no definite evidence against additivity of nuclear moments in the deuteron, although the ranges of error of the computed and measured values barely overlap. It seems, however, that a slight disagreement is produced if the relativity effect is included.

While the exact relativistic treatment of the deuteron problem is ambiguous, it is possible to determine the sign and the order of magnitude of the correction required in the magnetic moment. If we consider the proton alone and apply the first of formulas (5) with $j=\frac{1}{2}$, the correction is $-4\mu_0\bar{\epsilon}/3$. Now $\bar{\epsilon}$ may be computed from any model of the deuteron. It depends of course upon the type of force chosen for the interaction between proton and neutron, and there is a further uncertainty connected with the mass appearing in Mc^2. A reasonable estimate for $\bar{\epsilon}$ arrived at by the potential hole model, seems to be 0.006. This would make the correction -0.022 n.m. It is difficult to see how to treat the neutron and its negative moment. If its absolute value is also diminished in proportion to its μ_0 the sum of the moments will undergo a correction only about $\frac{1}{3}$ as large as the value stated, but the correction will still be negative. These matters, however, will be of greater interest when the neutron moment is known with greater accuracy.

I express my gratitude to Professor Wigner, whose remarks have stimulated these computations.

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The Gamma-Radiation from Nitrogen Bombarded by Deuterons

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The energies and the relative intensities of the gamma-rays emitted from nitrogen bombarded by deuterons of 700 kev energy have been measured by the positron-electron pairs and recoil electrons ejected from thin laminae placed inside a cloud chamber. The distribution of pairs ejected from a lead lamina 0.026 cm thick reveals two strong components of quantum energy 7.2±0.4 Mev and 5.3±0.4 Mev, and a number of weaker components which may be attributed to radiation of about 4 and 2 Mev. There are also a number of pairs which extend up to 11 Mev. The distribution of recoil electrons from a carbon lamina 0.12 cm thick indicates two strong groups of quantum energy 4.2 and 2.2 Mev. No attempt was made to extend the recoil measurements to higher energies. The 7.2-Mev radiation is attributed to the reaction

$$N^{14}+H^2\rightarrow C^{12}+He^4,$$

because radiation of this energy has been observed in other reactions producing C^{12}. The 5.3-Mev radiation is attributed to an excited state of N^{15} of this energy according to the reaction

$$N^{14}+H^2\rightarrow N^{15}+H^1$$

in good agreement with the value of 5.4 Mev predicted by the range measurements of Cockcroft and Lewis. An attempt is made to correlate the energies and intensities of the gamma-rays produced by excited states in C^{12}, N^{15} and O^{15} according to several reactions.

INTRODUCTION

THE gamma-radiation from nitrogen bombarded by deuterons was first investigated by Crane, Delsasso, Fowler and Lauritsen[1] by measuring the recoil electrons ejected from a thick glass wall of a cloud chamber. They obtained a complex spectrum consisting of a number of components at 1.9, 3.1, 4.0, 5.3 and 7.0 Mev. Employing the method of measuring gamma-ray energies by the positron-electron pairs and recoil electrons ejected from thin laminae placed inside a cloud chamber,[2] we have reinvestigated the radiation, and have obtained results which are not in contradiction with the

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[1] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 100 (1935).

[2] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 391 (1937); Fowler, Gaerttner and Lauritsen, Phys. Rev. **53**, 628 (1938).

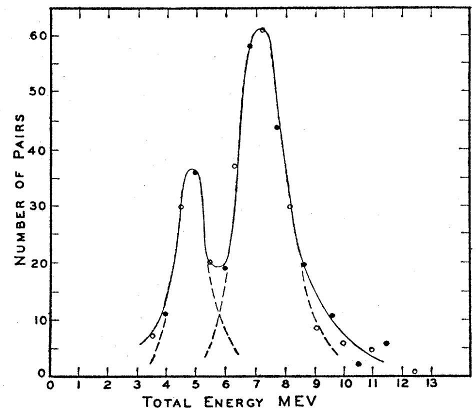

FIG. 1. Positron-electron pairs ejected from lead 0.026 cm thick by the gamma-radiation from nitrogen bombarded by deuterons, plotted in intervals of 0.9 Mev overlapping by one-half their width. $H=1650$ gauss.

