in the density (per unit energy) of Al^{28} levels, thus giving the appearance of single groups. Similar tendencies have been noticed in unpublished experiments done at this laboratory on other elements in this mass range. However, in some cases (e.g. Ne and A) pronounced groups are observed where the minima between groups is low compared to the maxima in these groups. This may be taken as evidence for the assumption that the density of nuclear levels is not only a function of the total number of particles from a statistical viewpoint but also depends critically upon the characteristics of a given nucleus, i.e., to what degree the nucleus approximates a closed-shell configuration in neutrons and protons. It is of interest to recall the work of Plain, Herb, Hudson and Warren[12] who found a large number of levels from observations on the excitation function for γ-rays produced in the reaction $Al^{27}(p, \gamma)Si^{28}$.

In comparing the present results on aluminum with those of McMillan and Lawrence it appears that the relative intensity of the groups is different from that published by the above writers. Perhaps this discrepancy results from the fact that the present experiment was conducted at higher bombarding energies, the higher excitation being responsible for this difference in relative intensities. Similar effects have been noted by Pollard, Davidson and Schultz[2] in the case of boron bombarded by deuterons. More likely it is caused by the difference in technique of detection.

In conclusion, it is a pleasure to thank Professor Ernest Pollard for much valuable help and advice. The writers are also indebted to Dr. M. E. Rose for discussion. A grant from the George Sheffield Fund is gratefully appreciated.

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[12] G. P. Plain, R. G. Herb, C. M. Hudson and R. E. Warren, Phys. Rev. 57, 187 (1940).

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Protons from the Separated Isotopes of Carbon and Neon under Deuteron Bombardment

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The protons arising from the bombardment by 2.54-Mev deuterons of CH_4 gas enriched in C^{13} isotope and neon enriched in Ne^{22} have been studied with a cloud chamber. It is shown that the yield of long range protons from the $C^{13}(dp)C^{14}$ reaction is less than four percent of the yield of shorter range protons from the $C^{12}(dp)C^{13}$ reaction at this deuteron energy. This low yield means that the half-life of C^{14} discovered by Ruben and Kamen is considerably less than their estimate and is probably about 100 years. In neon the longest range group of protons discovered by Pollard and Watson is shown to be complex, with an indicated doublet width of the ground state of Ne^{21} of 0.44 Mev. The only proton group definitely indicated for the Ne^{22} bombardment occurs at about 30 cm range.

INTRODUCTION

RECENT improvements in the production of separated isotopes have immediate application to problems in nuclear physics. In studies of proton groups emitted in transmutations, samples enriched in one or more of the isotopes are necessary where: (1) Proton emission caused by the rare isotope is normally so small as to make detection difficult even in the absence of interfering groups from the more abundant isotopes; (2) the group caused by the rare isotope may be fairly strong but be overlapped by equally prominent groups from the abundant species. The transmutation of C^{13} by deuterons is an example of (1), while the situation in the case of neon may follow (2).

This paper presents the results of experiments on the protons from carbon enriched in C^{13} and on neon with and without enrichment in Ne^{22}. The cloud-chamber method of detection of

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groups described in another paper[1] has been employed. The protons from both elements have previously been studied with the aid of counting technique. For work of this kind with separated isotopes it is more advantageous to use cloud-chamber detection as it enables the counting of every particle and hence the accurate measurements of relative yields.

