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Absolute Cross Sections of Proton Induced Reactions on ^{65}Cu, ^{64}Ni and ^{63}Cu

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Abstract

Absolute cross sections have been measured for (p, γ) reactions on ^{65}Cu, ^{64}Ni and ^{63}Cu over proton energy ranges of 1·05–3·25, 1·00–3·45 and 1·05–4·70 MeV respectively, for (p, n) reactions over proton energy ranges from threshold to 3·25, 3·80 and 4·86 MeV respectively, and for ^{63}Cu(p, p$'$)^{63}Cu over a proton energy range of 1·05–4·00 MeV. All the data are compared with global statistical model calculations. The agreement, to within a factor of 2, between theory and experiment is regarded as satisfactory for a global code, but the ^{64}Ni data are suggestive of a closed shell effect at $Z = 28$.

1. Introduction

The calculation of the relative abundances of all isotopes produced by nuclear reactions in evolving and exploding stars depends ultimately on a knowledge of a vast number of reaction cross sections (Clayton and Woosley 1974). Many of these reactions involve stable targets and their cross sections are therefore accessible to laboratory measurement, but the majority of them involve radioactive targets and one must rely on theoretical cross sections in such cases. Continuing programs of cross-section measurement, carried on in this and other laboratories, have provided extensive data for direct use in nucleosynthesis calculations, and also for testing the statistical model codes which are used for providing the theoretical cross sections. The calculation by Woosley *et al.* (1975), of statistical model cross sections for all neutron, proton and α-particle induced reactions on all stable target nuclei from ^{20}Ne to ^{70}Zn, initiated greatly increased activity directed towards the testing of statistical model codes. These calculations predicted dramatic drops in (p, γ) and (α, γ) cross sections at the neutron thresholds for a number of targets; it was this feature of the predicted excitation functions which experimenters first seized upon as providing a stringent test of certain features of the statistical model codes.

The first two reported measurements of the effects on (p, γ) cross sections of competition from the neutron channel were those of Mann *et al.* (1975) for ^{64}Ni(p, γ)^{65}Cu, and Switkowski *et al.* (1978*a*) for ^{65}Cu(p, γ)^{66}Zn. Both of these measurements were concerned solely with observation of the relative magnitude of the drop in the (p, γ) cross section as the neutron threshold was crossed and absolute cross sections were not measured. However, Switkowski *et al.* did make an

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absolute measurement of the ^{65}Cu(p, α_0)^{62}Ni cross section, which also shows a marked drop at the neutron threshold. Whilst these and other measurements of competition effects involving the opening of the neutron channel led to a realization of the importance of the inclusion of width fluctuation corrections in the statistical model codes, absolute cross-section measurements are needed if all aspects of the codes are to be tested. We therefore decided to repeat the measurements on ^{64}Ni(p, γ)^{65}Cu and ^{65}Cu(p, γ)^{66}Zn to make them absolute. Switkowski *et al.* (1978*b*) also made a relative measurement of the ^{65}Cu(p, n)^{65}Zn cross section (which they normalized to the absolute data of Collé *et al.* 1974) using a neutron detector which was later shown by Kennett *et al.* (1980) to have a markedly energy dependent detection efficiency. We therefore decided to repeat this measurement as well. Finally, Switkowski *et al.* (1978*a*) used a natural copper target and measured cross sections for (p, γ) and (p, α) reactions on ^{63}Cu concurrently with those on ^{65}Cu. Again the (p, γ) measurements were only relative. Furthermore, to limit damage to the Ge(Li) detector caused by neutrons from ^{65}Cu(p, n)^{65}Zn, they restricted their (p, γ) measurements to the energy range of interest in observing the competition effect in the ^{65}Cu(p, γ)^{66}Zn cross section; this did not include the ^{63}Cu(p, n)^{63}Zn threshold, which occurs some 2 MeV above that for ^{65}Cu(p, n)^{65}Zn. We decided to measure the cross section of ^{63}Cu(p, γ)^{64}Zn absolutely and, using an enriched ^{63}Cu target, to extend the energy range to above the neutron threshold, and also to measure the ^{63}Cu(p, n)^{63}Zn cross section. Measurements of inelastic scattering cross sections are also useful for testing statistical model codes and we have included ^{63}Cu(p, p$'\gamma$)^{63}Cu in the present work, this being the only (p, p$'\gamma$) reaction for which there was a measurable yield.

