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Inelastic Scattering of Protons and Deuterons from B^{10} and N^{14}†

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Proton and deuteron groups scattered from B^{10} and N^{14} targets were measured with a magnetic spectrograph. Accurate values for the level positions up to approximately 5-Mev excitation were obtained. One level in each nucleus failed to scatter deuterons. The operation of an isobaric spin-selection rule seems to be the most reasonable explanation of this behavior.

I. INTRODUCTION

The systematics of the binding energies of light mirror nuclei and the close correspondence of their excited states seem to establish the charge-symmetry of nuclear forces in the "classical" energy region. Moreover, the level structures of light isobars of even atomic weight support the hypothesis that nuclear forces are charge-independent. The evidence that certain states in such isobars have similar characteristics is, however, not extensive.

In B^{10}, the 1.74-Mev level is near the position expected for the analog to the ground state of Be^{10}. The intensities of the gamma rays[1] and the angular distribution of the neutron groups[2] from $Be^9(d,n)B^{10}$ suggest that this state has the required zero spin and even parity. In the isobaric-spin formalism, it is the $T_z=0$ member of the $T=1$ charge triplet, of which the Be^{10} and C^{10} ground states are the $T_z=+1$ and -1 components, respectively. Similarly, for $A=14$, a $T=1$ state would be expected in N^{14}, corresponding to the ground states of C^{14} and O^{14}. Adair[3] has pointed out that this may explain the lack of alpha particles to the 2.31-Mev level in the $O^{16}(d,\alpha)N^{14}$ reaction.[4–6] The reaction would be prohibited by the requirement of conservation of isobaric spin.

Such a selection rule would also prohibit the inelastic scattering of deuterons and alpha particles, which are characterized by $T=0$, from a state which differs in T from the ground state. The present report compares the inelastic scattering of deuterons with that of protons for the nuclei B^{10} and N^{14}. In the course of the work, an accurate measure of the positions of the levels was obtained. A preliminary report of this work has been published.[7,8]

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5 Van de Graaff, Sperduto, Buechner, and Enge, Phys. Rev. **86**, 966 (1952).
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II. METHOD

Protons or deuterons were accelerated by the MIT-ONR electrostatic generator to energies between 4 and 8 Mev. A magnet deflected the monatomic beam through 90 degrees and focused it in a horizontal line at the energy-defining exit slits, which had an opening of $\frac{1}{2}$ mm and were approximately 1 foot from the target. A $\frac{1}{4}$-inch vertical slit limited the length of the beam to prevent it from striking the target frame. The scattered particles leaving the target at 90 degrees to the incident beam were analyzed in momentum by the 180-degree magnetic spectrograph and registered on Eastman NTA photographic plates. The magnetic field was measured with a nuclear induction fluxmeter and the position of the tracks on the plates, with a microscope. The range of the tracks of known momentum serves to distinguish between protons, deuterons, and alpha particles.

The combination of the field and position measurements allows a comparison of the momentum of the scattered particles with that of polonium alpha particles. The point on the high-energy side of a peak that lies $\frac{1}{3}$ of the peak height above background was used as a reference for both the scattered and the calibration groups, since experience had indicated that this point is most consistent for targets of different thickness.

During the period in which the experiment was performed, some motion of the beam in the accelerating tube occurred. The lack of a mechanism for deflecting the beam made it necessary to open the entrance slit of the deflecting magnet to $\frac{1}{4}$ inch. Therefore, the deflecting magnet could not be used for measuring the beam energy. The incident particle energy was determined from the momentum of elastic groups. This procedure introduced a possible error, since the open entrance slits could allow a different beam momentum during the exposure for the inelastic groups than during the elastic measurements.

Further details of the method have been given in a recent paper.[9]

Calculations show that the errors introduced by the uncertainties in the fundamental constants, in the magnetic field measurement, in the $H\rho$ of polonium alpha particles, and in the reaction angle are small compared with the 0.2-mm uncertainty in determining the position

9 Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).

