$O^{16}(d,n)F^{17}$ and $Ca^{40}(d,n)Sc^{41}$ Reactions by Time of Flight

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A modified time-of-flight spectrometer has been used to check and correct results previously reported for the $O^{16}(d,n)F^{17}$ reaction and to determine the Q values of four low-lying states in Sc^{41} by means of the $Ca^{40}(d,n)Sc^{41}$ reaction. The "overlap" method of measuring the energies of neutrons is described.

I. INTRODUCTION

THE measurement of spectra and angular distributions for (d,n) and other neutron producing reactions are becoming increasingly important in nuclear spectroscopic studies, permitting, as they do, the study of levels not easily reached by other reactions. To date the most precise measurements of neutron energies in the region 1 to 15 MeV have been made using time-of-flight techniques. A time-of-flight spectrometer, described[1] previously, has been modified to permit spectra and angular distribution to be measured with a precision in energy and an operational convenience which approaches that of charged-particle spectrometers.

The instrument has been used to check and correct the results previously reported[1] for the $O^{16}(d,n)F^{17}$ reaction, and to determine the Q values of four low-lying states in Sc^{41} by means of the $Ca^{40}(d,n)Sc^{41}$ reaction. The measurements were made at scattering angles of 4° and 26°.

II. INSTRUMENTATION

The spectrometer, which utilizes the natural phase bunching of particles in the cyclotron, has been modified by replacing the beam pulser with an rf beam gate, and replacing the chronotron timing unit with a time-to-pulse height converter and a multichannel analyzer system. A block diagram of the apparatus is shown in Fig. 1.

The 7.7 MeV deuteron beam extracted from the University of Michigan 42-in. cyclotron consists of pulses of approximately 4 nsec (4×10^{-9} sec) width at half-maximum spaced by 99 nsec corresponding to the cyclotron rf frequency of $f_0=10.1$ Mc/sec. The period of the pulses striking the target is increased by a factor of four by applying to a pair of deflection plates a voltage of frequency $f_0/4$, synchronized with the cyclotron rf. In normal operation, without time of flight the deflection plates are used with a negative bias of approximately 10 kV to steer the beam to the target location. When used with the beam gate, a 6 kV bias of opposite polarity is applied together with the rf voltage as illustrated in Fig. 2. The rf voltage is accurately locked to the cyclotron rf through a scale-of-four frequency divider. The scaled-down signal is passed through a variable delay line to the power amplifier which drives the deflection plates. The phase of the gate with respect to the cyclotron rf can be varied by means of the delay line so that only one beam pulse in four, that labeled "D" in Fig. 2, is transmitted. A low-capacitance probe located directly behind the target permits observation of the individual pulses on an oscilloscope, and is used when adjusting the phase.

Pulses of deuterons transmitted by the gate strike the target in the scattering chamber located as shown in the floor plan of Fig. 3. The liquid-scintillation detector has been described previously.[1]

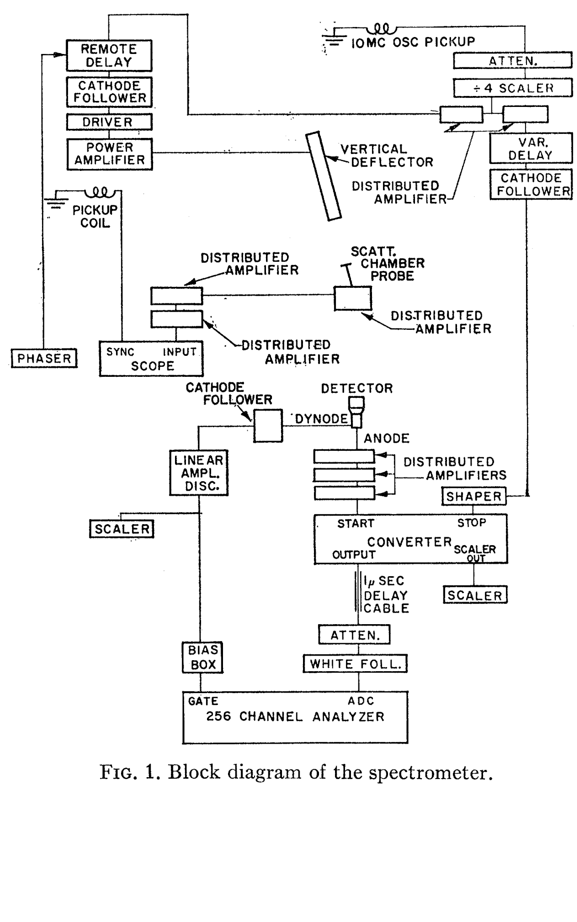

FIG. 1. Block diagram of the spectrometer.