2. Targets

The ^{63}Cu target was prepared by evaporating ^{63}Cu from an intimate mixture of CuO, enriched to 99·89% in ^{63}Cu, and graphite onto a gold substrate. The ^{65}Cu measurements were made with a natural Cu target prepared by evaporating metallic copper onto a gold substrate. The ^{64}Ni target was prepared by evaporation of metallic nickel powder, enriched to 96·48% in ^{64}Ni, also onto a gold substrate.

The target thicknesses of all targets were determined by direct weighing and by the three α-particle back scattering techniques described by Sargood (1982). All four techniques gave target thickness values in good agreement for each target. The adopted values were $3\cdot57\times10^{18}$ atoms cm^{-2} ±2% for the ^{63}Cu target, $1\cdot85\times10^{18}$ atoms of ^{65}Cu per cm^2 ±5% for the natural Cu target, and $6\cdot43\times10^{18}$ atoms cm^{-2} ±5% for the ^{64}Ni target.

Rutherford scattering measurements were made on all three targets before and after the reaction cross-section measurements and no target deterioration was observed.

3. Experimental Details

Charged particle beams were provided by the University of Melbourne 5U Pelletron accelerator and were collimated 40 cm upstream of the target by two 4 mm apertures. These apertures were followed by a grounded beam wiper and an electron suppressor ring held at -600 V.

The target chamber used for the $^{63}Cu(p,n)^{63}Zn$ and $^{64}Ni(p,n)^{64}Cu$ experiments consisted of a stainless steel cross constructed from tubing 3·8 cm in diameter. This was insulated from the beam line and was used as a Faraday cup for charge collection. The neutron detector consisted of two 50 cm long BF_3 tubes each of which was embedded in a $50 \times 15 \times 10$ cm block of paraffin. These were mounted in the forward hemisphere, one above and one below the line of the beam and at a distance of 10 cm from the target. The absolute detection efficiency of the neutron detector was determined by means of the reaction $^{48}Ca(p,n)^{48}Sc$, and was shown to be independent of neutron energy, over the range of energies encountered, by means of the $^{50}Ti(p,n\gamma)^{50}V$ reaction as described by Kennett *et al.* (1980).

For all other measurements a second stainless steel chamber was used, inside which a charged particle detector was mounted for the Rutherford scattering measurements, and which permitted the location of a Ge(Li) detector, in close proximity to the target, in the 55° direction. Gamma rays from the (p,γ) and $(p,p'\gamma)$ reactions were detected with a 120 cm^3 Ge(Li) detector when measurements were made below the neutron thresholds, and with a 60 cm^3 Ge(Li) detector for measurements above the neutron thresholds. Both detectors were placed 2·5 cm from the target and were calibrated in the conventional manner. Neutrons from $^{65}Cu(p,n)^{65}Zn$ were detected by means of a detector constructed around the target chamber in a similar manner to that described for the other (p, n) reactions except that the components were located in the backward hemisphere to make room for the Ge(Li) detector at 55°.

For the (p,γ) and $(p,p'\gamma)$ measurements, beam currents were typically $\sim 1\ \mu A$ and for the (p, n) measurements they were ~ 30 nA. Spectra from the detectors were collected in a PDP 11/40 computer and stored on magnetic tape. A pulser fed pulses into the Ge(Li) detector preamplifier and a scaler, and all measurements were corrected for dead time by means of the ratio of the number of counts recorded by the scaler to the number appearing in the pulser peak in the pulse height spectrum. The dead time corrections never exceeded 8%.

The ^{65}Cu and ^{64}Ni targets were 50 keV thick, and the ^{63}Cu target 28 keV thick, to protons of energy $\sim 2 \cdot 2$ MeV. The ^{65}Cu and ^{64}Ni excitation functions were measured with proton energy increments of 50 keV, the beam energy ranges being 1·05–3·25 MeV for $^{65}Cu(p,\gamma)^{66}Zn$, 2·20–3·25 MeV for $^{65}Cu(p,n)^{65}Zn$, 1·00–3·45 MeV for $^{64}Ni(p,\gamma)^{65}Cu$ and 2·50–3·80 MeV for $^{64}Ni(p,n)^{64}Cu$. The $^{63}Cu(p,n)^{63}Zn$ measurements were made with energy steps of 20 keV over the range 4·21–4·86 MeV. For the $^{63}Cu(p,\gamma)^{64}Zn$ measurement the target was turned through an angle of 55°, making its effective thickness the same as that of the ^{65}Cu and ^{64}Ni targets, and the excitation function was measured in energy steps of 50 keV over the range 1·05–4·70 MeV.