PRODUCTION OF THE SEPARATED ISOTOPES

The separated isotopes for these bombardment experiments were produced by the thermal diffusion method, as already described by one of us.[2] In particular the "heavy" neon was one of the samples used by Pollard and Watson,[3] with an Ne^{20}/Ne^{22} abundance ratio of about 84/16 as against the normal ratio of 90/10. The heavy methane has been produced in a six-unit, all-copper thermal diffusion apparatus, with a total column length of 12 meters. This apparatus is an extension of the two-unit model which increased the C^{13} content of the CH_4 to 2.77 times the normal amount.[2] Preceding these two 2-meter columns there were placed two additional columns identical in all respects except that the gap space between the hot and cold surfaces was increased $\frac{1}{16}$ inch, while following the two original columns two with this gap space decreased by $\frac{1}{16}$ inch were installed. These changes in dimensions were limited by available sizes of copper pipe, but the "staggering" effect thus produced is not far from that indicated by the Furry, Jones and Onsager theory[4] in order to give a maximum separation factor. All units are based on G. E. $\frac{1}{2}$-inch Calrod heaters with the hot coupling pipes all grouped together around a center post and wound with a common heater, the whole constituting a compact assembly of volume about eight liters.

Without the "staggering" of columns this six-unit model would be expected to give a factor of $(2.77)^3$ or 21. Actually one sample of heavy methane withdrawn after 36 days of operation showed a C^{13} content 22.4 times that in ordinary methane, with indications that equilibrium had not yet been reached and that considerable nitrogen was being accumulated, probably from a small leak in the apparatus. The CH_4 sample withdrawn for the transmutation experiments consisted of 15.6 percent C^{13}, the enrichment being limited by a rather fast withdrawal rate of about 55 cm^3 per day and possibly by increasing accumulation of nitrogen found in the withdrawn gas.

PROTONS FROM CARBON

Protons from C^{12} bombarded by deuterons are well known. The yield is quite prolific at bombarding energies of 3 Mev. On the other hand, the transmutation of C^{13} according to $C^{13}(dp)C^{14}$ is not as easily observed. Studies of this reaction have been carried out by two means: (1) observations on the production of radioactive C^{14};[5] (2) direct study of the emitted protons. The latter has been aided by the determination of the mass of C^{14} by Bonner and Brubaker[6] through the reaction $N^{14}(np)C^{14}$. Pollard[7] has detected a weak group at 81 cm range (3.2-Mev incident beam) from a thick target of carbon, while Bower and Burcham[8] using the cloud-chamber method in experiments on proton groups from fluorine found a contamination group which they attribute to C^{13}. On the other hand, Holloway and Moore[9] failed to find this group even though they employed concentrated C^{13}.

Recently, however, Bennett, Bonner, Hudspeth and Watt,[10] using targets prepared from methane with both increased and decreased C^{13} content, have reported measurements on these long range protons from the deuteron bombardment of C^{13}. With an ionization chamber they find that for 1.22-Mev deuterons the ratio of the proton yield from this reaction to that from $C^{12}(dp)C^{13}$ is 6.5 percent for like numbers of

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[1] H. L. Schultz, W. L. Davidson, Jr. and L. H. Ott, this issue.

[2] W. W. Watson, Phys. Rev. **57**, 899 (1940).

[3] E. Pollard and W. W. Watson, Phys. Rev. **58**, 12 (1940).

[4] W. Furry, R. Jones and L. Onsager, Phys. Rev. **55**, 1083 (1939).

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[6] T. W. Bonner and W. M. Brubaker, Phys. Rev. **49**, 778 (1936).

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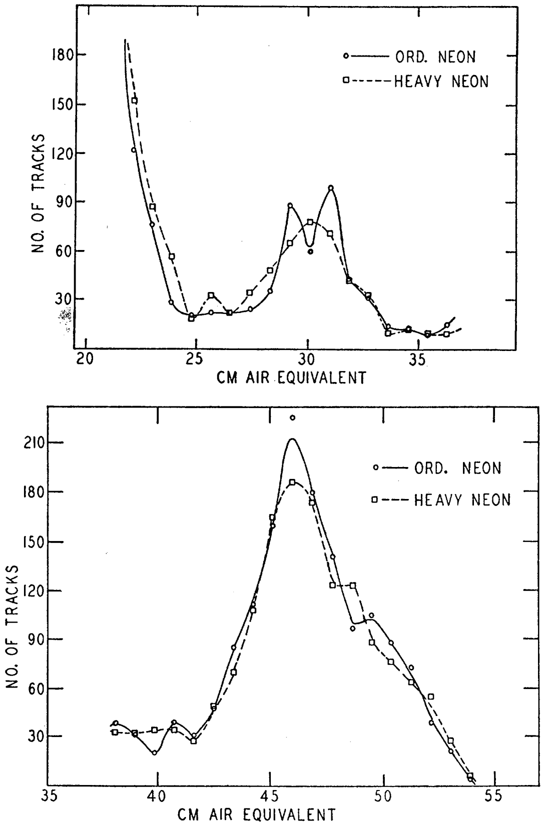
[8] J. C. Bower and W. E. Burcham, Proc. Roy. Soc. **173**, 379 (1939).

