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^{65}Cu(p,pn)^{64}Cu EXCITATION FUNCTION IN THE ENERGY RANGE 13–25 MeV*

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Abstract—The excitation function for the ^{65}Cu(p,pn)^{64}Cu reaction from 13 to 25-MeV has been determined. Absolute cross sections were obtained by assaying the 1345·8-keV γ-ray of the ^{64}Cu (12·7 hr) with calibrated Ge (Li)-spectrometers and by measuring beam intensities with a Faraday cup. The present results which have energy uncertainties of only ≈0·1 MeV extend the excitation function for this frequently used beam monitor reaction to energies where it was not well determined previously. The experimental excitation function is also compared with calculations based on a Monte Carlo intranuclear cascade-statistical evaporation model.

INTRODUCTION

THE ^{65}Cu(p,pn)^{64}Cu reaction has frequently been used for monitoring proton beam intensities. As a result, many measurements of other excitation functions are dependent on the absolute cross section values for this reaction. Although a substantial number of experimental studies of this excitation function have been made[1–7], previous cross section measurements for bombarding energies below 25 MeV are scarce and conflicting. Most of them were subject to large uncertainties due to (1) problems associated with the use of internal cyclotron beams, (2) the inherent errors accompanying energy degradation of the protons by large factors, (3) the use of other somewhat unreliable proton excitation functions for beam monitoring and (4) difficulties in the induced activity measurements.

Newton *et al.*[7] have recently made a rather complete study of the excitation function in the energy range from ≈25 to 100 MeV. They determined absolute cross sections to within a standard error of approx. ±6% by assaying the ^{64}Cu (12·7 hr) annihilation radiation and by measuring beam intensities with a Faraday cup. Utilizing the external proton beam facility of the McGill synchrocyclotron, the results have energy uncertainties of 1–2 MeV. The present investigation in the lower energy region (<25 MeV) is a useful and desirable extension of this important monitor reaction excitation function.

EXPERIMENTAL

The excitation function was measured by the foil activation method using the high resolution (≤0·1%) proton beams from the Brookhaven Tandem Van de Graaff accelerators. These measurements were an outgrowth of previously reported[8] cross section determinations for the ^{63}Cu(p,n)^{63}Zn and ^{65}Cu(p,n)^{65}Zn reactions. Therefore, only a summary of the procedures and those details applicable to the ^{65}Cu(p,pn)^{64}Cu cross section measurements are presented here. In fact, the data for these measurements were obtained simultaneously with those given in Ref. [8], although their use was not originally anticipated. For this reason, the experimental conditions for the ^{64}Cu assays were not optimized and, as a result, the uncertainties are perhaps slightly larger than would be necessary.

(i) *Irradiation procedures and energy determinations.* The irradiations were typically 5 min in duration and were performed with a large (1 cm^2 diam) uniformly diffused beam of 100–300 nA. Beam intensities were determined to ≈1% accuracy with a Faraday cup and calibrated current integrators. Energy degradation of the proton beam in passing through the Faraday cup window, small air path, and target was calculated using the fitted[8] stopping power tabulations of Northcliffe and Schilling[9] and Williamson *et al.*[10]. The mean energy of an irradiation was taken as the proton energy at the center of the target foil. The uncertainty in the mean energy was obtained by quadratically summing the uncertainty in the incident beam energy, the errors in the energy loss calculations for each absorber and target, and the energy straggling[8] for each absorber and target. Typically, these uncertainties in the mean energies are ≈100 keV. Corrections for energy resolution due to the finite target thicknesses (100–200 keV) were negligible (<1%) in all cases.

(ii) *Activity measurements and cross section determinations.* The target foils were assayed for ^{64}Cu without chemical separation by measuring the 1345·8-keV γ-ray with high resolution (FWHM of ≈2 keV at 1332 keV) calibrated Ge(Li) spectrometers. In most cases, the targets were counted several times over a period of 1–2 half-lives. Analysis of the γ-ray spectra was performed by means of a modified version of the BRUTAL computer code[11]. The resultant γ-ray decay curves were fitted to the known half-life (12·70 ± 0·01 hr)[12] with the least-squares CLSQ[13] program. A γ-ray abundance of (0·48 ± 0·02)%[14] was used to obtain the absolute disintegration rates. The uncertainties in the cross sections are typically in the range 7–15% and were obtained by propagating in quadrature the contributions from peak analyses (including counting statistics) and decay curve analyses (3–12%), absolute detector efficiencies (≈5%), γ-ray abundance (4·2%), target thicknesses (<1%) and current integration (≈1%).

