Energy Levels of Be^{10}* †

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A magnetic spectrograph has been employed to measure the momenta of proton groups emitted at 90 degrees from a thin beryllium target bombarded by deuterons. Groups were observed corresponding to the ground state of Be^{10}, as well as known levels at 3.37, 5.96, 6.26, 7.35, and 7.54 Mev. A new level at 6.18 Mev was also seen.

THE energy-level spectrum of Be^{10} below 3.5-Mev excitation, which includes the first excited state at 3.37 Mev, is well known from a number of studies of the Be$^9(d,p)$Be^{10} reaction.[1–4] Between 3.5 Mev and the neutron binding energy of 7.2 Mev, the earlier work of Boyer[5] has been supplemented by the more recent experiment of Rhodes and McGruer.[6] These authors report levels at 5.94 and 6.24 Mev. Above 7.2 Mev, the latter work is augmented by measurements of the total neutron cross section of Be^9, which indicate levels at 7.37, 7.54, and 9.27 Mev.[7,8]

The levels were observed as proton groups emerging at 90 degrees from thin beryllium targets bombarded by deuterons. Charged particles were analyzed in momentum by a 180-degree magnetic spectrograph and recorded on Eastman NTA plates. The position of the tracks in the emulsion is a measure of the radius of curvature of the particles which, when combined with magnetic field measurements obtained with a resonance fluxmeter, allows a comparison with the momenta of polonium alpha particles. A rough range measurement of the nuclear tracks is sufficient to distinguish protons from other charged particles of the same momentum. The deuteron beam was furnished by the MIT–ONR electrostatic generator. Currents of 0.1 μa with energy spreads of 0.1 percent were used. Further details of the experimental arrangement have been given in a recent article.[9]

For accurate measurement of Q-values, a number of targets were prepared from several sources of beryllium metal by evaporation from a wolfram filament onto a Formvar film supported by a wire frame. With spectrograph entrance slits open $\frac{1}{2}$ mm, the targets produced peaks about 0.7 mm wide, equivalent to an instrumental energy resolution of about 250. Examination of elastically scattered groups from these targets showed the presence of a heavy contaminant, perhaps mercury or wolfram picked up in the evaporator, but only traces of other nuclei, except beryllium, carbon, and oxygen.

Figure 1 shows the proton momentum spectrum observed with 7-Mev deuteron bombardment. The peaks are labeled by the state of the residual nucleus to which they correspond. All the groups attributed to the C$^{12}(d,p)$C^{13}, C$^{13}(d,p)$C^{14}, and O$^{16}(d,p)$O^{17} reaction are associated with well-known levels. Since the deuterium used in the ion source contains a small amount of ordinary hydrogen, a weak beam of singly ionized hydrogen molecules exists which has nearly the same momentum as the atomic deuterium beam. Small variations in generator voltage allow some molecular hydrogen through the energy defining slits. Each molecule yields two protons of one-half the incident energy when it strikes the target. The intensity of this beam was sufficient to produce a series of elastically scattered groups seen in Fig. 1 between $H\rho=238$ and $H\rho=268$ kilogauss-centimeters. The exposure was insufficient in this particular set of plates to bring out the elastic O^{16} peak.

The assignment of the remaining groups to Be^{10} was verified by observations at different bombarding energies between 5.4 and 7.4 Mev. For a 2-Mev change in incident energy, the change in energy of a (d,p) group resulting in a nucleus of mass 10 differs from that resulting in a nucleus of mass 11 by 40 kev, and the energy change is greater if the mass difference is greater. A 40-kev difference was easily measurable. At a deuteron energy of 7 Mev, the groups from O$^{16}(d,p)$O^{17*} (5.39) and Be$^9(d,p)$Be^{10*} (7.37) happen to coincide, as noted in Fig. 1; they were well separated at other energies.