4. Results and Analysis

The results of the cross-section measurements are displayed in Figs 1–4. The data points are plotted at the energy corresponding to the centre of the target and the two lowest energy points in the (p, n) excitation functions have been corrected to allow for the rapidly changing cross section (see Sargood 1982). Each lowest energy (p, n) point has also been corrected to allow for the fact that it corresponded to a thick target yield.

No corrections for angular distribution effects have been made to any of the measurements. This is justified on the grounds that the target thickness straddles many resonances in the compound nucleus and the incoherent summing of many unrelated angular distributions will, on average, lead to severe attenuation of the angular distributions. Furthermore, the wide acceptance angle of the neutron detector would lead to further attenuation of any residual angular distributions in the (p, n) yields and, since the Ge(Li) detector was located in the 55° direction, only any residual $P_4(\cos\theta)$ terms could contribute any angular distribution effects in the (p, γ) and $(p, p'\gamma)$ measurements.

The non-statistical errors associated with the measurements are attributed mainly to detection efficiency, and are 9% for γ-ray detection and 10% for neutron detection. Other sources of error which have been taken into account are target thickness (2–5%), beam current integration (2%) and γ-ray branching ratios (2–5%). The resultant errors are 11% for the reactions on ^{63,65}Cu and 13% for the reactions on ^{64}Ni.

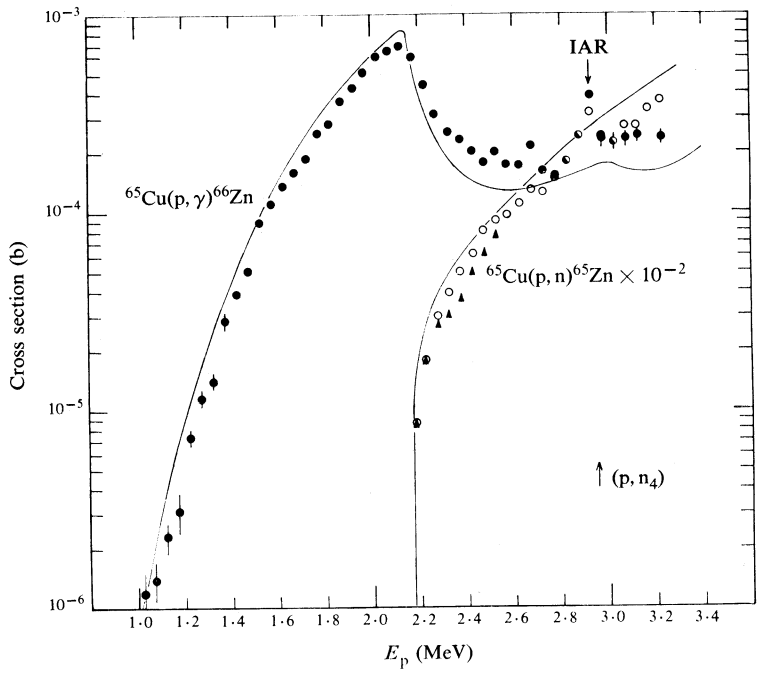

Fig. 1. Comparison between experimental data (points) and statistical model calculations (curves) for the cross section as a function of proton energy for the reactions ^{65}Cu(p, γ)^{66}Zn and ^{65}Cu(p, n)^{65}Zn. The circles are the present data and the triangles (p, n) data of Johnson *et al.* (1958). The error bars reflect statistical uncertainties only.

The curves in Figs 1–4 represent statistical model calculations made with the code HAUSER*4 (Mann 1976), using global optical parameters, and averaged over a smoothing interval equal to the energy thickness of the target used in the experiment.

