interaction. This could be done experimentally by studying deuteron production from other very light nuclei such as He^3 as well as by measuring the deuteron momentum spectra at larger angles where the pole and triangle contributions become more distinguishable.

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$(p,p'n)$, $(p,p'\gamma)$, AND (p,np') REACTIONS ON Sn^{119} AND Ni^{61} †

B. L. Cohen, E. C. May, T. M. O'Keefe, C. L. Fink, and B. Rosner*
University of Pittsburgh, Pittsburgh, Pennsylvania
(Received 6 May 1968)

The Weisskopf-Ewing assumption—that an (x,yn) reaction occurs with nearly unit probability if the first emitted particle, y, comes off with sufficiently low energy to make neutron emission energetically possible—is tested by coincidence studies of $(p,p'n)$ and $(p,p'\gamma)$ reactions on Sn^{119} and Ni^{61} and found to be grossly in error. In particular, $(p,p'\gamma)$ competes favorably with $(p,p'n)$ even when neutron emission is energetically possible by ~2 MeV. In Sn^{119}, the detailed shape of the energy spectrum of neutrons implies that spectra are drastically non-Maxwellian at low energies.

The standard theory of (x,yn) reactions, where x and y represent any nuclear particle, was first given by Weisskopf and Ewing,[1] and has since then been presented in standard textbooks,[2] and used widely in calculations of $(n,2n)$, (p,pn), $(p,2n)$, etc., reactions.[3] The basic assumption of this theory is that if the particle y is emitted with low enough energy for a neutron to be subsequently emitted, the neutron will come off with essentially unit probability. This is based on the supposition that γ-ray emission cannot compete with neutron emission in the MeV region. This premise, in turn, was based on the familiar situation in slow-neutron-induced reactions where (n,n) cross sections become larger than (n,γ) cross sections at energies of about 100 eV, which means that neutron emission with 100 eV occurs more rapidly than γ-ray emission with 8 MeV. Since neutron widths increase as $E^{1/2}$, at about 1 MeV they should be a hundred times larger than γ-ray widths.

In order to study the Weisskopf-Ewing assumption, measurements were made of energy and angular correlations between neutrons and protons emitted in coincidence from (p,pn) reactions on Sn^{119} and Ni^{61} induced by 17-MeV protons. The protons were detected with a surface-barrier detector, with the pulse height giving the proton energy, and the neutrons were detected with a Pilot B scintillator mounted on a 58AVP photomultiplier. Neutron energies were determined by the time difference between the neutron and proton pulses, and γ rays were simultaneously detected and identified by this time difference. The state in which the final nucleus is left is determined by the sum of the neutron and proton energies. Calculated efficiencies for neutron and γ-ray detection were used. In the Sn data, the γ-

ray efficiency is based on an assumed average γ-ray energy of 2.5 MeV (this is the average γ-ray energy in neutron capture); if the average γ-ray energy were 0.5 or 7.0 MeV, the efficiency would be doubled or halved, respectively. In the Ni data, the efficiency is based on an assumed γ-ray energy of the 1.4 MeV to facilitate a manipulation to be described in connection with it. Since the experimental measurements give no direct information on γ-ray energies, these efficiencies are uncertain, perhaps by as much as 50 %, but none of the conclusions of this paper are sensitive to them to that extent.

No effort was made to identify particles detected by the solid-state detector, and in the experimental results to be presented they are all taken to be protons. Separate experiments showed that there are many deuterons and alpha particles present. In the angular range where the principal data were obtained (35°-90°), the largest deuteron peaks have less than 30 % of the proton intensity at the same energy; alpha-particle intensities vary smoothly with energy and have less than 25 % of the proton intensity.

The presence of deuterons and alphas does not affect the n-p coincidence information as the kinematic locus of neutron energy versus proton energy guarantees that protons are being observed, but it does add to the results for p-γ coincidences and for "all protons." Since these results are quite uncertain in absolute magnitude, the additional uncertainty introduced by deuterons and alphas is unimportant; their most serious effect would be to introduce structure into the curves. Since the alpha-particle spectrum has little structure in the region of interest, it is of no consequence. The principal deuteron peaks, corresponding to transitions to the ground and first excited states of the same nuclei as are reached by (p,pn) reactions but with a Q value 2.2 MeV higher, are outside the region of greatest interest and their effect in any case would be to suppress the effects being reported. The deuteron spectrum in the energy region of principal interest is relatively smoothly varying and its intensity is less than 10 % of the proton intensity at the same energy. Moreover, the number of gammas following a (p,d) reaction is, on an average, considerably less than that following a (p,p') reaction. No aspects of the results to be presented are sensitive to even highly structured variations in the experimental curves for p-γ coincidences and "all protons" of less than 30 %.

