3% resolution folded in. It is clear that the tail of the μ spectrum follows very closely, and the probability for finding an event in the π-e region is very small. This is further demonstrated in Fig. 3. Figure 3 exhibits the spectrum of 3000 events measured for the purpose of a ρ-value determination. They are events with the normal π-μ-e sequence (see Fig. 3), and therefore, no π-e decays are expected. The fact that no high-energy events are found in this larger sample demonstrates that the μ-e contamination in the high-energy region is negligible.

We have also considered the possibility that the events are decays in flight of μ mesons, or perhaps π-μ decays in flight. These possibilities can be ruled out on kinematic grounds for each of the 6 events. We conclude that each event is a clear example of π-e decay.

The average energy for the 6 events is 72.9 ± 1.5 Mev. This is higher than the expected energy of 69.8 Mev. We have taken great care in the systematics of the energy measurement and are quite certain that this cannot be the cause. We are perplexed by the discrepancy and tentatively ascribe it to a statistical fluctuation in the measurement errors.

The relative rate of π-e decay is 6/65 000 or $1/10\,800 \pm 40\%$. This is unfortunately statistically poor, but serves to indicate that the decay is at least roughly as expected theoretically.

The method does not yield a precise measurement of the branching ratio and cannot reasonably be extended to do so. However, the results here offer a very convincing proof of the existence of this decay mode, and show that the relative rate is close to that expected theoretically.

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NEUTRON THRESHOLD MEASUREMENTS USING THE CHALK RIVER TANDEM VAN DE GRAAFF ACCELERATOR*

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As part of the program to test the operating characteristics of the first Tandem Van de Graaff accelerator,[1] a number of neutron threshold measurements were made in the proton energy range from 1.8 to 10.5 Mev. Three of these, $P^{31}(p,n)$, $Ni^{60}(p,n)$, and $Ni^{58}(p,n)$, all above 6.4 Mev, had not been measured previously. Over the complete energy range proton beams of 0.5 microampere or greater were available and the accelerator operated in a stable and reproducible fashion.

A momentum calibration of the 90° energy analyzing magnet was obtained by measuring a number of well known neutron thresholds using the conventional counter ratio technique.[2] The two neutron detectors were enriched B^{10} loaded scintillators[3] optically coupled by Lucite light pipes to 3 in. diameter photomultipliers. A cylinder of paraffin of suitable geometry surrounded the second detector to ensure uniform response to fast neutrons.

In a series of measurements carried out prior to final accelerator adjustments, the $Li^7(p,n)$, $Cu^{65}(p,n)$, $B^{11}(p,n)$, and $Al^{27}(p,n)$ thresholds[4] were used to calibrate the magnet momentum scale. With this calibration, thresholds for the $P^{31}(p,n)$ and $Ni^{60}(p,n)$ reactions were measured.

The first three lines of Table I list the (p,n) reactions used to calibrate the magnet in a second series of measurements carried out under improved operating conditions. To calibrate the magnet for particle momenta equivalent to higher proton energies, oxygen gas was supplied to the ion source. The threshold for the reaction $H^2(O^{16},n)F^{17}$ was observed by bombarding a deuterated zirconium target with O^{16} ions of charge +4 and +5. This threshold was computed to be 14.750 ± 0.024 Mev using the

Table I. Threshold measurements for $Ni^{60}(p,n)$ and $Ni^{58}(p,n)$ using the relationship given below between particle energy and proton resonance frequency of the 90° analyzing magnet field. In the equation q is the number of electrons the neutral particle has lost and M is the ion mass in amu.