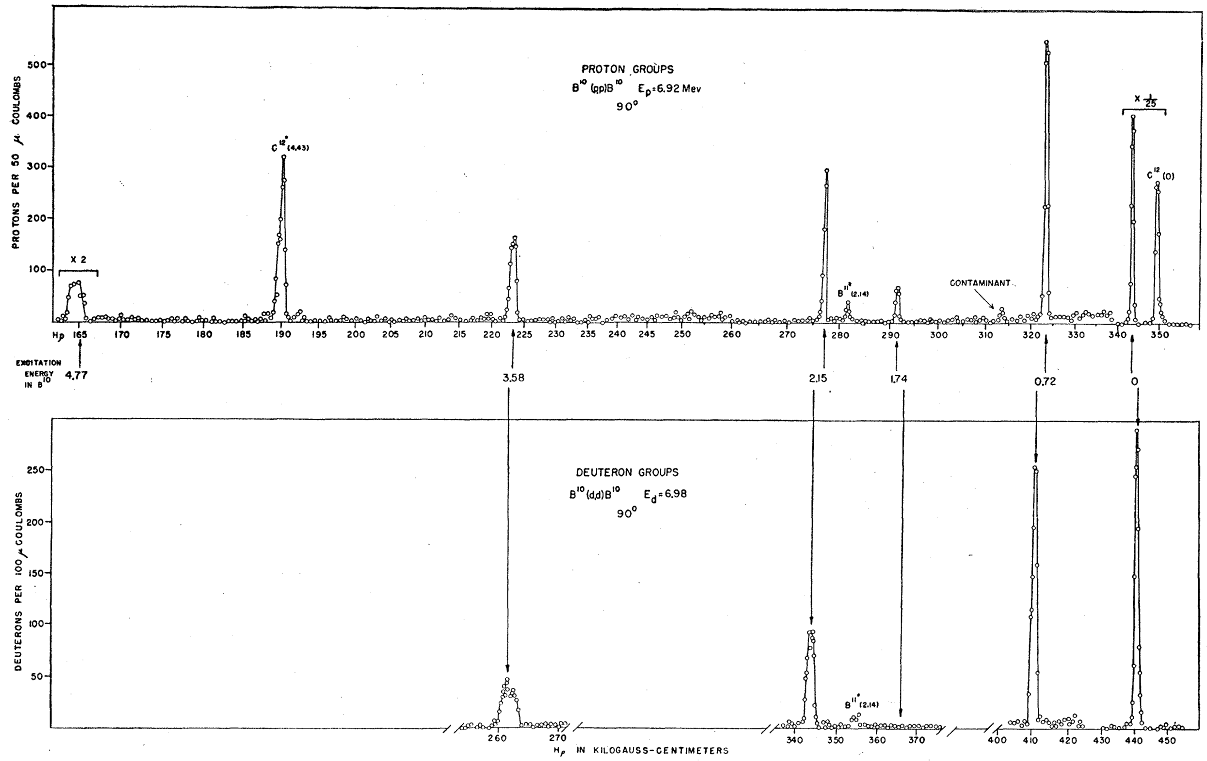

FIG. 1. Scattered proton and deuteron groups from B^{10} obtained at 90 degrees. Incident proton energy 6.92 Mev. Incident deuteron energy 6.98 Mev. Groups arising from B^{10} are labeled with the corresponding excitation energy. Other groups are identified with the contributing nucleus and its excitation. Note abscissa is not linear in $H\rho$ but in ρ. The B^{11} ground state observed with protons does not show on the reduced scale.

of the $\frac{1}{3}$ heights of the reaction peaks relative to the polonium alpha peaks. This factor alone contributes an uncertainty of approximately 2 kev to the total error. Although variations in incident trajectories which were geometrically possible with the open entrance slits could introduce larger errors, the over-all consistency of results leads to the belief that the errors quoted below are reasonable estimates.

For intensity comparisons between scattered groups, the integrated beam current incident on a catcher placed directly behind the target and biased to trap secondary electrons was used.[10]

III. RESULTS

A. Boron 10

Thin films of B^{10} were evaporated on Formvar films, supported on a wire frame. The enriched boron isotope was obtained from the Stable Isotopes Division of the U. S. Atomic Energy Commission, Oak Ridge.