[1] R. Grismore and W. C. Parkinson, Rev. Sci. Instr. 28, 245 (1957).

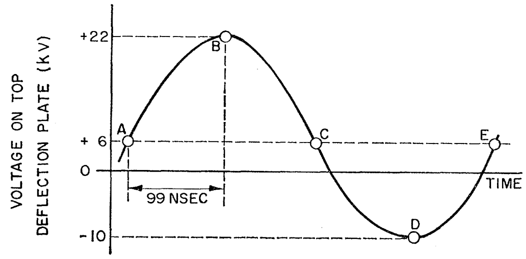

FIG. 2. Illustrating the operation of the rf beam gate. The beam pulses are shown as circles labeled A through E. Only pulse D is transmitted.

As in the Los Alamos timing scheme[2] a reference signal derived from the cyclotron rf is used as the "stop" pulse for the time-to-pulse-height converter; the "start" pulse is the amplified detector pulse. Thus, a pulse is obtained from the converter only when a neutron or gamma ray is detected. The "stop" pulse is taken from the output of the high-speed gate scaler, amplified, and coupled to the timing unit through a 0-500 nsec variable delay. The delay line provides a convenient means of adjusting the "zero-time" point on the time spectrum. Since the flight time is not measured directly, but rather is determined from the difference between the flight time and the period of the rf gate, it is essential that the deuteron pulses be stable with respect to the "stop" pulse. The time jitter between the deuteron pulses and the stop pulse was estimated to be less than 2 nsec by observation of the beam pulse signal on a fast oscilloscope triggered by the cyclotron rf. Since the natural width of the deuteron pulses is 4–5 nsec the resolution is not significantly reduced by using this "backward" timing system.

The time jitter associated with amplitude discrimination of the detector pulse "start" channel is minimized by the use of side-channel discrimination. The 256-channel analyzer used to record the output of the time-to-pulse-height converter is gated "on" only when the pulse appearing on the last dynode of the detector photomultiplier is of sufficient amplitude to insure that the anode signal will clear the fast discriminator by several volts.

The over-all resolution of the present system is 5–7 nsec as determined by the full-width at half-maximum of the prompt gamma-ray peak. This is consistent with the width of the deuteron pulse being about 4 nsec as measured previously with the chronotron.[1]

III. DETERMINATION OF NEUTRON ENERGY

In the time-of-flight technique, high resolution in energy dictates long flight paths, and a major limitation on the determination of the neutron energy is the precision with which long flight times can be measured. The necessity of measuring long time intervals has been eliminated by using the "overlap" of neutrons from one target pulse with the prompt gamma rays from a succeeding pulse. Good accuracy is obtained because the frequency of the beam pulses can be determined with high precision. Generally, there is also an overlap of lower energy neutrons from one beam pulse, and higher energy neutrons from the next, but any ambiguity can be resolved by observing the time-shift of each neutron group with changes in the path length.

By adjusting the length of the flight path, a neutron group of arbitrary energy may be made to fall in virtual coincidence with a prompt gamma ray from a succeeding beam pulse. Since, in this case, the two peaks would be indistinguishable, in practice two different flight paths are used, one slightly shorter and one slightly longer than the coincident length, so that the neutron is detected slightly before and slightly after the gamma ray, respectively. The length corresponding to exact overlap may then be determined by linear interpolation. The neutron flight time is then exactly equal to an integral number of beam-pulse periods plus the gamma flight time, and can, therefore, be determined with high accuracy. The principal uncertainty is in the determination of the coincident path length.