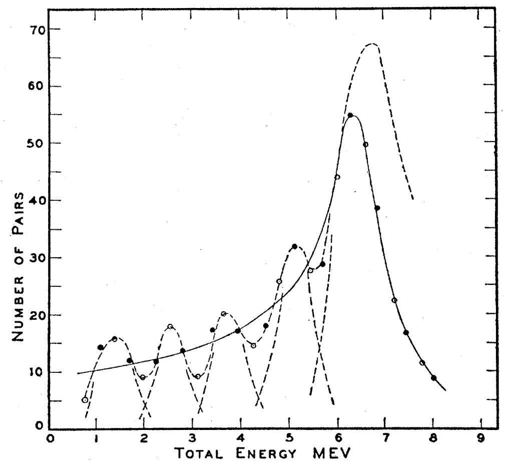

FIG. 2. Positron-electron pairs ejected from lead 0.026 cm thick by the gamma-radiation from nitrogen bombarded by deuterons, plotted in intervals of 0.55 Mev overlapping by one-half their width. $H=1000$ gauss. The solid curve is drawn through the average distribution of the pairs; broken curves are drawn in the regions where the statistical fluctuations are large, and also to indicate expected distributions of gamma-ray lines.

earlier experiments. We have measured the high energy components of the spectrum with pairs and the low energy ones with recoils. The work with recoils has been extended to higher energies by Crane and Halpern, and the results of their work appear in the *Physical Review*.[3]

The experimental arrangement of the cloud chamber was the same as that described in reference 2. The data were obtained with the a.c. accelerating tube operated at about 700 kv peak with a total ion current of about 20 microamperes during the chamber expansion, and with the pressure Van de Graaff generator operated at a voltage of 700 kv and a total ion current of 10 microamperes. The ion beam was not magnetically analyzed in either case, and consequently it consisted of a small amount of protons, estimated to be about 5 percent of the total current in the case of the a.c. tube. That there was little or no contribution from this source up to a voltage of 700 kv was indicated by experiments in which nitrogen (both N^{14} and N^{15})* was bombarded with protons. Targets of C.P. ammonium chloride and sodium nitrite were used, and frequently replaced due to their rapid decomposition in the ion beam. The consistency of the data obtained with the different targets and under different operating conditions supports the conclusion that the observed radiation is due predominantly to N^{14} bombarded with deuterons except for a small contribution from carbon which is always deposited on targets in apparatus employing oil diffusion pumps.

ENERGY OF THE GAMMA-RADIATION

Figure 1 shows the distribution in total energy (kinetic$+2mc^2$) of (208) positron-electron pairs ejected by the radiation from a lead lamina 0.026 cm thick and measured in a magnetic field of 1650 gauss. The pairs are plotted in overlapping intervals of 0.9 Mev. Fig. 2 shows a similar distribution of (277) pairs measured in a magnetic field of 1000 gauss and plotted in overlapping intervals of 0.55 Mev. Solid curves have been drawn through the average distribution of the pairs, and broken curves in the regions where the statistical fluctuations are large; and also to indicate the theoretical distribution of monochromatic lines broadened roughly to account for the errors in measurement. The broken portion of the curve on the high energy side of the upper group in Fig. 2 is drawn to show the amount which this group must be broadened to agree with the more reliable measurement of this group in the 1650-gauss field. This must be done because there is a tendency in the measuring process to discriminate against the high energy pairs obtained in

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[3] Crane, Halpern and Oleson, Phys. Rev. **57**, 13 (1940).

* N^{15} was generously furnished by Professor H. Urey.