Fig. 1 shows the $^{65}Cu(p,\gamma)^{66}Zn$ and $^{65}Cu(p,n)^{65}Zn$ results. The (p,γ) cross section is based on observation of the 1039 keV first excited state to ground state γ ray. From a study of the sum of all γ-ray spectra collected in the experiment, it was determined that this γ ray constitutes 94% of all transitions leading to the ground state, and therefore 94% of all (p,γ) reactions. The assumption that this fraction is constant over the proton energy range of the experiment is consistent with the spirit of the statistical model and is customarily made in measurements of this kind. As predicted by the statistical model calculations, the (p,γ) cross section drops sharply at the (p, n) threshold ($E_p = 2\cdot166$ MeV). The small predicted drop in the (p,γ) cross section at $E_p = 2\cdot947$ MeV is due to the opening of the (p, n_4) channel.

The prominent peak at $E_p = 2\cdot92$ MeV in both (p,γ) and (p, n) excitation functions is attributed to the isobaric analogue (IAR) of the 0·462 MeV fifth excited state of ^{66}Cu (Couchell *et al.* 1967).

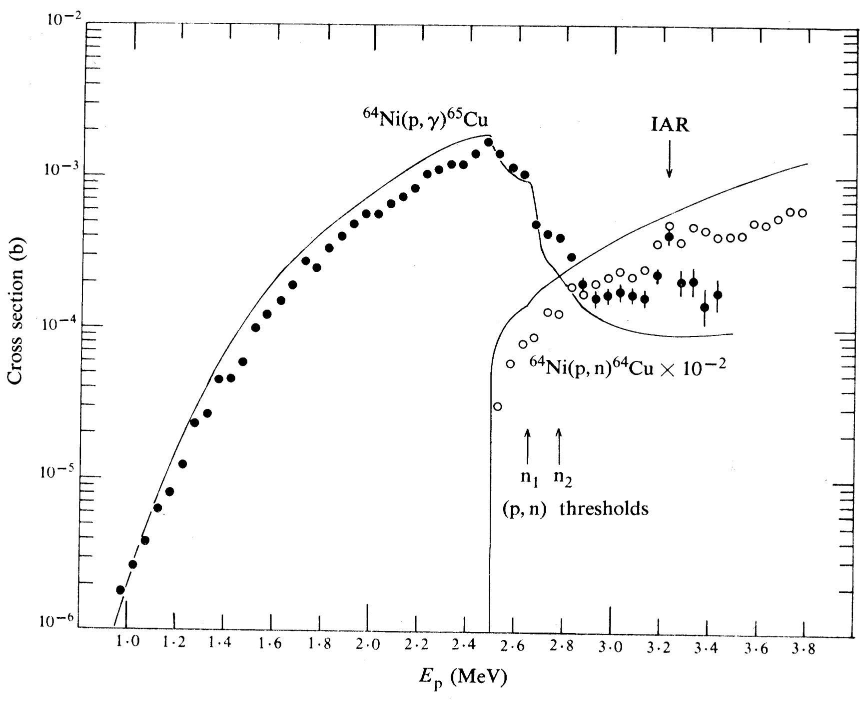

Fig. 2. Comparison between experimental data (points) and statistical model calculations (curves) for the cross section as a function of proton energy for the reactions $^{64}Ni(p,\gamma)^{65}Cu$ and $^{64}Ni(p,n)^{64}Cu$. The error bars reflect statistical uncertainties only.

Fig. 2 shows the $^{64}Ni(p,\gamma)^{65}Cu$ and $^{64}Ni(p,n)^{64}Cu$ results. Many γ-ray transitions to the ground state of ^{65}Cu were observed from the $^{64}Ni(p,\gamma)^{65}Cu$ reaction. The excitation function in Fig. 2 was based on the sum of the yields of 11 of these, with energies of 771, 1115, 1482, 1623, 1725, 2093, 2105, 2863, 2875, 2898, and 2901 keV. This sum represented 93% of the total of all observed ground state transitions. The pronounced drops in the (p,γ) cross section at $E_p = 2\cdot498, 2\cdot660$ and $2\cdot781$ MeV occur at the (p, n_0), (p, n_1) and (p, n_2) thresholds; the first two of these are well predicted by the statistical model calculation. The abrupt increase in the calculated (p, n) excitation function at $E_p = 2 \cdot 660$ MeV corresponds to the increase in cross section due to the opening of the (p, n_1) channel. The prominent peak at $E_p = 3 \cdot 22$ MeV, observed in both experimental excitation functions, is attributed to the isobaric analogue of the 0·064 MeV first excited state of ^{65}Ni (Browne *et al.* 1970).