[9] M. G. Holloway and B. L. Moore, Phys. Rev. **57**, 1086A (1940).

[10] W. E. Bennett, T. W. Bonner, E. Hudspeth and B. E. Watt, Phys. Rev. **58**, 478 (1940).



Figs. 1A (top) and 1B (bottom). Number-range distribution of protons from normal and "heavy" samples of neon bombarded by deuterons.

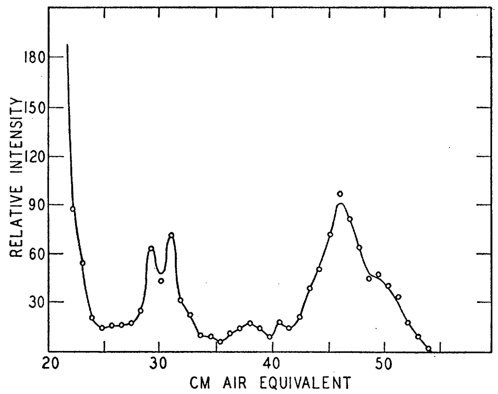


Fig. 1C. Composite curve plotted in terms of arbitrary scale along the ordinate to indicate relative intensities of groups for ordinary neon. Data of Figs. 1A and 1B have been used and adjusted as explained in the text.

atoms. Our cloud-chamber observations are in fair agreement with this value.

Importance attaches to an accurate knowledge of this yield since on it is based the estimate of the half-life of C^{14} recently discovered by Ruben and Kamen.[5] The half-life is too long for direct measurement and must be deduced from a knowledge of the number of atoms of C^{14} formed in a bombardment. From the figures given by Pollard, Ruben and Kamen estimate a half-life of 1000 years for C^{14}. The lower figures of Bennett, Bonner, Hudspeth and Watt would imply a half-life considerably less, about 200 years.

The CH_4 enriched in C^{13} was used at 18 cm pressure in the gas target cell with an effective thickness of 3 mm air equivalent. This sample was purified by condensation with liquid air. Preliminary observations showed a weak but definite group ending at 70 cm range (effective beam energy, 2.54 Mev) in good agreement with mass values assuming that C^{13} was responsible for this group. At the same time, however, protons of much longer range were present, suggesting nitrogen contamination. The sample was then purified much more thoroughly by repeated condensation, pumping off the undesirable residue each time. After this procedure a total of only four tracks of range greater than 35 cm (i.e., passing through chamber), two of which were of doubtful origin, were observed as compared to 720 ending in the chamber due to C^{12}. Since the number of long range tracks was so small, no attempt was made to locate their range by introducing additional foils between the cloud chamber and target. The sample of CH_4 may still have contained about one percent of uncondensed gas, which probably was mostly nitrogen. Hence one or more of these few long range tracks could possibly be from nitrogen.

With a C^{13}/C^{12} abundance ratio of 0.156 in the enriched sample, it must be concluded that the yield from C^{13} is less than four percent of that for C^{12} at the present deuteron energy. This ratio is considerably smaller than that estimated by Pollard (30 percent) and by Bower and Burcham (10 percent) but in fair agreement with that given by Bennett, *et al.* However, Pollard worked at somewhat higher energy, where no doubt the excitation curve for the less probable reaction is steeper than for the C^{12} to C^{13} transition. But it is doubtful whether this difference can be so pronounced as to account for the high yield given, and it is likely that in his experiments the yield from $C^{12} \rightarrow C^{13}$ was underestimated.

