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Recoil Coincidence-Absorption Measurement of Neutron Spectra from the Reactions $A^{40}(d, n)$ and $N^{15}(d, n)$*

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A counter method offering a more convenient and flexible measurement of neutron energy in the medium to high energy range is further described. Experimental results obtained by the application of this method to the reactions $A^{40}(d, n)$ and $N^{15}(d, n)$ are given.

For the argon reaction, Q-values of 5.97, 4.63, 2.87, and 1.57 Mev were observed. The $K^{41}-A^{40}$ mass difference was thus observed to be 0.99936±0.00027 MU.

For the nitrogen reaction, Q-values of 10.9, 4.8, 1.6, and 0.2 Mev were observed, the last value being in some doubt.

I. INTRODUCTION

THE results described in this paper were obtained using a recoil coincidence absorption technique, previously outlined,[1] in which the extrapolated ranges of recoil protons were measured. The recoils originate from the impingement of neutrons upon the hydrogen filling of the first of two proportional counters in coincidence. The two counters were separated so that variable amounts of absorption may be inserted for the purpose of determining the ranges of various proton groups. The use of coincidence counting insures that the recoils originate inside the first counter, and in addition greatly reduces the background counting rate.

This coincidence-absorption approach was undertaken because of the greater ease of collecting data as compared with the photographic emulsion and cloud-chamber measurements of neutron energy, and also because of the desirability of comparing the resolution with that of these methods. It was not believed that the coincidence-absorption technique was capable of greater accuracy than the cloud chamber of photographic emulsion approach at *medium* energies, but rather that it would be more flexible and much more rapid in the study of *high* energies and might prove to have inherently as good resolution in this energy region.

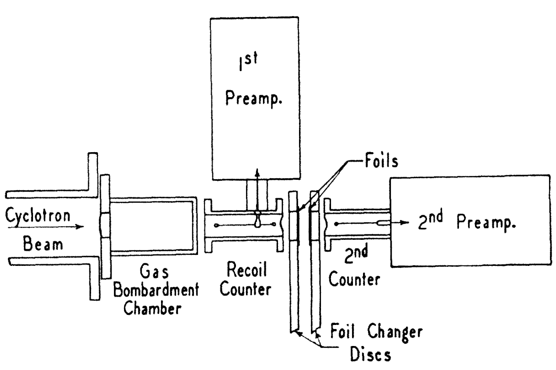

FIG. 1. Schematic diagram of the arrangement of counters, bombardment chamber, and foil changer.

II. THE EQUIPMENT

The physical arrangement of the counters, foil changer and target is shown in Fig. 1. The gas bombardment chamber may be seen just beyond the cyclotron vacuum gate port, and is shown in detail in Fig. 2. The chamber is offset so as most effectively to intercept the beam. Unfortunately aluminum foil could not be used since it gives a relatively large neutron yield and some low neutron-yield substance such as gold was required. This posed the additional problem of measuring the absorption inserted in the path of the beam, but by means of range data taken with an evacuated Faraday cage, this foil was determined to be 3.29 cm air equivalent. Thus the foil lowered the extrapolated energy of the transmitted beam from 3.92 Mev to 3.20 Mev. The foil required a double supporting grid over the bombarded area of slightly more than an inch. As an added precaution, a piece of gold foil (9 cm air equivalent) was fastened to the inside end of the chamber to prevent any yield from the brass at this solid angle-favored position. Actually, for the low bombarding energy used this was not necessary. The distance from the center of the grid to the end of the chamber was 6.5 cm.

With regard to the counters, the first (recoil source) was 8 cm long, was filled with hydrogen at a pressure of about 30 cm Hg, and was operated at a potential of about 1500 volts. The second was filled with hydrogen at 15 cm pressure, operated at about 1100 volts, and

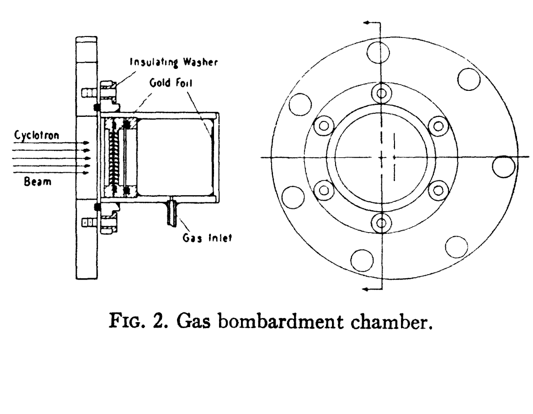

FIG. 2. Gas bombardment chamber.