RESULTS AND DISCUSSION

The experimental cross sections are tabulated in Table 1 and have been plotted as closed circles in Fig. 1 to define the excitation function from 13 to 25 MeV. Cohen *et al.*[2] measured relative cross sections for the ^{65}Cu(p,pn)^{64}Cu reaction by a stacked foil technique in the internal beam of the ORNL cyclotron. They used the value of 530 m.b. reported by Blaser *et al.*[15] for the ^{63}Cu(p,n)^{63}Zn reaction at 13 MeV to place their data on an absolute basis. A recent remeasurement[8] of this monitor cross section gave a lower value, 459 ± 33 m.b. at 13 MeV. For comparison with the present work, their [2] original values have been multiplied by a factor of 0·814 to account for this change in the monitor reaction and for changes in decay schemes[8]. Although the shape of this renormalized excitation function (shown as the dashed curve in Fig. 1) is in agreement with that of the present

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Table 1. Experimental cross sections for the $^{65}Cu(p,pn)^{64}Cu$ reaction

E_p (MeV)	σ (mb)	E_p (MeV)	σ (mb)
13.02 ± 0.13	5.9 ± 1.4	18.85 ± 0.19	227 ± 24
13.07 ± 0.12	8.7 ± 0.6	19.86 ± 0.11	276 ± 34
13.21 ± 0.12	11.1 ± 0.9	20.00 ± 0.09	264 ± 32
13.52 ± 0.09	15.9 ± 1.9	21.51 ± 0.09	322 ± 25
15.45 ± 0.09	90.8 ± 8.5	22.49 ± 0.19	348 ± 30
16.20 ± 0.15	132 ± 20	22.62 ± 0.18	350 ± 26
16.64 ± 0.12	163 ± 23	23.24 ± 0.13	346 ± 29
16.81 ± 0.11	153 ± 22	23.51 ± 0.09	358 ± 34
16.97 ± 0.09	169 ± 20	25.02 ± 0.09	392 ± 26
18.48 ± 0.09	234 ± 16		

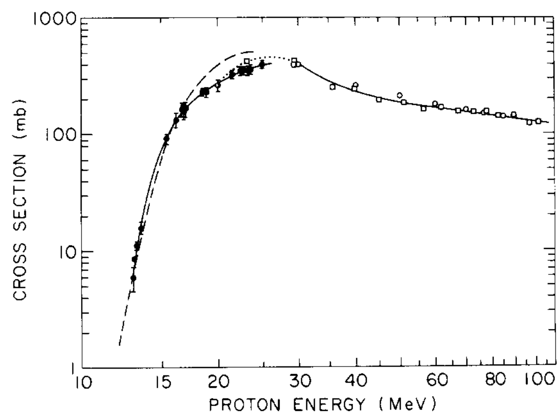

Fig. 1. Experimental excitation function for the $^{65}Cu(p,pn)^{64}Cu$ reaction. The closed circles and solid curve from 13 to 25 MeV represent the results from the present measurements. Previous experimental results of Cohen *et al.* (Ref. [2]) are shown as the dashed line. Results due to Meghir (Ref. [6]) and Newton *et al.* (Ref. [7]) are shown as open circles and squares, respectively. The solid line from 30 to 100 MeV shows their general trend. The dotted curve indicates a possible shape for the excitation function based on the data of Ref. [6, 7].

experiment for energies below ≈17 MeV, the cross sections of Cohen *et al.*[2] rise too rapidly between 17 and 23·5 MeV and are ≈40% higher than our value at 23·5 MeV.

Cross sections from two experiments at the McGill synchrocyclotron have also been plotted in Fig. 1. The open circles represent the measurements of Meghir[6] as renormalized and reported by Saha *et al.*[16]. Meghir's cross sections were measured in the internal beam relative to the $^{27}Al(p,3pn)^{24}Na$ and $^{12}C(p,pn)^{11}C$ monitor reactions. More recent values of the $^{65}Cu(p,pn)^{64}Cu$ cross section as measured by Newton *et al.*[7] in the external beam using a Faraday cup are shown as the open squares. For a comparison with other earlier measurements[1, 3–5] in this higher energy region, the reader is referred to their paper[7].

The solid line in Fig. 1 extending from 30 to 100 MeV traces the excitation function weighted to favor the points of Newton *et al.*[7]. The dotted curve from 30 to 20 MeV is a possible extension of this line to lower energies. Unfortunately, overlap with the present experiment is limited. A point due to Meghir[6] is in excellent agreement with our value at 20 MeV as shown by the half closed circle in Fig. 1. However, the cross section reported by Newton *et al.*[7] at 23·2 MeV is 24% higher than that from the present work. While these authors[7] appear to have taken precautions to avoid problems of beam contamination and energy spread and uncertainty common to many measurements in highly degraded beams, it seems reasonable that the "best" excitation function for the $^{65}Cu(p,pn)^{64}Cu$ reaction would be obtained by smoothly joining the two solid curves in Fig. 1.