Fig. 3 shows the ^{63}Cu(p, γ)^{64}Zn and ^{63}Cu(p, n)^{63}Zn results. The (p, γ) excitation function was based on the sum of the yields of the ground state γ rays from the 992 keV first excited state and 1799 keV second excited state of ^{64}Zn. These γ rays represented 85% and 10% respectively of all observed ground state transitions. Both the (p, γ) and the (p, n) excitation functions are comparatively featureless. No abrupt drop in the (p, γ) cross section occurs at the neutron threshold, nor is any predicted by the statistical model calculation, owing to the large number of proton and α-particle channels already open.

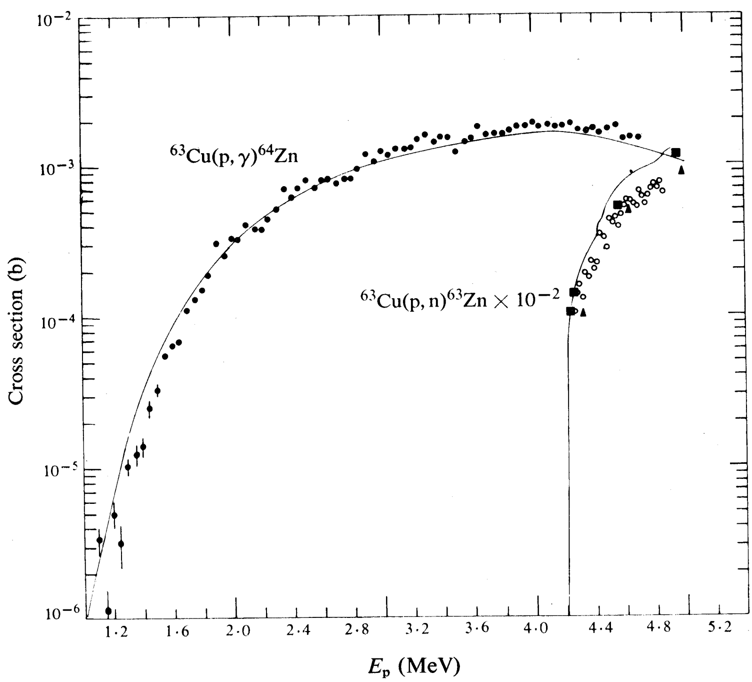

Fig. 3. Comparison between experimental data (points) and statistical model calculations (curves) for the cross section as a function of proton energy for the reactions ^{63}Cu(p, γ)^{64}Zn and ^{63}Cu(p, n)^{63}Zn. The circles are the present data, the triangles the (p, n) data of Collé *et al.* (1974), and the squares the (p, n) data of Mann and Kavanagh (1975). The error bars reflect statistical uncertainties only.

Fig. 4 shows the cross sections for ^{63}Cu(p, p_i) for i = 1–5. The cross sections were based on observation of the ground state γ ray from (p, $p_i\,\gamma$) for i = 1, 2, 4, 5, and of the 3→2 γ ray for i = 3. The branching ratios applicable to these γ rays were 100% for i = 1 and 2, 72% for i = 4, 80% for i = 5, and 16% for i = 3. The (p, $p_3\,\gamma$) ground state γ ray was obscured by that from ^{63}Cu(p, $\alpha_1\,\gamma$)^{60}Ni and could not be used. These branching ratio values, and those required to correct for feeding of lower energy states from above, were taken from the compilation of

Auble (1979). The (p, p′γ) data were not extracted above the neutron threshold because $^{63}Cu(p,n)^{63}Zn(\beta^+)^{63}Cu$ gave rise to the identical γ rays. The only noteworthy features in the excitation functions are the peaks at 2·6 and 3·0 MeV in the (p, p_1) plot. These occur at the correct energies to be the isobaric analogues of the 1^+ states in ^{64}Cu at 0·9 and 1·3 MeV.