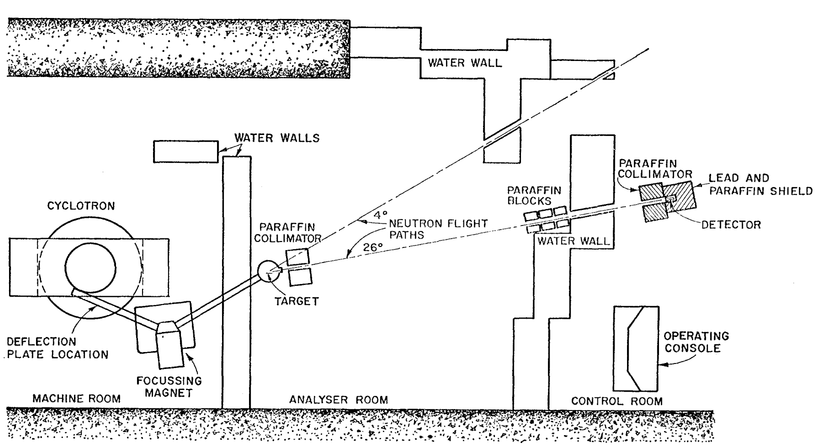

FIG. 3. Floor plan of experimental facility. Flight paths up to 14 m are provided at angles of 4° and 26°.

[2] W. Weber, C. W. Johnstone, and L. Cranberg, Rev. Sci. Instr. 27, 166 (1956).

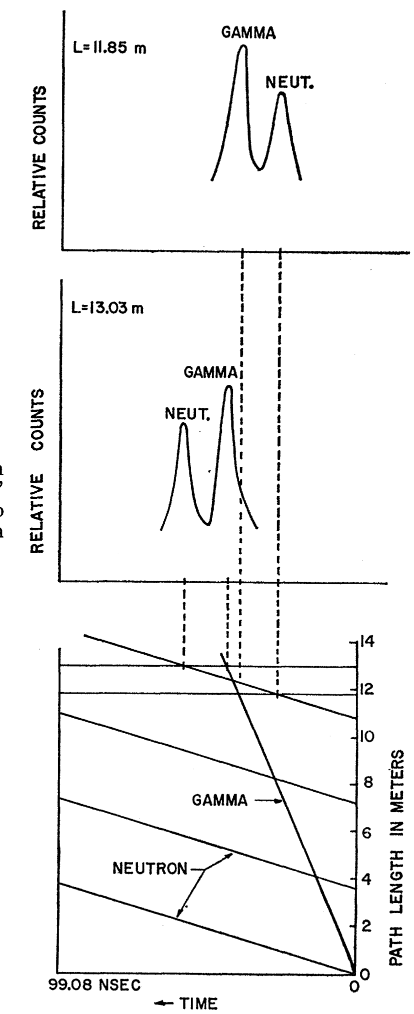

FIG. 4. Illustration of the "overlap" technique used to measure neutron energies.

In some cases the neutron energies were such, that coincidence with the first group of delayed gamma rays occurred at an inconvenient path length. For these the nongated 10 Mc/sec pulses were used, and coincidence arranged with a gamma peak delayed a convenient number of periods.

The "overlap" technique using the nongated pulses is illustrated in Fig. 4 for the ground-state group from the $C^{12}(d,n)N^{13}$ reaction. The neutron and gamma-ray flight times are plotted as a function of path length in the lower part of the figure. The time scale corresponds to one period of the beam pulse, about 99 nsec. Since neutron flight times differing by an integral number of periods are indistinguishable, all are reduced to the same cycle by subtracting the largest integral number of periods in the actual flight time. Flight paths of approximately 4.1, 8.3, and 12.4 m result in flight times for the neutron apparently equal to the first, second, and and third overlap gamma rays, respectively. The time-of-flight spectra in the upper part of the figure are for two path lengths chosen to bracket the value expected to give coincidence with the third overlap gamma, as indicated by the horizontal lines on the bottom diagram. From the spacings of the peaks in the two spectra, the interpolated coincidence path length is determined to be $12.45\pm.01$ m, leading to a neutron energy of $7.12\pm.02$ MeV.

IV. EXPERIMENTAL RESULTS

Since considerable information is available[3] for the $C^{12}(d,n)N^{13}$ reaction, it was used as a check on the performance of the spectrometer. The data obtained at scattering angles of 4° and 26° are shown in Fig. 5.