The Be^{10} groups shown were obtained from the same target and are normalized to the same deuteron bombardment. The areas under the peaks may be taken as a rough indication of their relative intensity at this energy and angle. The least intense group (6.18-Mev level) is about 5 percent of the strongest (the 6.26-Mev level). From the survey, it appears that there are no

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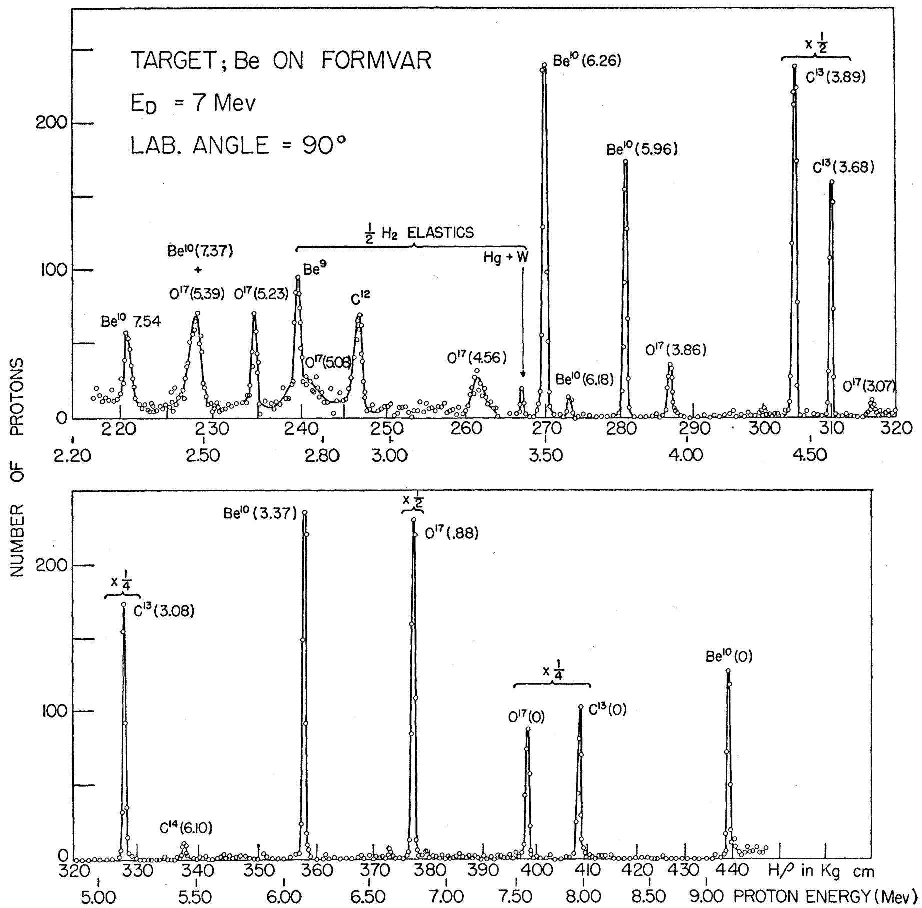

FIG. 1. Proton momentum spectrum observed at 90 degrees from a beryllium target bombarded by 7-Mev deuterons. The number of proton tracks in a ½-mm strip across the nuclear emulsion is plotted against the momentum measured in kilogauss-centimeters. The peaks are labeled by the state of the residual nucleus to which they belong. The beryllium peaks are from the same target and are normalized to a 200-microcoulomb exposure.

other groups attributable to Be^{10} which produce a peak more than 3 percent as strong as the 6.26-Mev level at this energy and angle. At the other deuteron energies investigated, the relative intensities do not seem to differ markedly. Peaks other than those assigned to Be^{10} were obtained from targets which differed in thickness; their intensities are not significant.

The observed width of the groups attributed to the 7.37-Mev level is consistent with a level width of about 25 kev, as observed in the neutron total cross section.[8] The 7.54-Mev Be^{10} level appears to be narrower and approaches the instrumental width of some 10 kev in this region. For these levels, the energies corresponding to the point on the high-energy side of the peak at which the count reaches one-third of its maximum give the most consistent Q-values, and agree to within 10 kev with level positions obtained from the neutron resonance energies. For narrow peaks, the one-third point appears least dependent on instrumental factors and is used as the reference point.

TABLE I. Measured Q-values of $Be^9(d,p)Be^{10}$ reaction.