Reaction	Threshold energy E (Mev)	Proton resonance frequency f (Mc/sec)	$k \times 10^5$
$B^{11}(p,n)$	3.015 ± 0.003	12.322 ± 0.003	2004 ± 2
$Na^{23}(p,n)$	5.061 ± 0.007	15.950 ± 0.020	2010 ± 4
$Al^{27}(p,n)$	5.798 ± 0.005	17.080 ± 0.010	2009 ± 4
$H^2(O_{+5}^{16},n)$	14.570 ± 0.024	21.555 ± 0.020	2008 ± 5
$H^2(O_{+4}^{16},n)$	14.570 ± 0.024	26.940 ± 0.020	2008 ± 6
		Average	2008 ± 2
$Ni^{60}(p,n)$	7.028 ± 0.020	18.814 ± 0.010	$k \times 10^5$ = 2008 ± 2 (assumed)
$Ni^{58}(p,n)$	9.459 ± 0.070	21.840 ± 0.080	

$$E(1 + E/2Mc^2) = kf^2q^2/M$$

value of 1.836 ± 0.003 Mev for the $O^{16}(d,n)$ threshold[4] and the masses of Mattauch et al.[5] The equation relating ion kinetic energy and the frequency of a proton resonance probe used to measure the field of the 90° magnet is given in Table I. The charge-four and -five O^{16} beams provided magnet calibrations near 14.47- and 9.33-Mev equivalent proton energies, respectively, and the experimental results are shown in Fig. 1.

Because of the large center-of-mass energy, neutrons in this reaction are emitted at threshold with an energy of about 700 kev in a narrow forward cone whose half angle is only 7° at 100 kev above threshold. The fast-neutron detector alone was used at 0° at two different distances. Near threshold the counting rates are nearly equal at the two distances. As the energy above threshold increases, the counts detected at the larger distance diminish because the counter no longer includes the whole cone. It has been suggested that the background below threshold could possibly be due to the $H^2(d,n)He^3$ reaction initiated by knock-on deuterons produced by the incident O^{16} ions.[6]

As can be seen from Table I, the magnet constant k shows no indication of a variation with proton energy between 3 and 14 Mev. The listed errors for each value of k arise from the combined uncertainty in the threshold energy[4] and the uncertainty in estimating the frequency at which the threshold occurs.

A typical run for the $Al^{27}(p,n)$ reaction using a thin aluminum target evaporated on a bismuth backing is shown in Fig. 2. The aluminum target thickness was 6.5 kev for 6-Mev protons. The structure observed is due to resonances in Si^{28} since, in analogy to Al^{27}, it is unlikely that there are any excited states in Si^{27} below 0.5 Mev which could give rise to additional neutron thresholds. Four of the observed resonances have widths of approximately 25 kev. They correspond to levels in Si^{28} 17.5 Mev above the ground state and are unstable to proton, neu-

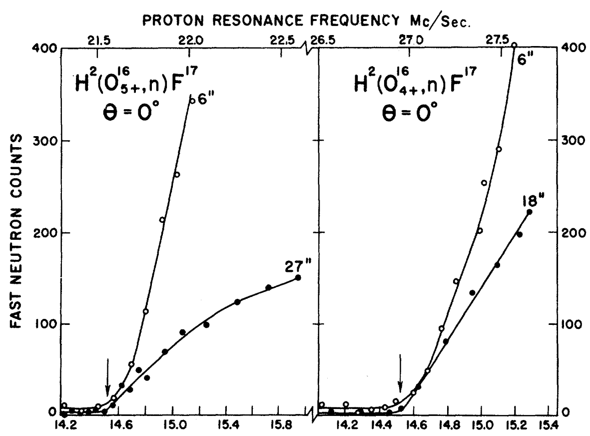

FIG. 1. Thick-target threshold measurements for the $H^2(O^{16},n)F^{17}$ reaction using O^{16} atoms with 5 electrons removed (left-hand curves) and 4 electrons removed (right-hand curve). The fast-neutron yield for a detector at 0° is plotted both against the frequency of the proton resonance used to measure the field of the 90° analyzer magnet and against O^{16} ion energy. In both cases the measurements were made with the detector at two distances from the target.