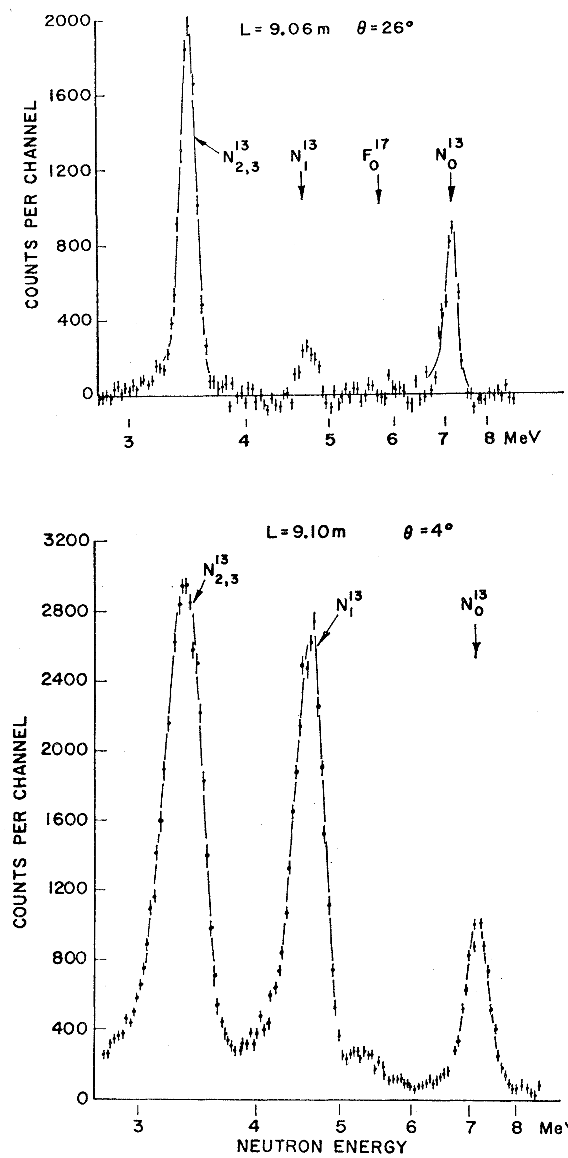

FIG. 5. Neutron spectra from deuteron bombardment of a carbon target.

[3] F. Ajzenberg and T. Lauritsen, Nucl. Phys. 11, 155 (1959).

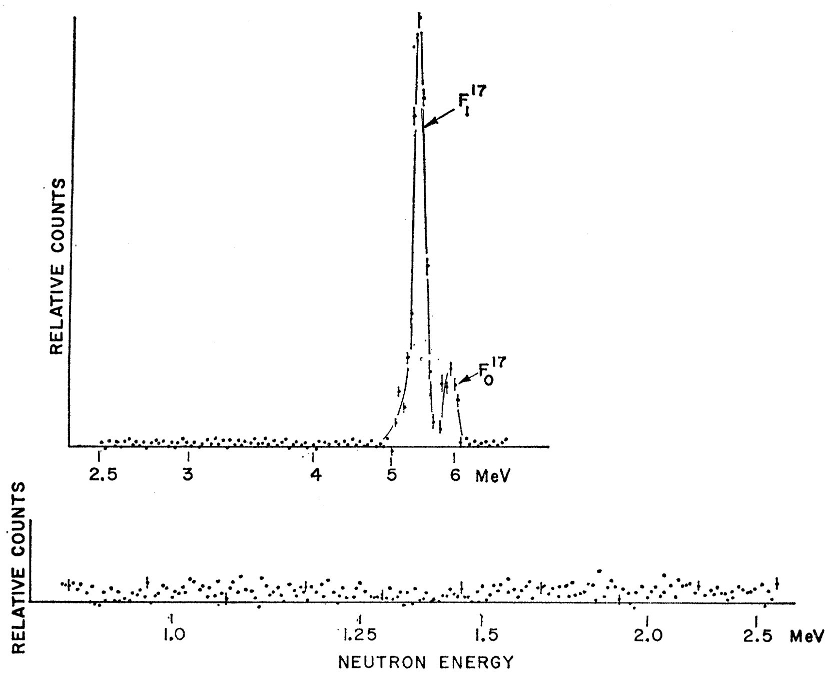

FIG. 6. Neutron spectrum obtained at a scattering angle of 4° from deuteron bombardment of a WO_3 target.