In order to investigate the origin of the weak 70-cm group found with the first sample of enriched CH_4, tank nitrogen was put into the gas target cell at 8 cm pressure. Protons of 70 cm were again observed in somewhat greater numbers. Although nitrogen has not been investigated in detail, there is indication of a new group at a Q value of 5.9 Mev from that element. This weak group does not seem to be the one found by Holloway and Moore.[11]

PROTONS FROM NEON

Ordinary neon and neon enriched in the heavier isotope (Ne^{20}/Ne^{22} abundance ratio of 84/16) were bombarded in the gas target cell. Figure 1A shows the results with no absorption between the cloud chamber and target proper other than the basic, while Fig. 1B depicts the data taken with an additional 18-cm absorption in the form of aluminum foils. The first set of data just overlaps the second. In each figure the needed adjustment of one curve with respect to the other has been made so that the same total number of tracks is represented.

Figure 1C represents a combination of the data for the normal sample plotted on a scale of relative intensity of groups. In order to do this these two sets of data from Figs. 1A and 1B were joined so that the total number of tracks passing completely through the chamber with no additional absorption equaled the number ending in the chamber with the additional foils.

There are indications that the broad group of protons distributed about the maximum at 46 cm range is complex, and that it arises very largely from the Ne^{20} in both gas samples. The total number of tracks represented by the plots in Fig. 1B is large enough to guarantee that the irregularity and asymmetry on the high energy side of this group are real. This less intense group of protons on the high energy side has an extrapolated range of 54.2 cm while that of the more intense component comes at about 48.5 cm. This interval of roughly 0.44 Mev may well represent the doublet splitting of the ground state of the Ne^{21} nucleus formed in the reaction.

The Ne^{21} nucleus is also formed in the reaction $Na^{23}+H^2 \rightarrow Ne^{21}+He^4$ studied by Murrell and Smith.[12] It would be interesting to see whether the doublet structure of the ground state also appears here. However, their maximum energy group is somewhat overlapped by an oxygen group, and in addition the difference of 0.4 Mev would represent only a small difference in α-particle range. Hence it is difficult to say whether or not this doubling is present in their case.

Between 35 cm and 42 cm range there seem to be a number of weak proton groups, with one at 40 cm due to Ne^{22}. Also at about 30 cm range we observe a definite difference between the protons from ordinary neon and those from the neon enriched in the heavy isotope. Whereas there is an apparent doubling of the proton group at 30 cm with ordinary neon, the group appears single when the gas with the larger Ne^{22} content is bombarded. At about this range then there seems to be definitely a proton group resulting from the deuteron bombardment of Ne^{22}.

Associated with the doublet at 30.2 cm and 33.5 cm the Q values are 2.78 and 2.94 Mev, respectively. This is apparently the first excited state of Ne^{21}. As for the Ne^{23} resulting from the Ne^{22} bombardment, the proton group at 40 cm has a corrected extrapolated range of 41.5 cm which is a Q value of 3.5 Mev. The first excited state of Ne^{23} comes then at about 2.85 Mev, the mean of the values of the first excited state of the Ne^{21} nucleus.

These results with neon are in substantial agreement with those of Pollard and Watson[3] obtained by amplifier detecting methods. As already noted in this earlier work, the bombardment of Ne^{22} does not give rise to any strong proton groups, in agreement with the fact that the induced radioactivity of the resulting Ne^{23} is weak. It is evident that a considerably greater concentration of Ne^{22} is necessary in order to establish definitely the location of all the proton groups from this isotope.

We wish to thank Professor Ernest Pollard for much helpful advice and encouragement, and Dr. D. Rittenberg of Columbia University for the mass-spectrometer analysis giving the C^{13} enrichment.

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[12] E. B. M. Murrell and C. L. Smith, Proc. Roy. Soc. **173**, 410 (1939).