PHYSICAL REVIEW C VOLUME 8, NUMBER 6 DECEMBER 1973

Neutron Spectra at 0° from 724 -MeV Protons on Be and Cu

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(Received 17 July 1973)

Neutron spectra above 175 MeV were measured at 0° from 724-MeV proton bombardment of beryllium and copper. Measurements were made at the 184-in. cyclotron of the Lawrence Berkeley Laboratory with a self-contained time-of-flight spectrometer. The results are compared with the predictions of the intranuclear cascade model for the interval from 0 to 5°. Comparison of the measured and predicted spectra from beryllium indicates that the intranuclear cascade model underestimates the neutron production both in the quasifree peak and in the continuum between 300 MeV and the cutoff energy at 175 MeV. The position of the quasifree peak is observed at the proton bombarding energy in agreement with theory. The measured spectrum from copper shows a substantial contribution in the continuum between 300 MeV and the cutoff energy at 175 MeV. In this continuum region, the measured spectrum from copper increases with decreasing energy, whereas the calculated spectrum decreases with decreasing energy.

[NUCLEAR REACTIONS Be(p,n), Cu(p,n), E=724 MeV; measured n spectra above 175 MeV.]

I. INTRODUCTION

The intranuclear cascade calculation[1-5] predicts energy and angular distributions of the secondary particles produced in nuclear reactions involving either nucleons or pions on complex nuclei. Existing experimental data[6-10] for evaluation of the intranuclear cascade model above the pion-production threshold is limited mainly to measurements of the secondary proton spectra emitted in the region from 9 to 60°. Bertini[11] has shown that there is reasonable agreement between these experiments and the predictions of the intranuclear cascade model. The analysis by Fullwood *et al.*[12] of the thick-target measurements of Fraser, Hewitt, and Walker[13] at 1 GeV and the thick-target measurements of Madey and Waterman[14] at 740 MeV indicate that the neutron yield predicted by the intranuclear cascade model at wide angles (45 to 135°) is too low; furthermore, these results show that the discrepancy between experiment and theory increases with increasing angle of emission. Wachter *et al.*[15] reported a similar discrepancy in the cross section for the production of neutrons at 135° from 63-MeV protons incident on carbon and aluminum targets.

In this paper, we present the results of measurements of the neutron spectra emitted at 0° from beryllium and copper targets bombarded by the circulating beam of 724-MeV protons at the 184-in. cyclotron of the Lawrence Berkeley Laboratory (LBL). The purpose of these measurements was to investigate the production spectra from these targets and to generate data to test the validity of the intranuclear cascade calculation in the forward direction. Prior to these measurements, the data of Kiselev *et al.*[16] represented the only neutron spectra at 0° for proton bombarding energies above the pion-production threshold. Kiselev *et al.* measured the neutron spectrum at 0° from 680-MeV protons on beryllium and observed prominent peaks of approximately equal amplitude at about 280 and 610 MeV.