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[1] D. C. Worth, Phys. Rev. 75, 903 (1949).

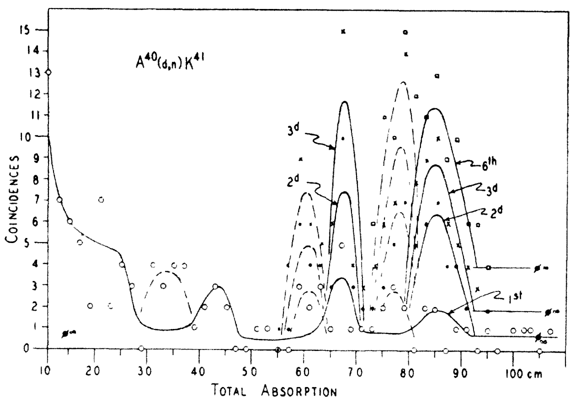

FIG. 3. Complete proton recoil spectrum from the bombardment A^{40} by 3.2-Mev deuterons. Numbers refer to successive runs on the long range groups.

had an average effective counter depth of 1.5 cm. Both counters had 0.005-in. tungsten center wires and 1-inch brass cathodes, with the center wire of each kept at a high potential above ground. (D.c. blocking condensers served to introduce the count pulses to the preamplifiers.) The reason for using hydrogen in the second counter was to reduce the number of elastic recoil counts by reason of the smaller scattering cross section over that of a conventional filling, e.g., argon. As shown in the original sketch, there was for some time a foil at the cyclotron end of the first counter in order to obtain test coincidences; but it later developed that extraneous groups were observed because of recoils from grease layers outside this foil. The two counters were so spaced that the air gap between the foils was 1.9 cm, while the separation between the end of bombardment chamber and the inside front of the first counter was 7 mm.

The remainder of the counting equipment has been outlined previously. Of prime importance to this experiment is the coincidence circuit, particularly the feature of adjustable counting levels by means of a diode discriminator, since the proper setting of counting levels is necessary in order to obtain meaningful data. In general, the higher the background level (due to accidental coincidences between the two channels), the less "peaked" is the counting. However, the background must not be so high as to worsen the relative statistics between true counts and accidentals. For "peaked" operation, the first channel counting rate was some three times that in the second—group structure would be seen even more clearly with a higher degree of peaking (higher bias, smaller counting rate) in the second channel, but this would impair the statistics even further. In the present work the largest beam current that could reliably be obtained from the cyclotron was 0.5 μa (and sometimes less) so that this put a limitation on both the peaking and the statistics. The usual resolution time employed in the coincidence circuit was 2.5×10^{-7} sec.

TABLE I. Observed extrapolated group ranges and corresponding energies for the $A^{40}(d, n)K^{41}$ reaction.

Observed extrap. range	Corrected extrap. range	Extrap. recoil energy
29 cm	29.5 cm	4.74 Mev
46	47.3	6.06
71	73.5	7.82
94	97.8	9.15

Normalization of the observed coincidence counting rate by means either of the first channel counting rate or of the integrated beam current is satisfactory. The data presented here involved the use of the beam current integrator.

As may be seen from the various dimensions given, the geometry was hardly ideal and is difficult to evaluate. This condition was imposed by the small beam currents available. The spread in recoil energy allowed over the average angular aperture from scatterer to second counter (half-angle of 10° 17′) is 3.2 percent and this uncertainty predominates over errors arising from beam inhomogeneity as well as range and angle straggling.

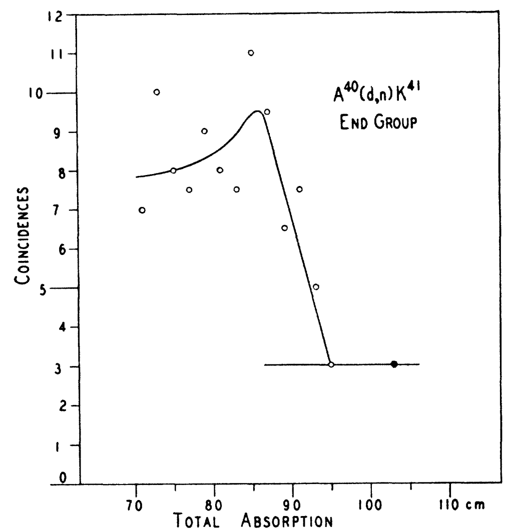

FIG. 4. Unpeaked curve of the end group yield from argon.

III. EXPERIMENTAL RESULTS

A. Bombardment of Argon

In this experiment, tank argon was bombarded by 3.2-Mev deuterons. The principal reason for the choice

TABLE II. Summary of Q-values and excitations observed in the $A^{40}(d, n)K^{41}$ reaction.