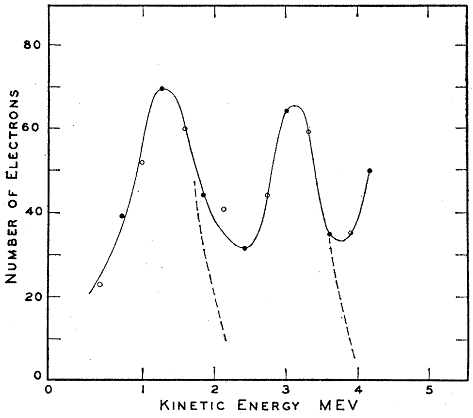

FIG. 3. Recoil electrons ejected from carbon 0.12 cm thick within an angle of 20° with the forward direction of the gamma-radiation from nitrogen bombarded by deuterons, plotted in intervals of 0.64 Mev overlapping by one-half their width. Combined results of measurements in magnetic fields of 1000 and 1500 gauss.

the lower field. The distribution of Fig. 1 reveals two strong groups, whose average energies are 5.3 and 7.4 Mev (after adding 0.3 Mev for the thickness of the scatterer), and a number of pairs extending up to 11 Mev. Similarly in Fig. 2 the average values of the prominent groups are 5.4 Mev for the lower one and 7.0 Mev for the broadened upper group. Consequently, the average values of the quantum energies with their estimated probable errors for the two prominent groups in the spectrum are 5.3±0.4 and 7.2 ±0.4 Mev. In addition to these two groups, there are a number of pairs forming a "tail" extending to lower energies. This "tail" might be due either to bremsstrahlen produced by the 5.4- and 7.0-Mev radiation, or to a number of gamma-ray lines. The latter conclusion seems more likely since the "tail" contains one-third of the total number of pairs. Furthermore, similar pair distributions from other reactions, notably from the 6.0-Mev line of $F^{19}+H^1$, do not extend to such low energies.[3]

Figure 3 shows the distribution in kinetic energy of (320) electrons ejected from a carbon lamina 0.12 cm thick within an angle of 20° with the forward direction of the quanta, and plotted in overlapping intervals of 0.64 Mev. These electrons were measured in magnetic fields of 1000 gauss and 1500 gauss. The distribution reveals two groups whose extrapolated end points are about 2.0 and 4.0 Mev. Adding 0.25 Mev to the extrapolated recoil energies gives the most probable energies of the two groups as 2.2 and 4.2 Mev. The existence of these two components in the electron distribution affords some justification for drawing the groups corresponding to these quantum energies in the pair distribution of Fig. 2. The fact that the radiation in the neighborhood of 3 Mev is suppressed in the electron distribution and not in the pair distribution may be due in part to the absence of carbon contamination while the recoil data were obtained. This fact was supported by recoil measurements with the new Van de Graaff generator where the carbon contamination was small.

THE RELATIVE INTENSITIES OF THE GAMMA-RAY COMPONENTS

Estimates of the relative intensities of the gamma-rays from both the pair and recoil data are given in Table I. In estimates from the pair curves the relative intensities have been corrected for the variation in the pair formation with energy. In Fig. 1 the relative intensity of the 7.2-Mev component is taken from the corrected curve. Those of the lower energy components are taken from the dotted curves which give roughly the expected distribution of pairs produced by monochromatic lines. The best measure of the relative intensities of the 5.3-Mev group and the 7.2-Mev group can be obtained from Fig. 1. The estimates from the recoil curves have been corrected for the total Klein-Nishina cross section.

TABLE I. *Estimated relative intensities of gamma-rays. π is pair-formation cross section and σ is Klein-Nishina cross section.*

GAMMA-RAY ENERGY	RELATIVE INTENSITIES	RELATIVE CROSS SECTIONS	INTENSITY
Pairs			
2	0.25	0.21	~1.2
4	0.25	0.54	~0.45
5.3±0.4	0.5	0.74	0.7
7.2±0.4	1.0	1.00	1.0
11	0.1	1.3	~0.1
Recoils			
2.2	1.0	1.35	0.75
4.2	1.0	1.0	1.0

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[3] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 527 (1937).