Carbon targets were prepared by collecting lampblack from a kerosene flame on gold-leaf backing. The data have been corrected for background by substituting plain gold leaf for the target. Neutron groups corresponding to all previously reported states in N^{13} which can be excited with a deuteron energy of 7.7 MeV are observed, and no evidence was found for any new groups down to the instrumental threshold of about 1 MeV neutron energy, corresponding to an excitation of about 5.7 MeV in N^{13}. The excitation of the centroid of the unresolved $N_{2,3}^{13}$ neutron groups (the second and third groups observed above the ground state) was determined to be $3.58\pm.02$ MeV.

The only reported observation of neutron groups in the $O^{16}(d,n)F^{17}$ reaction corresponding to states in F^{17} other than the ground and first excited (0.50 MeV) states was that made using the original version of this spectrometer.[1] Since the level structure of F^{17} is of considerable interest, the reaction was re-examined with special emphasis on detecting neutron groups from levels of higher excitation. Targets were prepared by evaporating tungsten trioxide (WO_3) on 0.1-mil gold foil to thicknesses from 10–50 keV energy loss for 7.7-MeV deuterons. A composite of the data obtained at several path lengths for scattering angles of 4° and 26° is shown in Figs. 6 and 7. Each spectrum consists of a low- and a high-energy range corresponding to detector biases of approximately 0.5 and 1.5 MeV, respectively. The low-energy ranges show the increased statistical uncertainty introduced by the larger background at low-detector pulse heights. Only two neutron groups corresponding to the ground and 0.50 MeV levels in F^{17} were observed in the large number of spectra taken under a wide variety of detector conditions, path lengths, and targets.

The time-of-flight spectra obtained at scattering angles of 4° and 26° for the $Ca^{40}(d,n)Sc^{41}$ reaction using targets of natural calcium evaporated on gold foil are shown in Fig. 8. The widths of the 0, 1.74, and 2.46 MeV groups are consistent with that expected from the instrumental resolution. The group corresponding to an excitation of 3.41 MeV in Sc^{41}, however, has a significantly larger width. Some of the data suggests that this group consists of more than one level. The groups labeled F^{17} are due to oxidation of the calcium and were minimized by preparing fresh targets immediately before each measurement. The Q values of the four groups listed in Table I were calculated assuming a Q of -0.286 MeV[3] for the $C^{12}(d,n)N_0^{13}$ neutron group which was used to calibrate the energy of the deuteron beam.

TABLE I. Comparison of measured Q-values for $Ca^{40}(d,n)Sc^{41}$.

Sc^{41} excitation energy (MeV)	Wegner and Hall[a]	Macefield *et al.*[b]	Present authors	Plendl and Steigert[c]
0	-1.32 ± 0.07	-1.145 ± 0.015	-1.11 ± 0.03	-0.57
1.74	-2.85 ± 0.03	-2.854 ± 0.035	-2.86 ± 0.02	-2.43
2.46		-3.621 ± 0.035	-3.57 ± 0.03	-2.64
3.41			-4.53 ± 0.04	-2.85

[a] H. E. Wegner and W. S. Hall, Phys. Rev. **119**, 1654 (1960).
[b] B. E. F. Macefield, J. H. Towle, and W. B. Gilboy, Proc. Phys. Soc. (London) **A77**, 1050 (1961).
[c] H. S. Plendl and F. E. Steigert, Phys. Rev. **116**, 1534 (1959).