A typical proton momentum spectrum obtained at a bombarding proton energy of 6.92 Mev is shown in the upper part of Fig. 1. Peaks appear which arise from B^{10}, B^{11}, and C^{12}. The mass of a light nucleus responsible for a peak was determined by observing the change in momentum of the group as the bombarding energy was varied. Groups arising from nuclei other than B^{10} are labeled on the graph and have been identified with well-known levels. The origin of the peak at $H\rho=314$ kilogauss-centimeters is not known, but energy shifts make it possible to assign it to a level in a nucleus of mass considerably greater than 10.

The unlabeled groups in Fig. 1 are produced by inelastic scattering from levels in B^{10}. A number of measurements of these peaks on different B^{10} targets at different energies, using deuterons as well as protons when possible, were used to calculate the excitation energies. These energies were derived by inserting the measured energy of the inelastic group and the bombarding energy calculated from an elastic group in the relativistic Q equation for 90 degrees. The excitation energies obtained from the proton measurements are listed in the first column of Table I, together with an estimate of the rms error. The deuteron data checked these numbers but with larger errors.

TABLE I. Levels of B^{10} and N^{14}.

B^{10} excitation (Mev)	N^{14} excitation (Mev)
0.717±0.005	2.313±0.005
1.739±0.005	3.945±0.005
2.152±0.005	4.910±0.010
3.583±0.005	5.104±0.010
4.771±0.005	

[10] H. Enge, Rev. Sci. Instr. 23, 599 (1952).

TABLE II. Relative intensities of inelastic groups.

Levels in B^{10}	6 Mev Proton	6 Mev Deuteron	7 Mev Proton	7 Mev Deuteron	7.6 Mev Proton	7.6 Mev Deuteron
0	100	100	100	100	100	100
0.72	7	7	6	9	4	7
1.74	1	<0.4	1	<0.15	1	<0.15
2.15	6	2	5	4	3	4
3.58	4	...	5	4	7	7

The lower part of Fig. 1 shows sections of the spectrum of scattered deuterons with an incident energy of 6.98 Mev. Portions are shown which correspond to those excitation energies in B^{10} below 4 Mev at which proton peaks were seen. Groups are shown which correspond to the ground state, and excited levels at 0.72, 2.15, and 3.58 Mev. However, in the region where a group from the 1.74-Mev level would be expected, only a low uniform background of deuterons was seen even from bombardments some ten times greater than those necessary to bring out other peaks. This sort of background was common to all plates exposed in this momentum region and was presumed to be instrumental in origin. The measurements were repeated at energies of 7.3 and 7.6 Mev, but no deuteron peak was observed which could be associated with the 1.74-Mev level in B^{10}.

An estimate of the intensities of the inelastic scattering relative to the elastic scattering from B^{10} was obtained by comparing the number of tracks in each peak for a given incident charge on a particular target. The intensities, relative to the proton and deuteron elastic groups at the three energies, are listed in the appropriate column in Table II. Each of these numbers is the average of at least two runs, except in the case of deuteron scattering to the 1.74-Mev level, where the upper limit is derived from the longest exposure undertaken. The relative intensities so measured varied by as much as 30 percent. Errors in current integration may have contributed, but the most likely source of these variations was changes in the current distribution across the bombarded area of the target. Different portions of the target subtend different solid angles at the nuclear plate so that variations in current distribution amount to a change in the effective solid angle of the analyzer. This effect is increased if the targets are not uniform.

At a bombarding energy of 7.6 Mev, a deuteron peak resulting from inelastic scattering from the 4.77-Mev level was seen, but no measurements of its intensity were made. At lower bombarding energies, this group was not seen, presumably because of the Coulomb barrier.