Some of the results for Sn^{119} are shown in Fig. 1, where the curves represent averages over several runs at different angles between 35° and 90° (differences with angle are relatively minor). The abscissa is the energy of the emitted proton; the top curve represents the intensity distribution of charged particles, which are presumably nearly all protons; the next lower curve represents the intensity of protons in coincidence with γ rays, and the lower solid curves represent the intensity of protons in coincidenc with neutrons when the sum of the neutron and proton energies corresponds to leaving the final nucleus, Sn^{118}, in its ground state, in its first excited (2^+) state at 1.22 MeV, and in one of the group of states (including a 4^+) at about 2.2 MeV. These last three curves are labeled G, 1, and 2, respectively, and the vertical dashed lines similarly labeled represent the maximum energy with which a proton can be emitted and still allow neutron emission leaving the nucleus in these states.

These results are clearly in violation of the Weisskopf-Ewing assumption for the following reasons:

(1) The intensity of p-γ coincidences does not fall off sharply below the threshold for neutron emission.

(2) The probability for neutron emission to each final state decreases as more energy for its emission becomes available (i.e., $E_{p'}$ decreases). The only simple explanation for such a probability decrease would be competition from emission to higher excited states, but the probability decreases take place well above the

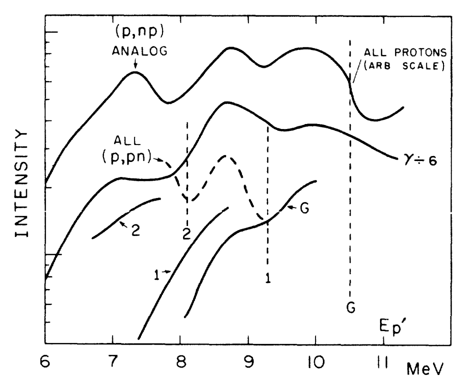

FIG. 1. Results for $Sn^{119}(p,p'n)$ and $(p,p'\gamma)$ reactions. The curves are intensity distributions of all charged particles (essentially all protons), of p'-γ coincidences, and of p'-n coincidences leaving the final nucleus in its ground (G), first excited (1), and 2.2-MeV (2) states; abscissa is the energy of the emitted protons. Vertical dashed lines are energetic thresholds for excitation of the designated states.

threshold for these competitive processes.

(3) As a result of (2), the sum of all (p,pn) reactions, shown as a dashed curve so labeled, behaves in an unbelievably strange manner, having two maxima and two minima within about 2.2 MeV.

These observations are strong evidence that the observed n-p coincidences are from (p,np') rather than from $(p,p'n)$ reactions. Thus the total $(p,p'n)$ probability is at least ten times less than that for $(p,p'\gamma)$ for at least 2 MeV beyond the threshold for neutron emission. This represents a gross violation of the Weisskopf-Ewing assumption; instead of neutron widths being a hundred times larger than gamma-ray widths, they are ten (or more) times smaller.

One possible explanation for this might seem to be penetration of angular momentum barriers;[4] barrier transmissions as low as 10^{-3} are experienced for 1-MeV neutrons for $l>4$ and for 2-MeV neutrons for $l>5$. However it is difficult to see why many, if not most, states populated in (p,p') reactions should not have $I<5$. If even 10% had $I<4$, or if 0.5% had $I<3$, angular-momentum barriers could not explain the results for the ground-state transitons. That the experimental behavior is similar for transitions to the 2^+ and 4^+ excited states makes the angular-momentum argument even more difficult to accept.

A more acceptable explanation would seem to be that there is generally a poor overlap between the states excited in (p,p') reactions and the final nucleus plus a neutron. This overlap is clearly very much less than the nearly perfect overlap expected in the slow-neutron elastic scattering discussed above.

Once we accept the fact that the observed n-p coincidences arise from (p,np') reactions, the curves shown represent the spectrum of neutrons with their energy measured to the left from the threshold. These spectra are peaked at about 0.5 MeV; so if these spectra are considered to be Maxwell distributions, the nuclear temperature is about 0.5 MeV. This is in rather poor agreement with the determination of Wood, Borchers, and Barschall,[5] $T\approx 0.9$ MeV. As the latter measurement was taken from the high energy part of the spectrum, the simplest explanation is that the energy spectrum is very different from a Maxwell distribution. Direct measurements of neutron spectra cannot determine the low-energy portion because of background and scattering difficulties, but these difficulties are eliminated here by the rigid time-energy relationship between the neutrons and protons.