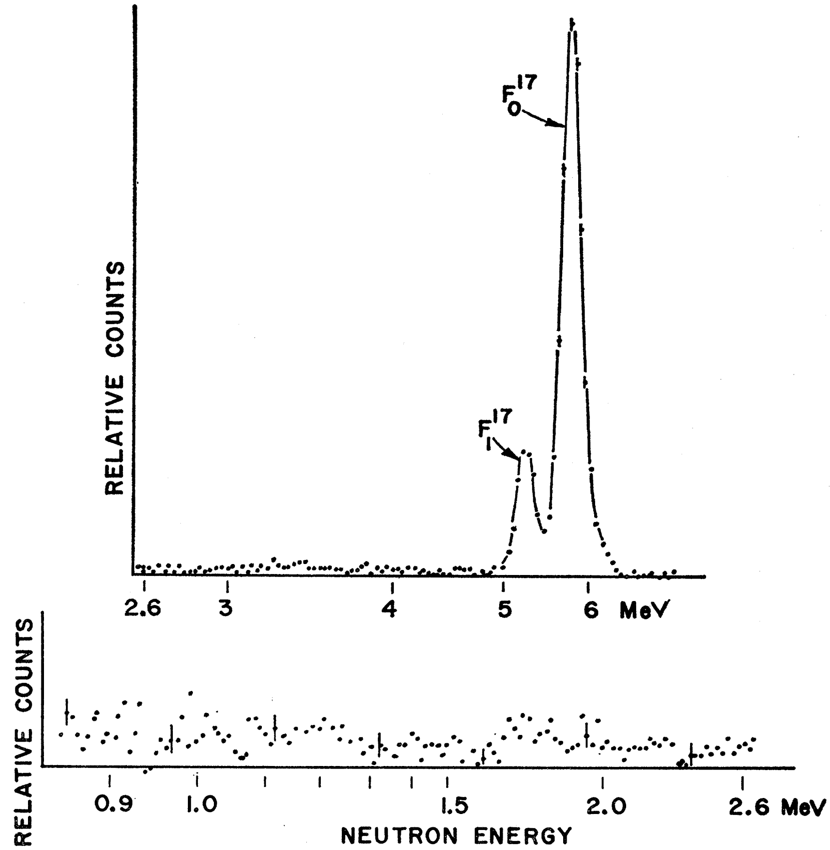

FIG. 7. Neutron spectrum obtained at a scattering angle of 26° from deuteron bombardment of a WO_3 target.

V. DISCUSSION

The gamma ray "overlap" method has permitted the measurement of neutron energies up to 7 MeV with an uncertainty as low as 20 keV. The method is particularly suited for the measurement of strong and well-separated groups. The time resolution of the instrument, approximately 6 nsec, corresponds to an energy resolution of 100 keV at 4 MeV for a path length of 14 m. A serious limitation in the use of the present instrument is the magnitude of the cyclotron-associated background which puts a limit on the intensity of the neutron groups that can be detected reliably. The sharp rise in background at low-detector biases prevents the measurement of neutrons of energies below about 1 MeV. This limitation will largely be removed because of the better shielding available when the cyclotron is moved to a new building in the near future.

The excitation energy determined for the unresolved $N_{2,3}^{13}$ neutron group is in good agreement with the accepted value[3] for the N_3^{13} level, which is believed to have a much larger stripping cross section than the N_2^{13} level. This, together with the fact that the observed relative intensities of the three neutron groups are in agreement with published results,[4] was taken as an indication of the proper performance of the instrument during the initial stages of its use.

The most significant feature of the F^{17} data is the absence of positive indications of neutron groups corresponding to levels above the ground and first excited (0.50 MeV) states. There is no evidence in support of the level previously reported[1] at 3.03 MeV. A group with a relative intensity one-tenth that reported should have been observed in the present measurements. The discrepancy is particularly striking since a strong neutron group from the $C^{12}(d,n)N^{13}$ reaction, located only 800 keV higher in neutron energy is observed in both the earlier work and in the present measurements. There is also no evidence for the level reported at 4.74 MeV excitation, although at this low neutron energy, only very intense groups would have been detected. The much greater beam intensities available and automatic data recording, together with a careful calibration of the energy response of the detector, contribute to the confidence in the reliability of the present results.

The Q values for the four neutron groups observed in the $Ca^{40}(d,n)Sc^{41}$ reaction are shown in Table I together with previously reported data. With the exception of the results shown in the last column the values are in good agreement. The group with $Q=-4.53$ MeV has not

[4] J. M. Calvert, A. A. Jaffe, and E. E. Maslin, Proc. Phys. Soc. (London) **A70**, 78 (1957).