II. INTRANUCLEAR CASCADE CALCULATION

For comparison with this experiment, Bertini[17] has calculated the neutron spectra above 50 MeV predicted by the intranuclear cascade model for 724-MeV protons incident on ^{9}Be and ^{64}Cu. The predicted spectra for ^{9}Be are plotted in Fig. 1 for neutrons emitted in the intervals from (a) 0 to 0.25°, (b) 0.25 to 0.50°, (c) 0.5 to 1.0°, (d) 1.0 to 2.0°, (e) 2.0 to 5.0°, and (f) 0 to 5°. Similarly, the predicted spectra for ^{64}Cu are plotted in Fig. 2 for neutrons emitted in the intervals from (a) 0 to 1°, (b) 1 to 2°, (c) 2 to 5°, and (d) 0 to 5°. Note that the shape of the spectrum in Fig. 1 changes appreciably as the emission angle increases from 0 to 5°. This sensitivity of the spectral shape to small changes in the angle of emission near 0° is a consequence of two predictions of the calculations: (1) The intense peak at an intermediate energy of about 475 MeV in the interval from 0 to 0.25° decreases by a factor of about 70 in magnitude and shifts to about 300 MeV in the interval from 2 to 5°; and (2) the magnitude of the high-energy peak (at 724 MeV) remains relatively constant as the angle of emission increases from 0 to 5°. As is evident in Fig. 2, the theoretical spectra for ^{64}Cu exhibit similar rapid changes as the emission angle increases from 0 to 5°. On account of the sensitivity of the shape and magnitude of the theoretical spectra to small changes in the angle of emission near 0°, caution must be exercised in comparing experiment with theory. The sensitivity of the spectral shape to small changes in the angle of emission near 0° is a result of a discontinuity built into the intranuclear cascade model. According to Bertini,[17] the intermediate peak at about 400 MeV in the calculation results from decay of the very short-lived isobars that are formed in the pion-production process. For incident nucleons from 500 MeV to 1 GeV, the intranuclear cascade model assumes that the angular distribution of isobars in the center-of-mass system is 75% isotropic, 12.5% forward, and 12.5% backward for single-pion production and 50% forward and 50% backward for double-pion production. These discontinuities in the isobar angular distribution at 0 and 180° were assumed for convenience in Monte Carlo sampling and are intended as a reasonable representation of the forward-backward tendencies in the free nucleon-nucleon data rather than as a precise representation of the data at 0 and at 180°. Bertini suggests that the effects of this discontinuity can be smoothed out by comparing the experimental results at 0° to the theoretical predictions averaged over the interval from 0 to 5°.

III. SPECTROMETER

The spectra reported in this paper were measured with a self-contained time-of-flight spectrometer for neutrons from about 150 MeV to 1 GeV. Since this spectrometer is detailed elsewhere,[18] only a brief description is given here. The spectrometer, shown schematically in Fig. 3, consists basically of four scintillation counters designated as D1, D2, D3, and D4. The principle of the spectrometer requires an incident neutron to scatter elastically through an angle θ from a hydrogen nucleus in the D1 scintillator, travel over a fixed flight path X, and interact in the D2 scintillator. The time interval between these scintillation pulses is the time of flight t of the scattered neutron. The kinetic energy of the incident neutron is specified from kinematics by the neutron scattering angle θ, the flight path X, and the time of flight t of the scattered neutron. A counter telescope consisting of scintillation counters D3 and D4 detects the recoil proton in coincidence with the scattered neutron. For an event to be accepted, a D1-D2-D3-D4 coincidence is required