Be^{10} excitation	Q in Mev
0	4.586±0.009
3.37	1.218±0.009
5.96	−1.373±0.008
6.18	−1.592±0.007
6.26	−1.676±0.007

The measured Q-values for the sharp levels are listed in Table I. Incident energies were obtained from the energy of deuterons elastically scattered from Be^9. Targets were changed frequently to avoid accumulating deposits on the beryllium. The measured energies were inserted in the 90-degree Q-equation, and relativity corrections were made. The values in Table I represent averages of at least three separate runs. It should be noted that, for the weak group corresponding to the 6.18-Mev level, exposures three times larger than that represented in Fig. 1 were necessary to obtain the positions of the high-momentum edge accurately. The reaction angle was measured as 90.0°±0.1° by comparing energies of alpha particles scattered from gold and lithium targets at constant input energy. Under the conditions of the present experiment, the errors arising from uncertainties in the fundamental constants, in the absolute value of $H\rho$ for polonium alpha particles, and in the measurement of fluxmeter frequencies and reaction angle were smaller than the uncertainty in determining the position of one-third height of the peaks. The square root of the sum of the squares of all these errors for a typical set of measurements is quoted in Table I as the error.

These results confirm the existence of the levels at 5.96 and 6.26 Mev and show an additional level, previously unreported, at 6.18 Mev.

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Angular Distribution of Protons from (d,p) Reactions on Be^9, N^{14}, and Zn^{68}†*‡

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The (d,p) stripping theory of Butler has been employed in the interpretation of the angular distributions of protons resulting from the bombardment of foil targets of Be^9, N^{14}, and Zn^{68} by 11.9-Mev deuterons. A NaI(Tl) scintillation counter was used to detect protons emitted between angles of 5° and 90°, and pulses were recorded on a 35-mm film strip for pulse height analysis. The distribution of protons from the reaction $N^{14}(d,p)N^{15}$ leaving N^{15} in its doublet first excited state was found to have a peak in the forward direction, indicating that the conclusion previously reached, i.e., that high momentum transfers are involved in this reaction, is probably incorrect. Although it was not possible to do so in the present work, it appears that stripping theory might be used to account for the proton distribution from this reaction if deuterons of higher energy were used. The orbital momenta of a pair of isomeric levels in the nucleus Zn^{69} as determined from the proton distributions and stripping theory are in agreement with the shell model assignments of $p_{1/2}$ for the ground state and $g_{9/2}$ for the 436-kev level. Higher excited levels of Zn^{69} are indicated at about 770 kev and 1.6 Mev. The distribution of the proton group leaving the final nucleus with an excitation of 770 kev is characterized by a momentum transfer, $l_n=2$. The Q value for the reaction leaving Zn^{69} in the ground state was determined to be 4.16±0.15 Mev.

I. INTRODUCTION

THE reaction chamber and experimental arrangement which are described in the first part of this paper have been used to study the angular distributions of proton groups resulting from the deuteron bombardment of thin targets of Be^9, N^{14}, and Zn^{68}. Previous investigations of proton distributions from (d,p) reactions on Be^9 have been made at deuteron energies of 3.6 Mev,[1] 7.7 Mev,[2] 8 Mev,[3] and 14.5 Mev,[4] as well as 18 energies between 300 kev and 1.3 Mev. The present work was carried out with 11.9-Mev deuterons, and the proton groups associated with the ground state and the first excited state of Be^{10} were observed at laboratory angles between 5° and 85°. In an earlier experimental study of the reaction $N^{14}(d,p)N^{15}$ with 8-Mev deuterons,[5] the proton group associated with the doublet first excited state of N^{15} was shown to have a nearly isotropic distribution. This result has been interpreted by Butler[6] as indicating that the reaction proceeds primarily through the formation of a compound nucleus with little or no contribution from a stripping process. It was considered worth-while to investigate this reaction again using a higher deuteron energy and to extend the measurements to lower angles.

The successful use of stripping theory in interpreting the angular distributions of protons from (d,p) reactions has been restricted almost entirely to relatively light nuclei. Reactions involving the target nucleus Sr^{88} have been investigated by Holt and Marsham[7] and were found to lead to complex proton distributions which could not be explained in a simple way in terms of stripping theory. In the present work (d,p) reactions on Zn^{68} were studied for the purpose of comparing the results obtained from an interpretation of the proton distributions in terms of stripping theory with information which can be inferred from other knowledge about

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