyl, $H_3B^{10}CO$. This spectrum is complicated because of the K splitting of both the $J=1$ and the $J=2$ levels. The calculated spectrum consists of 20 lines in a region extending over 3 Mc/sec. Because of the great theoretical importance[2] of the certain knowledge of the B^{10} spin value, it was felt that an independent determination of the spin should be made.

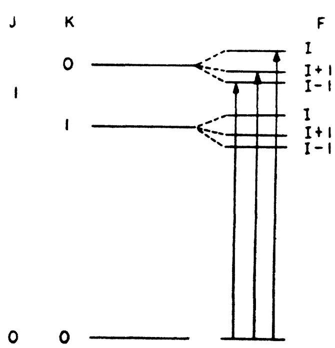

FIG. 1. Energy level diagram for $J=0$ and $J=1$ of $H_3B^{10}CO$ (not to scale).

THEORY

For our experiment we have taken advantage of the simplicity of the borine carbonyl $J=0\rightarrow1$ transition near 17,960 Mc/sec. This rotational transition would produce a single absorption line were it not for the interaction of the nuclear electric quadrupole moment with the molecular electric fields. For a symmetric top molecule this energy of interaction is related to the molecular and nuclear parameters by[3]

$$E=-eqQ\left[1-\frac{3K^2}{J(J+1)}\right]\frac{[\frac{3}{4}C(C+1)-I(I+1)J(J+1)]}{2I(2I-1)(2J-1)(2J+3)}$$

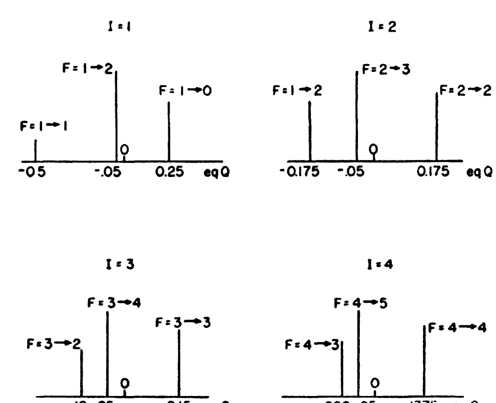

FIG. 2. Fine structure for $J=0\rightarrow1$ transition for several values of I.

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[1] Gordy, Ring, and Burg, Phys. Rev. **74**, 1191 (1948).
[2] M. Goldhaber, Phys. Rev. **74**, 1194 (1948).
[3] J. Bardeen and C. H. Townes, Phys. Rev. **73**, 97 (1948).

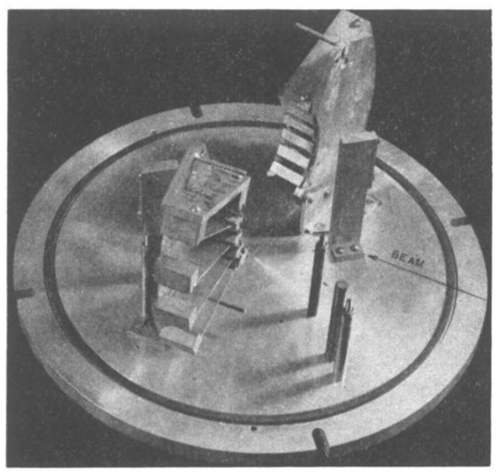

FIG. 1. General view of the construction of the camera.