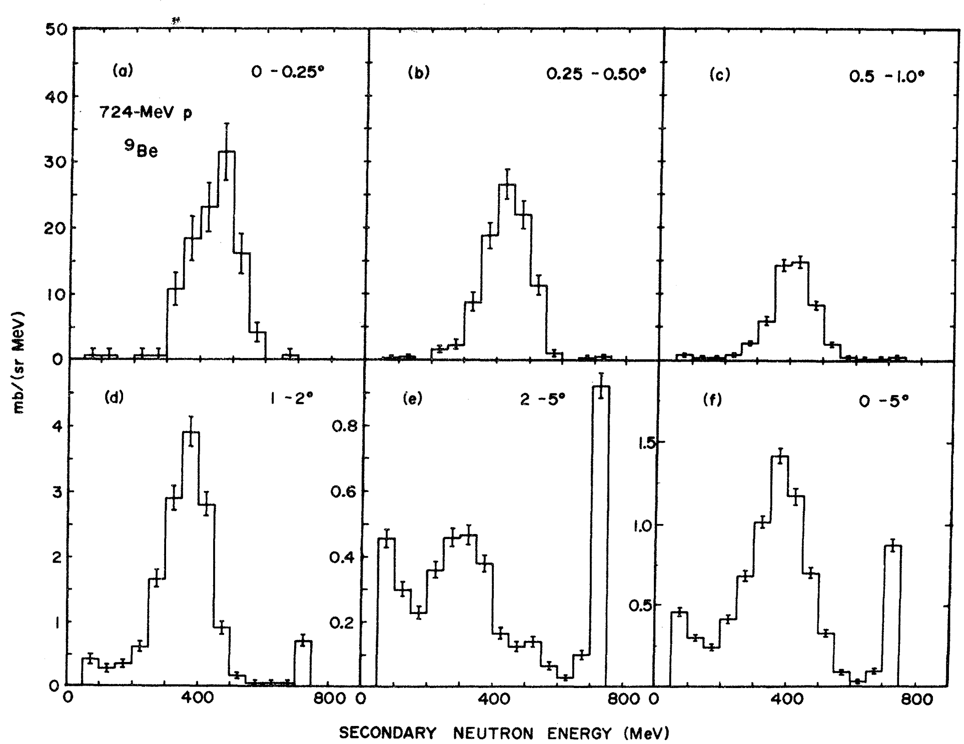

FIG. 1. Secondary neutron spectra predicted by the intranuclear cascade model for 724-MeV proton bombardment of ^{9}Be. Spectra are shown for neutrons emitted in the intervals from (a) 0 to 0.25°, (b) 0.25 to 0.50°, (c) 0.5 to 1.0°, (d) 1 to 2°, (e) 2 to 5°, and (f) 0 to 5°. Note the scale changes of the ordinate in (d), (e), and (f).

without a veto from either anticoincidence detector A1 or A2; hence, neutrons detected in D2 from inelastic carbon and hydrogen interactions in D1 are not accepted unless a charged particle is detected also in D3 and D4.

IV. EXPERIMENTAL ARRANGEMENT

In these experiments, measurements were made with a 2.54-cm-thick beryllium or a 0.64-cm-thick copper target placed inside the LBL 184-in. cyclotron at a radius of 205 cm. This radius corresponds to a circulating proton beam energy of 724 MeV; however, the mean bombarding energy will be lower than this value on account of the energy loss on each traversal of the target. In each of these targets, the energy loss of 724-MeV protons is about 9.4 MeV per traversal. As a result of multiple scattering, the mean square angle of deflection of 724-MeV protons in the beryllium target is ±0.3° per traversal, whereas that in the copper target is ±0.7° per traversal. The protons deflected vertically by 0.5° or more will intercept the cyclotron dees; hence, fewer multiple traversals would be expected with the copper target. The neutron beam at 0° was viewed through a steel collimator 5.1 cm high by 2.5 cm wide by 122 cm long embedded in the concrete shielding wall of the cyclotron. The neutron emission angle was determined[19] by survey to be within 5 min of 0°. The exit aperture of the collimator was 15 m from the target. A quadrupole magnet located just beyond the collimator exit aperture deflected away more than 95% of the charged-particle contamination in the neutron beam and reduced the count rate in the D1 detector by a factor of 3.

The (6.4-cm-diam by 6.4-cm-high) D1 detector was centered in the neutron beam 3.8 m downstream from the exit aperture. The (22.9-cm-diam by 20.3-cm-thick) D2 detector was positioned 5 m from D1 and at an angle $\theta = 50°$. The recoil-proton telescope, which consisted of the (10.2- by 10.2- by 0.6-cm) D3 and the (15.2- by 10.2- by 0.64-cm) D4 detectors, was positioned at an angle $\phi = 35°$ with respect to the direction of the incident neutrons, or at an angle $\psi = 85°$ with respect to the direction of the scattered neutrons. The D3 and D4 detectors were 25 and 40 cm from D1, respectively. For incident neutron energies above 175 MeV, all recoil protons from neutrons scattered elastically into D2 have sufficient energy to reach D4. For this experiment, the following three factors resulted in a divergence of about ±6° in the direction of the recoil protons: (1) multiple scattering of the recoil protons in the D1 detector,