B. Nitrogen 14

For measurements of the inelastic scattering from N^{14} targets of thin Nylon were used. The upper part of

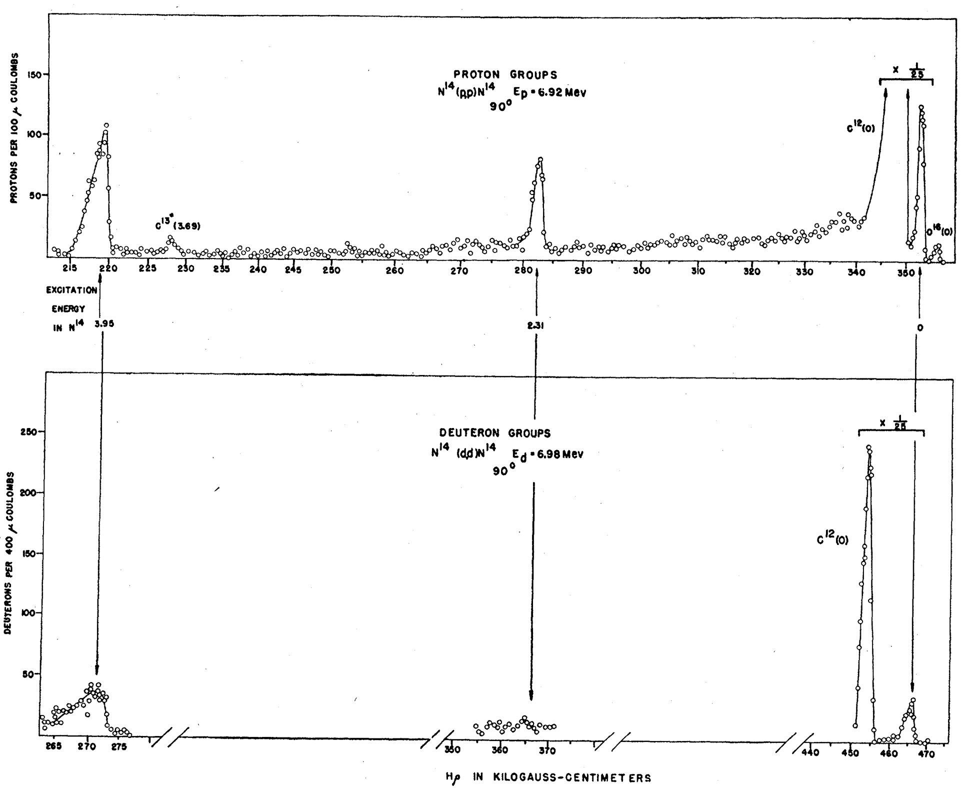

FIG. 2. Scattered proton and deuteron groups observed at 90 degrees from a Nylon target. Incident proton energy = 6.92 Mev. Incident deuteron energy = 6.98 Mev. Groups arising from N^{14} are labeled with the corresponding excitation energy.

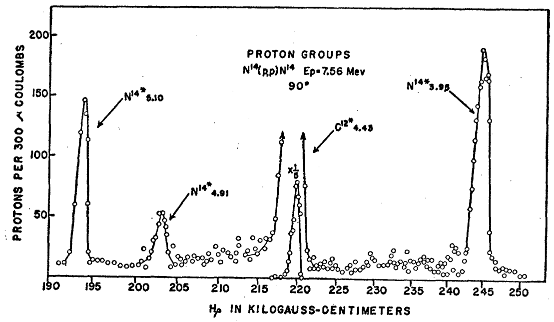

FIG. 3. Inelastic proton groups observed at 90 degrees from a Nylon target with 7.56-Mev bombarding energy.

Fig. 2 shows a momentum spectrum of scattered protons when the incident energy was 6.92 Mev. The ground-state groups from N^{14} and C^{12} appear, and a known level in C^{13}, as well as the first two excited states of N^{14}. A second level in C^{13}, at an excitation energy of 3.89 Mev, is buried under the front edge of the N^{14} 3.95 level at this energy. Because of the low intensity of the groups associated with higher nitrogen levels at this bombarding energy, the next two levels were measured at higher energies. The results with 7.6-Mev incident protons are graphed in Fig. 3. The N^{14} level at 3.95 Mev is shown again, and the C^{12} level at 4.43 Mev appears. Two peaks ascribed to levels in N^{14} at 4.91 and 5.10 Mev also are seen. The measured excitation energies for the four N^{14} levels are given in the second column of Table I with estimated rms errors.