Angular-distribution measurements indicate that both the neutrons and the protons involved in n-p coincidences increase in intensity in the forward direction. This might be interpreted to mean that the neutron and proton are ejected directly and simultaneously, but it would then be difficult to explain the uneven distribution of energy, $E_n \sim 0.5$ MeV, $E_p \sim 8$-10 MeV. A more likely explanation is that the neutron is emitted after only a few collisions and the proton is emitted after only a few more.[6]

Results for $Ni^{61}(p,pn)Ni^{60}$ are shown in Fig. 2. In addition to the curves analogous to those of Fig. 1, the ratio of the curves for γ-p coincidences and for all protons is shown by the curve labeled γ/p. It is normalized by assuming that the low-lying quadrupole collective states decay to the ground state with emission of a single γ ray. The dashed lines on the curves for γ rays and γ/p are corrections for the gamma rays emitted when the 1.33-MeV excited state in Ni^{60} decays to the ground state. It is immediately seen that the probability of $(p,p'\gamma)$ does indeed decrease beyond the threshold for neutron emission, especially beyond the threshold for neutron emission leaving Ni^{60} in the 1.33-MeV state. This indicates that here we do have $(p,p'n)$ reactions. The fall-offs in the neutron curves for decreasing $E_{p'}$ do not occur until the threshold for exciting higher states is passed; so these fall-offs can be explained by competition. On the

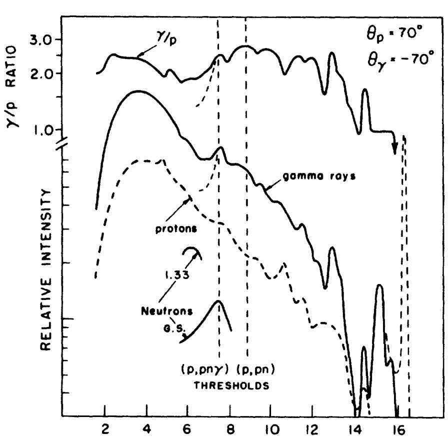

FIG. 2. Results for $Ni^{61}(p,p'n)$ and $(p,p'\gamma)$ reactions. See caption for Fig. 1 and text. Curve labeled γ/p is the ratio of the p-γ coincidences to all protons; it is normalized to unity in the region of the collective quadrupole states.

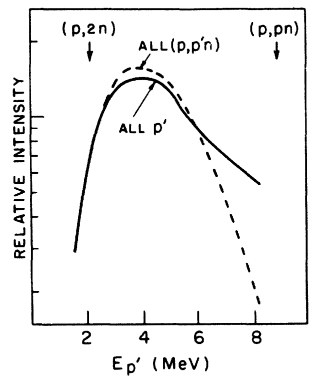

FIG. 3. Intensity distributions for all protons and for p-n coincidences from $Ni^{61}(p,p'n)$ reactions.

other hand, there is no evidence that transitions to the ground state are not predominantly (p,np').

The curve for all protons from Fig. 2 is reproduced in Fig. 3; also shown in Fig. 3 is the intensity of p-n coincidence integrated over all neutron energies for each proton energy. The two curves have the same shape at low energies, which may be interpreted to mean that all low-energy protons are followed by neutron emission; so the two curves should coincide at low energies. If the curves are normalized under that assumption, deviations begin to occur at about $E_{p'} = 5.5$ MeV, more than 3 MeV below the threshold. By 7.4 MeV, or 1.5 MeV below the threshold, only one-half of the protons are followed by neutron emission. Thus we again have rather gross violations of the Weisskopf-Ewing assumption; $(p,p'\gamma)$ competes favorably with $(p,p'n)$ even when neutron emission is possible with 1.5 MeV, and the competition does not become one-sided until this energy exceeds 3 MeV.

For emitted proton energies between 2 and 5.5 MeV, the peak of the neutron energy spectrum corresponds to Ni^{60} being left at an excitation energy of 2.5 MeV. At this energy there is a $3^+, 4^+$ doublet. The strong excitation of these may be explained by their high angular momenta, which allow them to be reached by emission of neutrons with relatively low l values.

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*Present address: University of Pennsylvania, Philadelphia, Pa. Permanent address: Israel Institute of Technology, Haifa, Israel.

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REACTION $Li^6(\pi^+,pp)He^4$ AND $T=1$ STATES IN He^4 †

R. L. Burman and M. E. Nordberg, Jr.*
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 June 1968)

An analysis of the reaction $Li^6(\pi^+,pp)He^4$ shows that the mechanism for transitions to the ground and excited states in He^4 is dominated by a single-pole model when the momentum transfer is restricted to small values. Preferential excitation of the $T=1$ levels in He^4 is observed and is explained on the basis of the single-pole model.

Phase-shift analyses[1] of $p+He^3$ and $n+T$ elastic-scattering experiments have shown the need for several $T=1$ excited levels in the $A=4$ nuclei. In He^4, four $T=1$ levels are proposed by Meyerhof and Tombrello[2] at excitation energies ranging from 24.3 to 27.8 MeV. A level scheme for He^4 taken from Ref. 2 is given in Table I. We report here a direct observation of these levels through the reaction $Li^6(\pi^+,pp)He^{4*}$.

A 31-MeV positive-pion beam from the University of Rochester 130-in. cyclotron was used to bombard a 0.07-g/cm² Li^6 target. The data were obtained with an optical spark-chamber system, triggered by a coincidence requirement of an incoming pion and two outgoing charged particles. Thin-foil chambers recorded the directions of