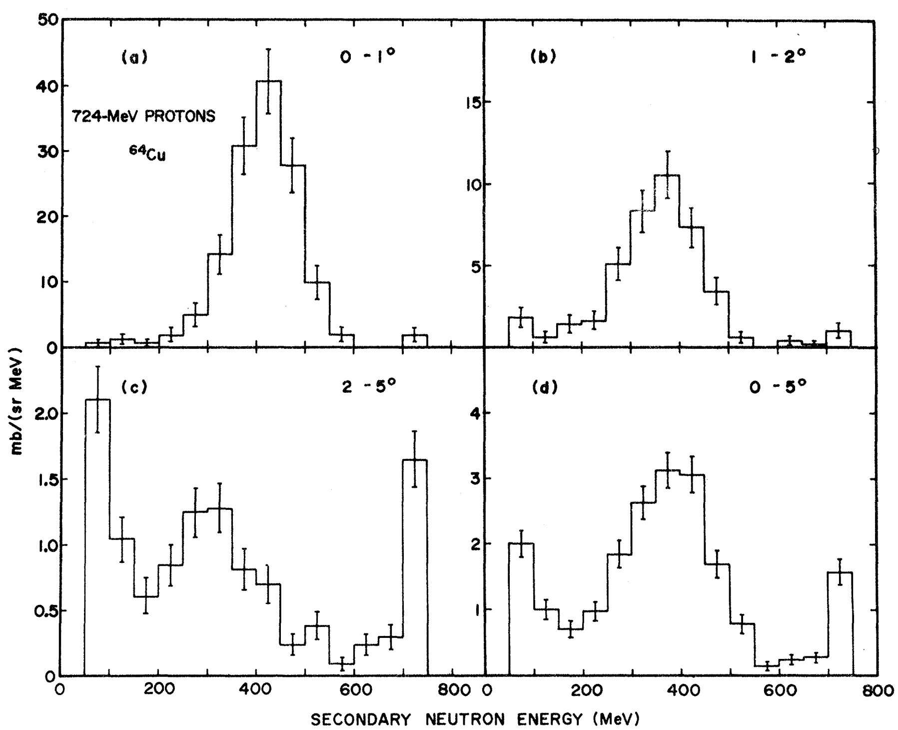

FIG. 2. Secondary neutron spectra predicted by the intranuclear cascade model for 724-MeV proton bombardment of ^{64}Cu. Spectra are shown for neutrons emitted in the intervals from (a) 0 to 1°, (b) 1 to 2°, (c) 2 to 5°, and (d) 0 to 5°. Note the scale changes of the ordinate in (b), (c), and (d).

(2) the finite dimensions of the D1 and D2 detectors, and (3) the slight kinematic decrease of the recoil-proton scattering angle with increasing incident neutron energy. Since the recoil-proton telescope subtended an angle of $\pm 10°$ from the center of D1, recoil-proton losses from the above factors were negligible.

V. MEASUREMENTS

Figure 4 is the time-of-flight spectrum of neutrons at 0° from 724-MeV proton bombardment of beryllium. This spectrum was measured with the NE-228 D1 scintillator. The small peak centered at channel 139 in Fig. 4 is the γ-ray time-of-flight peak. Since the statistics in the γ-ray peak are poor, a separate γ-ray time-of-flight spectrum was recorded with a ^{60}Co source for energy calibration of the neutron time-of-flight spectrum. The level of accidentals (at a mean value of 14.5 events/channel) can be seen to the left of the γ-ray peak. In Fig. 4, the quasifree neutron peak at about 700 MeV is discernable on the left-hand side of the neutron time-of-flight spectrum.