ORIGIN OF THE RADIATION

To account for the emission of alpha-particles, protons, and neutrons when nitrogen is bombarded by deuterons, the following reactions have been proposed (Q values given by Livingston and Bethe):

$$_7N^{14}+{}_1H^2\rightarrow{}_6C^{12}+{}_2He^4+13.37\text{ Mev} \quad (1)$$

$$_7N^{14}+{}_1H^2\rightarrow{}_7N^{15}+{}_1H^1+8.57\text{ Mev} \quad (2)$$

$$_7N^{14}+{}_1H^2\rightarrow{}_8O^{15}+{}_0n^1+5.1\text{ Mev.} \quad (3)$$

Cockcroft and Lewis[4] observed two discrete groups of alpha-particles of ranges 11.37 and 6.18 cm which they attributed to (1); the longer one forming C^{12} in the ground state and the shorter one forming C^{12} in an excited state 4.32 Mev above ground. In addition to these discrete groups of alpha-particles they observed a continuous distribution or possibly a number of closely spaced groups extending up to 3.2 Mev. They also observed two discrete groups of protons of ranges 85 cm and 18.3 cm which they attributed to (2), forming N^{15} in an excited state 5.4 Mev above ground. The intensity of the short range protons was found to be $\frac{1}{4}$ to $\frac{1}{3}$ that of the short range alpha-particles (6.18 cm) at a bombarding voltage of 0.530 Mev. Stephens, Djanab and Bonner[5] observed two groups of neutrons according to (3), indicating an excited state in O^{15} at 4.0 Mev. All three reactions were observed to have about the same yield at 550 kv.

The group structure of the heavy particles (1), (2) and (3) indicate the existence of 4.32, 5.5 and 4.0-Mev radiation from excited states in C^{12}, N^{15} and O^{15}, respectively. The observed 4.2-Mev gamma-radiation may be attributed to (1) and (3). From energy considerations the 7.2-Mev radiation may be attributed either to (1) or (2) but it is more reasonable to assign it to (1) because radiation of about this energy has been observed in other reactions in which C^{12} is formed; namely, in the reaction,

$$B^{11}+H^2\rightarrow C^{12}+n^1 \; ^6$$

and in the reaction

$$Be^9+He^4\rightarrow C^{12}+n^1. \; ^7$$

These experiments give strong support for the existence of a level in C^{12} at about 7 Mev. The absence of a group of alpha-particles in (1) which would couple with this gamma-ray to give the total disintegration energy shows that an alpha transition to this level in C^{12} must be very weak if not entirely forbidden. This radiation must then be produced by gamma-ray transitions from levels lying at higher energies which are strongly coupled to the 7.2-Mev level but weakly coupled with the ground state. The presence of such levels is suggested by a number of pairs extending up to about 11 Mev. The corresponding group or groups of alpha-particles would be contained in the continuous distribution of alpha-particles. The 5.3-Mev radiation may from energy considerations be attributed to (1) or (2), but it is tempting to attribute it entirely to (2) because of the good agreement between the observed quantum energy (5.3 Mev) and the value of (5.4 Mev) predicted from (2).

One difficulty arises from the fact that the ratio ($\frac{1}{4}$ to $\frac{1}{3}$) of the number of short range protons from (2) to the short range alpha-particles from (1) is too small to account for the observed ratio (~ 2) for the 5.3- to 4.0-Mev radiation if all the 5.3-Mev radiation is due to N^{15}. This difficulty can be removed by assuming that there is another level in N^{15} above 5.4 Mev which is strongly coupled to this level but weakly coupled with the ground state of N^{15}.

The assistance and encouragement of Professor C. C. Lauritsen throughout this work is gratefully acknowledged. The authors are indebted to Professor Lauritsen, Dr. W. A. Fowler and Dr. T. Lauritsen for placing the pressure Van de Graaff generator at their disposal for a part of this work. One of us (E.R.G.) is also indebted to the Graduate School of the University of Michigan for an H. H. Rackham Post-Doctoral Fellowship.

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[4] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 261 (1936). See also M. G. Holloway and B. L. Moore, Phys. Rev. **56**, 705 (1939).

[5] Stephens, Djanab and Bonner, Phys. Rev. **52**, 1079 (1937).

[6] Gaerttner, Fowler and Lauritsen, Phys. Rev. **55**, 27 (1939).

[7] W. Bothe, Zeits. f. Physik **100**, 273 (1936).