In Fig. 2 the experimental excitation function obtained in this manner (the heavy solid line) is compared with Monte Carlo intranuclear cascade-statistical evaporation model calculations[17–20] which have been previously described[21]. The results of these calculations are shown as filled circles with their associated statistical uncertainties. The dashed curve indicates their general trend. For these calculations, the cascade stage was calculated with a modified STEPNO version of the VEGAS code of Chen *et al.*[18] (incorporating the improved nucleon density distribution[19]) which was followed by the DFF code of Dostrovsky *et al.*[17] for the evaporation stage.

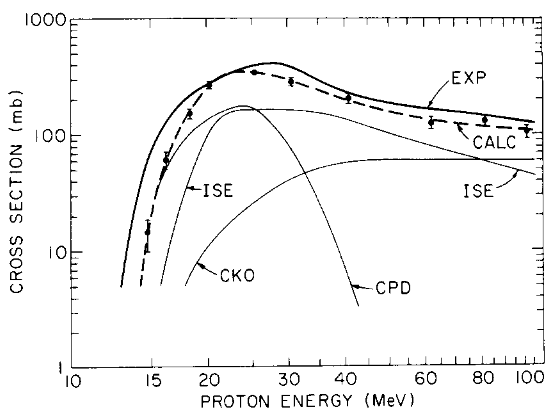

Fig. 2. Comparison of the experimental $^{65}Cu(p,pn)^{64}Cr$ reaction excitation function with cascade-evaporation calculations. The heavy solid curve is the experimental excitation function obtained by smoothly joining the solid curves in Fig. 1. The closed circles represent the results of the VEGAS-DFF cascade-evaporation calculation with associated statistical uncertainties. The dashed curve indicates their general trend. The light lines labeled CPD, ISE and CKO represent contributions to the calculated cross sections from three mechanisms.

Parameters for the DFF calculation were $r_0 = 1{\cdot}7$ fm, $a = A/20$, and a set of pairing and shell correction energies due to Hillman[22]. These had been found[21] to give better agreement with some experimental (p,n) cross sections than did the original parameters suggested by Dostrovsky *et al.*[17].

The fractional production probabilities from the VEGAS–DFF calculations were converted to production cross sections using the ^{65}Cu optical model reaction cross sections, σ_R, given by Mani, Melkanoff and Iori[23] (MMI). Because the MMI tables extended only up to 50 MeV and because their choice of optical model parameters was based heavily on low-energy data, values of σ_R for higher energies were obtained by an ABACUS-2 calculation using parameters supplied by Auerbach[24]. These calculations gave σ_R values for ^{65}Cu of 1240 and 1148 m.b. at proton energies of 30 and 50 MeV, respectively, in good agreement with those deduced by Thomas[25] from a detailed analysis of angular distribution and polarization measurements.

From intermediate output of the VEGAS–DFF calculations it is possible to divide the calculated cross sections into contributions from three mechanisms[26]. Excitation functions for these processes are shown by the light lines labeled CPD, ISE and CKO in Fig. 2. Production of ^{64}Cu via compound nucleus formation (CPD) plays a major role for energies up to ≈25 MeV but then declines rapidly, a consequence of decreasing probability for compound nucleus formation in the cascade step and the fact that, if compound nuclei are formed, they have sufficient excitation to emit more than two particles. Inelastic scattering followed by evaporation of a nucleon (ISE) contributes significantly at all but the lowest energies. The probability for clean knockout reactions (CKO), i.e. prompt cascades which produce ^{64}Cu with too little excitation for further particle emission, rises slowly with energy and reaches a plateau value of ≈60 m.b. at ≈40 MeV.

Comparison of experiment with the calculation in Fig. 2 shows major discrepancies for energies below 20 MeV. The threshold for the $^{65}Cu(p,pn)^{64}Cu$ reaction is at 10·06 MeV. An effective Coulomb barrier[17, 22] of 3·61 MeV below which protons cannot be emitted raises the practical threshold for the calculated curve to ≈13·7 MeV. For several MeV above this energy, the calculation strongly favors the production of ^{64}Zn; e.g. at 16·2 MeV the $^{64}Zn/^{64}Cu$ ratio is 7·75. It is clear that some further [27] softening of the barrier would be necessary to improve agreement with the experimental data.

For energies above 30 MeV, the calculated curve has the same shape as the experimental one, but is ≈25% low. Still lower calculated cross sections [(95 ± 10) m.b. at 80 MeV and (64 ± 11) m.b. at 102 MeV] have been reported by Newton *et al.*[7]. Their results were obtained from a VEGAS–DFF calculation which differed from the present one in two significant ways. Firstly we have normalized the calculated cross sections on the basis of σ_R values from optical model calculations which are 20–30% greater than values of σ_R from VEGAS, and secondly, we have used a larger nuclear radius parameter, $r_0 = 1{\cdot}7$ fm instead of $r_0 = 1{\cdot}5$ fm, which has the effect of lowering the barrier to the emission of charged particles[27]. The net effect is improved agreement with the experimental data.

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