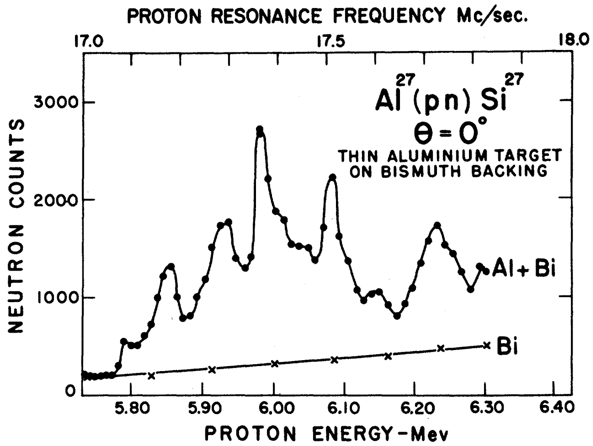

FIG. 2. A typical thin-target threshold measurement for Al^{27} (p,n). The target was 6.5 kev thick for 6-Mev protons. The lower curve through the crosses represents background using a bismuth backing alone. Both proton energy and proton resonance frequency label the abscissa. The ordinate shows counts in the slow-neutron detector.

tron, and alpha particle emission. Background runs on a similar bismuth backing were taken and the results are also shown in Fig. 2. Comparison of this excitation curve with previous cyclotron measurements[7] shows the fine structure which can be resolved using the lower beam-energy spread available from the tandem accelerator.

Thick-target neutron yields for sintered NiO targets[8] are shown in Fig. 3. Here both the counts in the slow-neutron detector and the ratio of these to the counts in the fast-neutron detector are plotted as functions of proton energy. In both cases a large neutron background is observed below threshold, probably from beam striking the magnet slits and perhaps the frame holding the small sintered target. Careful focussing of the beam was required as the energy was varied, particularly for the $Ni^{58}(p,n)$ measurement to minimize such background. The threshold energies obtained in this second series of experiments are given in Table I. In the first series of measurements, the threshold energies obtained for the $P^{31}(p,n)$ and the $Ni^{60}(p,n)$ reactions were 6.417 ± 0.020 Mev and 7.012 ± 0.030, respectively. The two results for $Ni^{60}(p,n)$ agree to within the quoted errors. The higher value was determined under better experimental conditions and is probably the more reliable.

Measurements[9] of the positron decay of Cu^{60} give a threshold for the $Ni^{60}(p,n)$ reaction in the

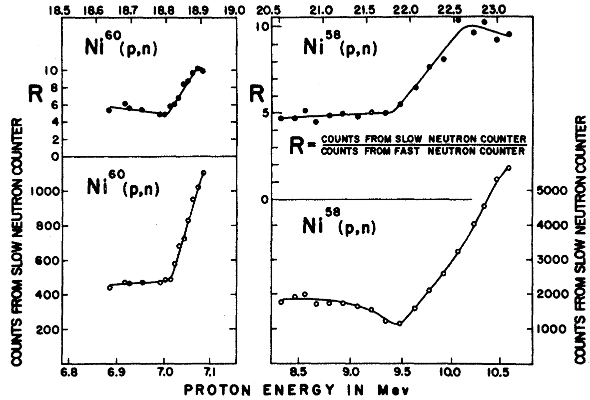

FIG. 3. Thick-target threshold measurements for $Ni^{60}(p,n)$ and $Ni^{58}(p,n)$. Both the yield of slow neutrons and the ratio of counts in the slow-neutron detector to those in the fast neutron detector (both at $0°$ to the beam) are plotted against proton energy and the frequency of the proton resonance.

range from 7.04 to 7.17 Mev. The higher energy positron decay of Cu^{58} is much less accurately known[10] and the threshold for the $Ni^{58}(p,n)$ reaction derived from the measurement is in the vicinity of 9.2 Mev. Positron decay measurements[11] of S^{31} yield a value for the threshold of the $P^{31}(p,n)$ reaction of 6.50 ± 0.10 Mev.

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