Background from the inelastic reactions $n+p \to n+n+\pi^+$ and $n+p \to n+p+\pi^0$ is expected to be small for the following reasons: (1) The background events must satisfy the kinematic and coplanarity requirements for n-p elastic scattering; (2) only neutrons above about 500 MeV have a significant n-p inelastic cross section; (3) the total n-p inelastic cross section in the region from 500 to 725 MeV is less than 25% of the total cross section for n-p elastic scattering; (4) only about 30% of the incident neutrons in the beryllium spectrum are above 500 MeV. (For the copper spectrum, this fraction is less than 15%.) Based on these considerations, we estimate the background from n-p inelastic reactions to be smaller than 5%.

A measure of the background from n-p inelastic reactions in the spectrum shown in Fig. 4 was obtained from coincidence counting rates observed with the D3 detector in three different positions that kinematically exclude n-p elastic scattering events; in these tests, D4 was not used and D2 was fixed at a neutron scattering angle $\theta = 50°$. Elastic n-p scattering events can be excluded either (1) by positioning the D3 detector such that the included angle ψ is smaller or greater than that required by n-p kinematics or (2) by positioning the D3 detector above or below the neutron scattering plane defined by the incident and scattered neutron directions. In the first two tests, the D3 positions defined included angles $\psi = 25$ and 120° in the neutron scattering plane. In the third test, D3 was positioned at the included angle $\psi = 85°$ for elastic n-p scattering, but raised 12.7 cm above the neutron scattering plane. The counting rates with D3 in each of these three positions were about 15% of that observed with D3 at the included angle $\psi = 85°$ in the neutron scattering plane. Except at $\psi = 25°$, the measurements described above were made with both NE-102 and NE-228 D1 scintillators[20] in order to subtract the background from neutron-carbon interactions.[21] Based on the statistics obtained in these tests, the background from n-p inelastic reactions is less than (8^{+10}_{-8})% of the total n-p scattering events. While the statistics in these tests are poor on account of the low counting rates observed with the D3 detector positioned to exclude n-p elastic scattering events, this measurement serves as an upper limit of the magnitude of the background from n-p inelastic interactions. The magnitude of the measured background is consistent with the estimated value of less than 5%.

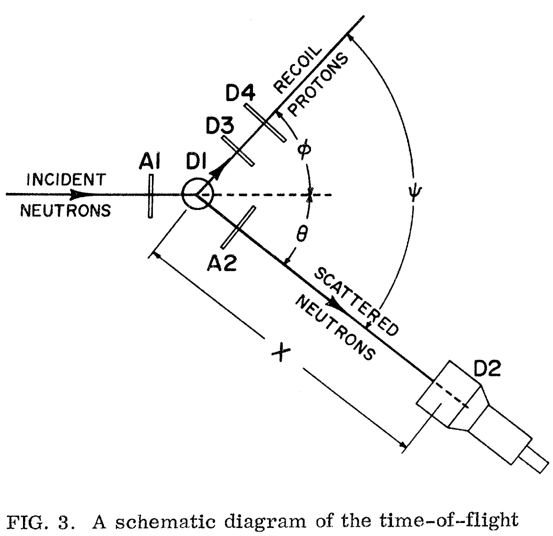

FIG. 3. A schematic diagram of the time-of-flight spectrometer.

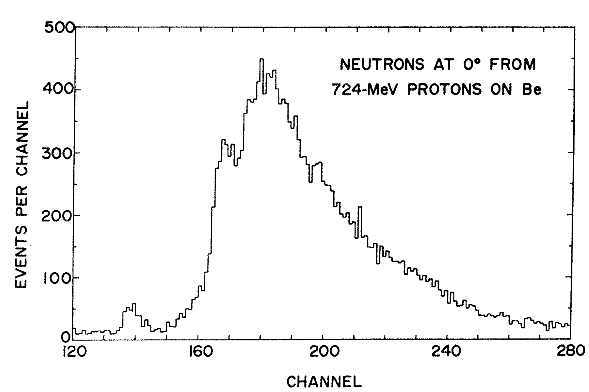

FIG. 4. Neutron time-of-flight spectrum at 0° from 724-MeV proton bombardment of beryllium. This measurement was made with an NE-228 liquid D1 scintillator.