Level	Q-value (Mev)	Total excitation (Mev)	Level spacing (Mev)
Ground	5.97±0.25	0	
			1.34
1st excited	4.63±0.20	1.34±0.15	
			1.76
2nd excited	2.87	3.10	
			1.30
3rd excited	1.57	4.40	

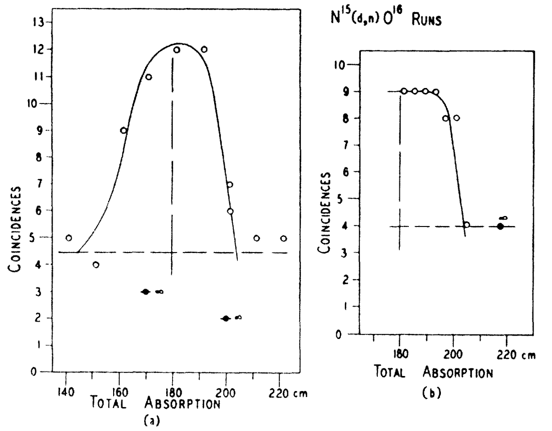

FIG. 5. Long range recoil yield from the bombardment of N^{15} by 3.2-Mev deuterons. Curve (*a*) is peaked, curve (*b*) unpeaked.

of argon was that the energy levels of K^{41} are of interest because of recent work in this region of the periodic table. The (d, n) reaction has not previously been reported. Furthermore, Sailor had noticed an unusually high background yield in his proton study of deuteron-bombarded argon,[2] and it was felt that this indicated a fairly high neutron yield, particularly in view of the high atomic number involved. As it turned out, however, most of this high yield was associated with the short range groups and the outer range groups were much smaller in magnitude.

Despite this relatively high neutron yield, the various factors which militate against coincidence yield (low beam intensity, successive solid angles, small scattering efficiency, and peaking) reduced it to the order of a few counts per minute. In order to obtain any accuracy in the results, long counting periods were necessary. In fact, it was most convenient to make a series of four-minute-count runs, adding the statistics for each absorption point so that the last two groups observed might be seen to emerge progressively from background. Actually, this is a rigorous test, since if the counts observed as a slight peak in one run were of spurious origin, subsequent runs would show a cancellation of this peak. A plot of the original survey run and the successive long range runs is shown in Fig. 3, and an unpeaked curve of the end group is shown in Fig. 4.

In Fig. 3, the dotted groups represent those which are believed to originate from external grease layers, as mentioned above. This conclusion has been reached by noting a constant range difference from each of the real groups, this difference corresponding to the absorption of the entrance foil. Note that the agreement in the extrapolated range of the end group in the peaked and unpeaked runs is satisfactory.

A rather thick target (4 cm air equivalent) was used because of yield considerations. The basic absorption was 11.3 cm, of which 9.5 cm was aluminum, 0.7 cm was the maximum absorption in the recoil counter, and 0.2 cm was the absorption in the second counter corresponding to the correct counter depth (argon gas was used in this counter at this particular time). Observed ranges are listed in Table I.

Substituting these values of the extrapolated recoil energy (hence that of incident neutrons) in the well-known Q-equation, one obtains the results of Table II.

Only one determination of any energy level of K^{41} previously reported.[3] Bleuler *et al.* found from their studies of the beta-decay of A^{41} that the excitation of the first level in K^{41} is 1.37 Mev, a value in good agreement with the above determination.

These results indicate the mass difference $K^{41}-A^{40}$ to be 0.99936 ± 0.00027 MU in agreement, just within the experimental error, with the value 0.99976 ± 0.00020 MU predicted from the best values for the $K^{41}-A^{41}$ and $A^{41}-A^{40}$ mass differences.[4]

B. Bombardment of N^{15}

At the time that this work was undertaken, no report of such studies had been published. Recently the results of photographic emulsion study of this reaction have been reported.[5]

Ammonia gas, enriched to 61.5 percent in N^{15}, was formed from enriched ammonium nitrate[6] by mixing the nitrate with concentrated sodium hydroxide solution in an evacuated generating system.[7] The gas was then water dried by passing it through pulverized potassium hydroxide, and condensed in a Toepler pump

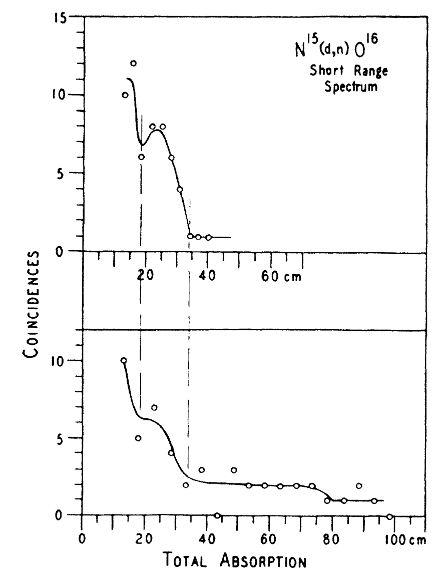

FIG. 6. Short range recoil yield from N^{15}.