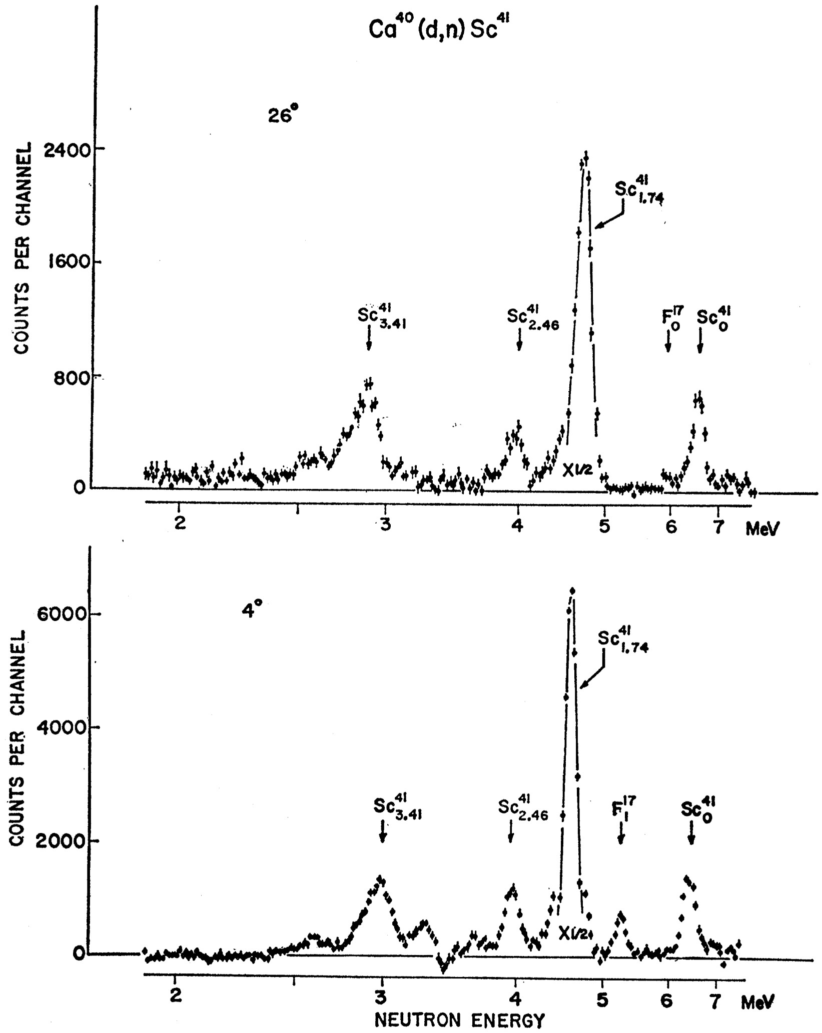

FIG. 8. Neutron spectra from deuteron bombardment of a natural calcium target.

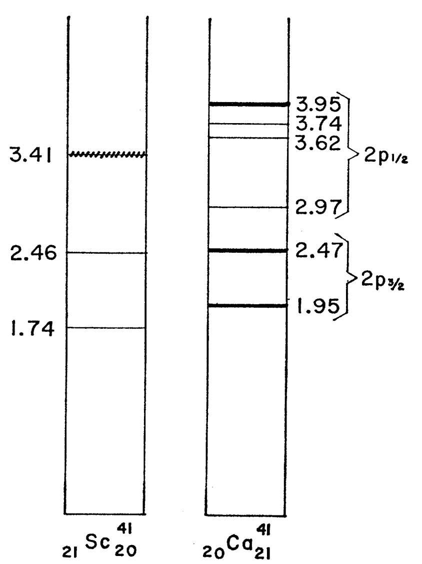

FIG. 9. The energy level diagrams of Sc^{41} and Ca^{41}. Weak levels are omitted.

been previously reported. The measured ground state Q is in good agreement with recent changes[5] in the accepted value of the mass of Sc^{41}.

The levels determined in Sc^{41} are compared with the strong levels[6] of Ca^{41} in Fig. 9. While little can be said directly about the spectroscopic nature of the levels in Sc^{41}, a comparison of the energies and relative intensities suggests that the 1.74 MeV level in Sc^{41} is a $2p_{3/2}$ state, and 3.41 level a $2p_{1/2}$ state.

ACKNOWLEDGMENTS

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[5] J. W. Butler, Phys. Rev. **123**, 873 (1961).

[6] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).