The lower part of Fig. 2 shows portions of the momentum spectrum of scattered deuterons in regions of excitation of N^{14} where proton groups to the three lowest states were seen. A typical run at 6.98 Mev is shown. The ground state and the 3.95-Mev level appear, but nothing above background is seen in the region corresponding to the 2.31-Mev level.

Because the Nylon targets were somewhat unstable under bombardment, less reliance is placed in the nitrogen intensity measurements. Further complication is added by the presence of the C^{13} 3.89 level in the region of the N^{14} 3.95 group. However, exposures on polyethylene targets which contained at least as much carbon as did the Nylon targets showed that the C^{13} level contributes only a small amount to the peaks attributed to the N^{14} 3.95 level. From Fig. 2 for protons the intensity ratios to the ground state are 5 percent and 10 percent for the 2.31- and 3.95-Mev levels, respectively. For deuterons the ratio for the 3.95-Mev state is 10 percent, while an upper limit of about 0.5 percent is set for the 2.31-Mev level. Similar results were obtained at 7.6-Mev bombarding energy. No attempt was made to observe deuteron scattering to the 4.95- and 5.10-Mev states.

IV. DISCUSSION

The level scheme observed for B^{10} up to an excitation of 4.8 Mev agrees with that seen by other investigators.[2,6] The gamma-ray energies measured by Rasmussen[1] agree with the present results within the stated errors.

Thomas and Lauritsen[11] have observed gamma rays of 1.638 and 2.310 Mev, among others, which fit into the present level scheme of N^{14}.

In both B^{10} and N^{14}, a level that scatters protons fails to scatter deuterons at various bombarding energies. Although observations were made only at 90 degrees, it does not seem reasonable to account for this behavior in terms of an angular-momentum or parity-selection rule. Kroll and Foldy[12] have given a possible explanation based on charge-symmetry of nuclear forces. However, in each case here the level in question lies at the place expected for the analog to the ground state of the neighboring isobars. This is illustrated in Figs. 4 and 5 where the level structure for the isobar with $T=0$ ground state is shown, together with the ground states of the $T=1$ members of the triad. The position of these ground states has been drawn after the observed binding-energy differences were adjusted to account for the differences in the $n-H$ masses and Coulomb energy. A rough Coulomb energy difference

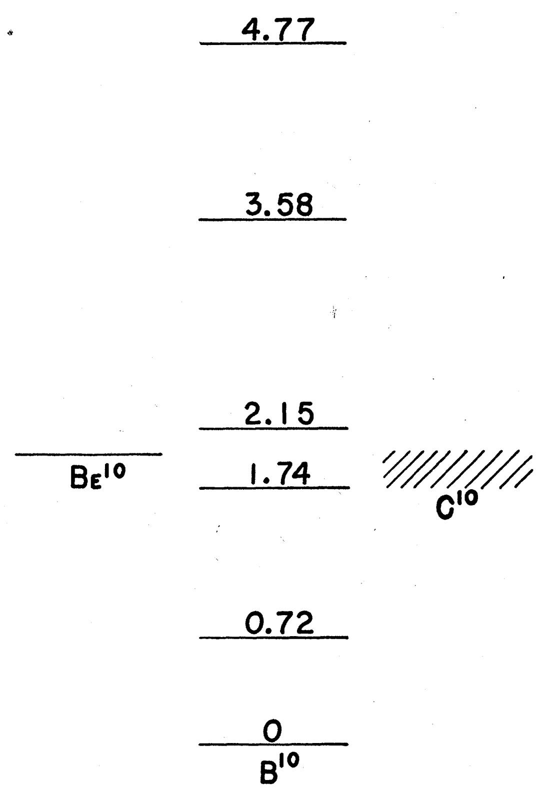

FIG. 4. Energy levels for the mass-10 triad. The positions of the Be^{10} and C^{10} ground states have been corrected for the $n-H$ mass difference and Coulomb energy difference.