VI. RESULTS AND DISCUSSION

Figure 5 is a plot of the measured spectrum of neutrons at 0° from 724-MeV protons on beryllium. The vertical error bars denote the statistical uncertainty only; the horizontal error bars denote the bin width in MeV. Corrections have been made to the data for the energy dependence of the *n-p* differential scattering cross section and for the efficiency of the D2 detector. The *n-p* differential cross sections for this purpose were obtained from the parametrizations of Bertini.[22] The neutron detection efficiency of the D2 detector was computed with a program written by Kurz[23] for neutrons from 1 to 300 MeV. It should be noted that since the incident neutrons were required to scatter through an angle of 50°, all scattered neutron energies in this measurement were less than 300 MeV. Also plotted in Fig. 5 is the spectrum predicted by the intranuclear cascade model for neutrons emitted in the angular interval from 0 to 5°. For purposes of comparison, the measured spectrum was normalized to the predicted cross section above 200 MeV. The measured spectrum is broadened as a result of the energy resolution of the spectrometer. In view of the fact that the width of the observed quasifree peak is in agreement with the calculated energy resolution of the spectrometer, the shapes of the observed and predicted spectra are in general agreement; however, the relative number of neutrons in the quasifree peak to the number in the pion production peak is greater in the measured spectrum than in the theoretical spectrum. *A priori,* it is expected that the predicted high-energy peak at 0° will be smaller than the measured peak because the contribution to this peak from collective effects and off-energy-shell effects are not accounted for in the intranuclear cascade model. The positions of the quasifree and the pion-production peaks agree within experimental error with the predicted positions. The position of the quasifree peak has an uncertainty of ±20 MeV as a result of an uncertainty of ±0.2 nsec in the time calibration of the detection system. It should be noted that the theoretical calculation appears to underestimate the number of neutrons produced below about 300 MeV. Since the energy resolution at 300 MeV is about 11%, the discrepancy between experiment and theory below 300 MeV is not a result of the resolution broadening of the pion-production peak.

In comparing our measurement with the previous measurement of Kiselev *et al.* at 680 MeV, there is an apparent discrepancy in both the magnitude and position of the quasifree peak. Kiselev *et al.* observed the quasifree peak 50 MeV below the mean proton bombarding energy; whereas in our

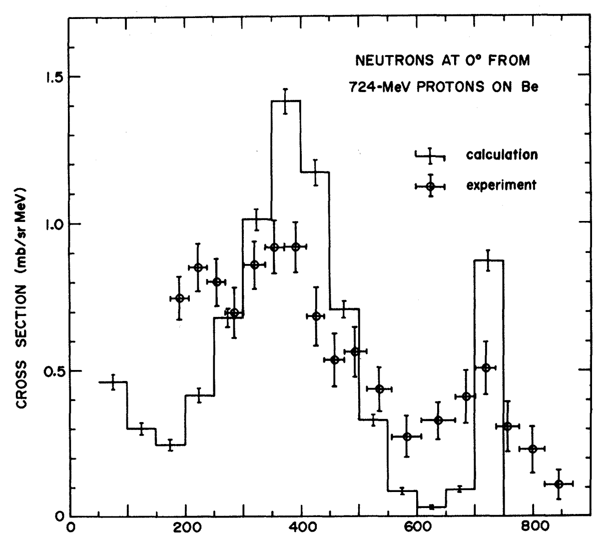

FIG. 5. Measured spectrum of neutrons emitted at 0° from 724-MeV proton bombardment of beryllium. The histogram is the spectrum predicted by the intranuclear cascade model for secondary neutrons emitted in the angular interval from 0 to 5°. The measured spectrum is normalized to the predicted cross section above 200 MeV.