[2] V. L. Sailor, Phys. Rev. 75, 1836 (1949).

[3] Bleuler, Bollman, and Zunti, Helv. Phys. Acta 19, 419 (1946).

[4] I am indebted to V. L. Sailor for these values derived from his studies of this section of the periodic table.

[5] E. L. Hudspeth and C. P. Swann, Phys. Rev. 76, 464 (1949).

[6] Obtained from Eastman Kodak Company, Rochester, New York.

[7] Built jointly by L. D. Wyly and the author.

TABLE III. Observed extrapolated group ranges and corresponding energies for the $N^{15}(d, n)O^{16}$ reaction.

Observed extrap. range	Corrected extrap. range	Extrap. recoil energy
19 cm	19.0 cm	3.58 Mev
33	33.5	4.96
78	80.7	8.20
204	216	14.2

filling system by the use of liquid aid. The final target was about 3.5-cm air equivalent thickness, and the rest of the arrangement was the same as for the argon bombardment.

The long range end group is shown in Fig. 5 (curve *a*), while an unpeaked curve is shown in Fig. 5 (curve *b*). The latter plot is the sum of two successive runs. Note that these plots cover the absorption region beyond 140 cm air equivalent. Figure 6 shows two runs (taken a month apart) on the short range region from 13 cm to 98 cm. The unplotted region from 100 cm to 140 cm exhibited no counts above background. The uncorrected extrapolated ranges that seem to be indicated are: 19, 33, 78, and 204 cm. The corrected ranges and recoil energies are given in Table III.

On the assumption all the groups are due to the $N^{15}(d, n)$ reaction, the Q-values found are given in Table IV.

The 33-cm group cannot be due to deuterium contamination, and does not seem to be due to $N^{14}(d, n)$. This level may be the one recently suggested by Hudspeth and Swann;[5] the 19-cm group represents a possible unreported level. Note that the observed excitation of the first level is in agreement with the value determined by $F^{19}(p, \alpha)$ observation.[8]

Fairly conservative experimental errors are assigned to these Q-values because of the rather poor statistics and the indeterminancy of geometric corrections. Particularly in the case of the long range group there is a question about the reliability of present range-energy data.

IV. COMMENTS ON THE METHOD

The results obtained are gratifying, considering the early stage of development of this technique, and seem to indicate the value of its further exploitation. As employed, the method allowed data to be gathered in a few hours. When the second counter is at low bias, there is no impairment of the statistics with increasing neutron energies such as is caused in other methods by a decreasing angular aperture in which the longer recoil tracks must end. There is a worsening of the statistics due to the decreasing neutron-proton scattering cross section, but this is common to all recoil methods. The flexibility of the technique may be seen in that the particular arrangement allowed observation of neutron energies from 1.5 Mev to nearly 15 Mev. End group yield can be increased at the expense of excited state resolution by using high gas pressure or a polystyrene radiator in the first counter.

TABLE IV. Summary of Q-values and excitations observed in the $N^{15}(d, n)O^{16}$ reaction.

	Q-value (Mev)	Total excitation (Mev)	Level spacing (Mev)
Ground	10.9±0.5	0	
			6.1
1st excited	4.8±0.3	6.1±0.3	
			3.2
2nd excited	1.55	9.3	
			1.4
3rd excited	0.19	10.7	

Of course, there are various factors which make application of this technique difficult. Foremost among these is the very low scattering efficiency compatible with low recoil absorption by the scattering medium. (Here the counting rate was lowered by a factor of 10^5 below that of charged particle counting due to the necessity of using the intermediate elastic collision process.) In order to have good geometry and to overcome the impairment of the statistics just mentioned, it is necessary to have a fairly intense ion beam. Furthermore, faster counters and coincidence circuit would help to reduce the relative number of accidental coincidences, and thus improve the statistics by allowing higher counting rates.

The author is happy to express his gratitude to Professor E. C. Pollard, who suggested this problem, for his helpful advice and encouragement.

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[8] Lauritsen, Lauritsen, and Fowler, Phys. Rev. **59**, 241 (1941).