[11] R. G. Thomas and T. Lauritsen, Phys. Rev. 88, 969 (1952).
[12] N. Kroll and L. Foldy, Phys. Rev. 88, 1177 (1952).

was computed from the relation

$$\Delta E_c = \frac{3}{5}\frac{e^2}{r_0 A^{\frac{1}{3}}}\{(Z+1)Z - Z'(Z'-1)\}. \qquad (1)$$

It is seen that, for both B^{10} and N^{14}, the level that has been observed not to scatter deuterons is close to the position expected for a member of a charge triplet. Since charge-symmetry would not account for the existence of charge triplets, the assumption of charge-independence of nuclear forces, giving rise to a selection rule for isobaric spin, seems a more nearly complete explanation of the present results.

Competition with neutron emission should reduce the intensity of inelastic proton scattering to the $T=1$ states relative to the $T=0$ states. Ignoring the effect of other factors which might govern the intensities, one would expect the intensity of the proton group to the 1.74-Mev level in B^{10} to be $\frac{1}{3}$ of the proton intensity to the $T=0$ levels. Although insufficient information is available to estimate the barrier penetrabilities, at 7.6-Mev incident energy, the energies of both the protons and deuterons emitted to the 1.74 and 2.15 states are nearly equal and greater than the Coulomb barrier, so that one might expect that the barrier penetrabilities do not differ greatly. It is interesting to note that the ratio of proton intensities for these two levels reaches its maximum value of $\frac{1}{3}$ in this case.

Again at 7.6 Mev, Table II shows that the upper limit for deuterons emitted to the 1.74-Mev state is 4 percent of those to the 2.15-Mev level. If the deuteron penetrabilities are approximately equal and if the difference in matrix elements for inelastic deuteron scattering to these two levels is attributed entirely to the isobaric spin-selection rule, the measurements indicate that a $T=0$ component in the wave function of the 1.74-Mev state must be less than 20 percent of the $T=1$ component. This upper limit is considerably greater than the impurity of a few percent estimated by Radicati[13] and quoted by Wilkinson[14] for other $T=1$ levels.

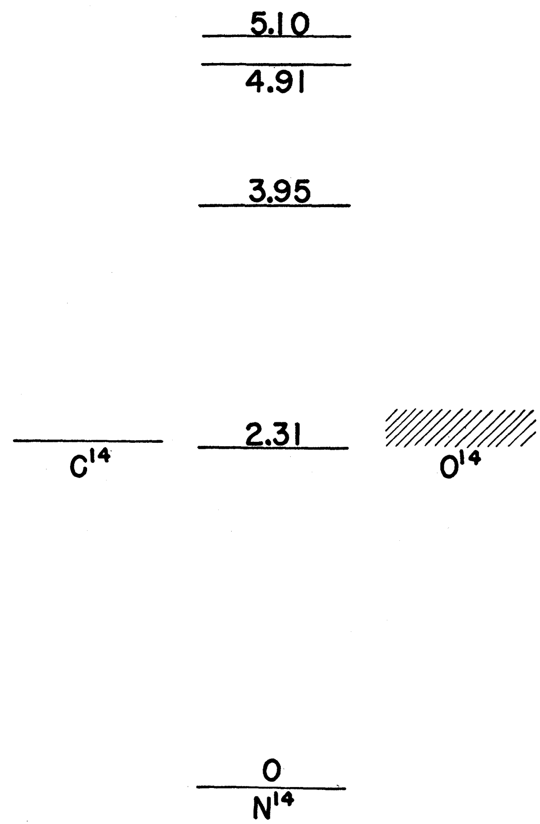

FIG. 5. Energy levels for the mass-14 triad. The positions of the C^{14} and O^{14} ground states have been corrected for the $n-H$ mass difference and Coulomb energy difference.

The authors are indebted to W. A. Tripp, Lee Stone, and Janet Frothingham for assistance in reading many of the plates. We are also grateful to Dr. M. M. Elkind for preparation of the boron targets.

[13] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).
[14] G. Jones and D. Wilkinson, Phys. Rev. **90**, 722 (1953).