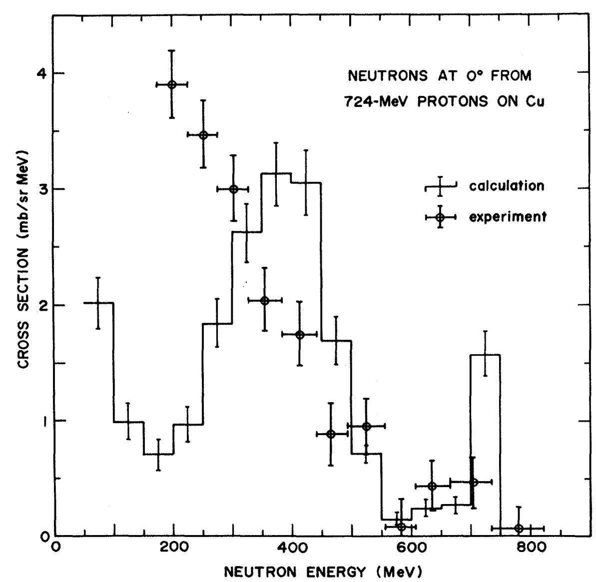

FIG. 6. Measured spectrum of neutrons emitted at 0° from 724-MeV proton bombardment of copper. The histogram is the spectrum predicted by the intranuclear cascade model for secondary neutrons emitted in the angular interval from 0 to 5°. The measured spectrum is normalized to the predicted cross section above 200 MeV.

measurement, the position of the quasifree peak and the mean proton bombarding energy agree within experimental error. In the measurement of Kiselev *et al.*, peaks approximately equal in magnitude were observed at 280 and 610 MeV, whereas in our measurement, the magnitude of the quasifree peak is about 0.4 of that of the 350-MeV peak. The difference in the relative magnitudes of these peaks can be accounted for by the fact that the energy resolution in the measurement of Kiselev *et al.* appears to be about 8% at 610 MeV, whereas in our measurement, the energy resolution at 700 MeV is about 16%.

A priori, one expects the intranuclear cascade calculation to give better results for nuclei containing many nucleons. The measured spectrum of neutrons at 0° from 724-MeV protons on copper is plotted in Fig. 6. Also plotted in Fig. 6 is the spectrum predicted by the intranuclear cascade model for neutrons emitted in the angular interval from 0 to 5° from 724-MeV protons on ^{64}Cu. For purposes of comparison, the measured spectrum was normalized to the predicted cross section above 200 MeV.

It is evident from Fig. 6 that there is a serious discrepancy between the theoretical and experimental spectra for copper. The measured spectrum from copper shows a substantial contribution in the continuum between 300 MeV and the cutoff energy at about 175 MeV. In the continuum region, the measured spectrum increases with decreasing energy, whereas the calculated spectrum decreases with decreasing energy. The measured spectrum exhibits also a small peak at about 700 MeV.

VII. CONCLUSION

Comparison of the measured spectrum at 0° from 724-MeV protons on beryllium with the predictions of the intranuclear cascade model for the interval from 0 to 5° indicates that the intranuclear cascade model underestimates the neutron production in the quasifree peak and in the continuum between 300 MeV and the cutoff energy at about 175 MeV. The position of the quasifree peak is observed at the proton bombarding energy in agreement with theory. A similar comparison for copper indicates that there is a serious discrepancy between experiment and theory in connection with neutron production in the continuum between 300 MeV and the cutoff energy at about 175 MeV. In this continuum region, the measured spectrum from copper increases with decreasing energy, whereas the calculated spectrum decreases with decreasing energy.

ACKNOWLEDGMENTS

We are grateful to Dr. Hugo Bertini for valuable discussions and for performing the intranuclear cascade calculations for comparison with these measurements. We are indebted also to the Lawrence Berkeley Laboratory for use of the 184-in. cyclotron and to Jimmy Vale, Lloyd Hauser, and the cyclotron crew for their cooperation. This work was supported in part by the U. S. Atomic Energy Commission under Contract No. AT (11-1)-2231.

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