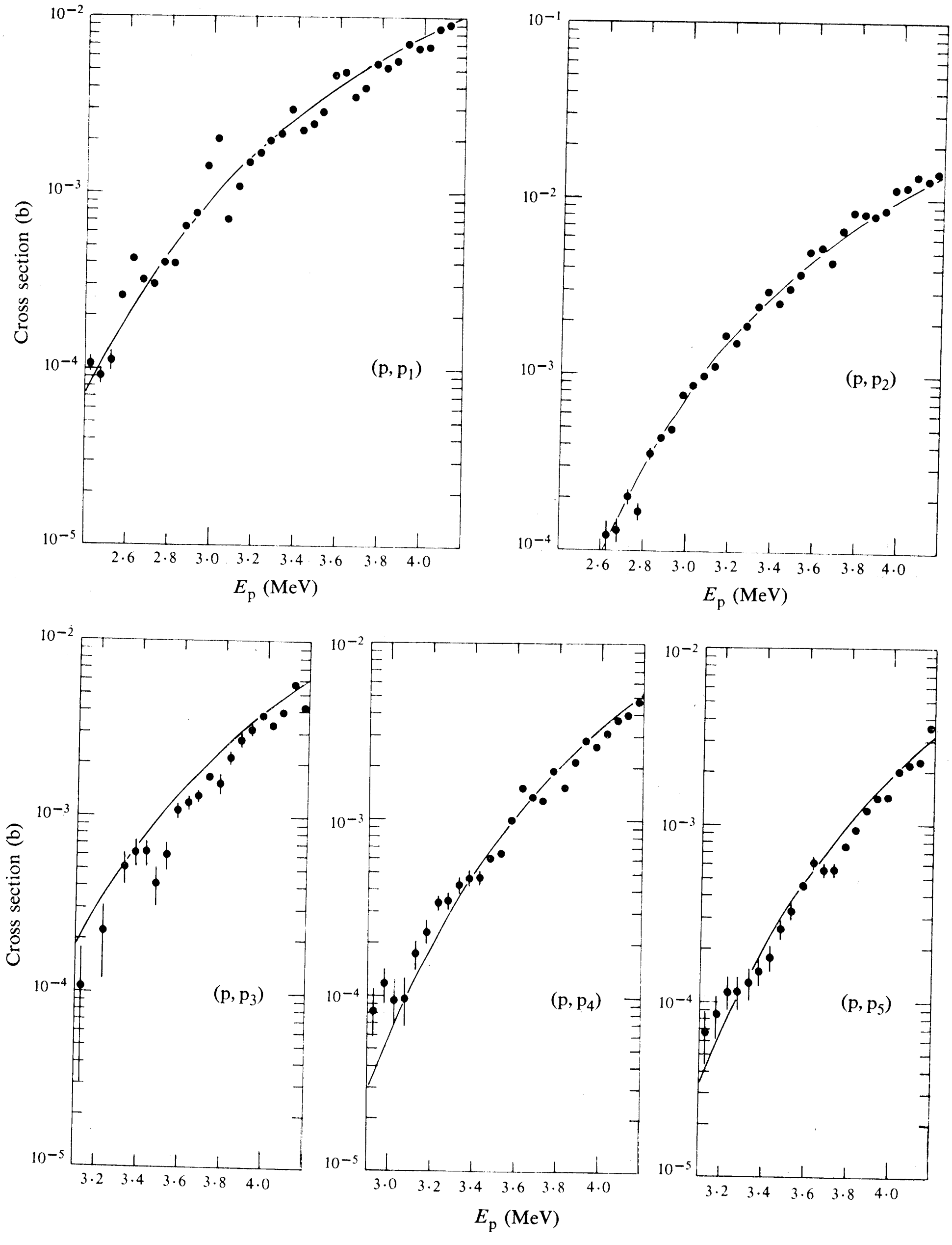

Fig. 4. Comparison between experimental data (points) and statistical model calculations (curves) for the cross section as a function of proton energy for the reactions $^{63}Cu(p, p_i)^{63}Cu^i$ for i = 1–5. The error bars reflect statistical uncertainties only.

5. Discussion

The ^{65}Cu(p, γ)^{66}Zn data (Fig. 1) reproduce in detail all the features of the unnormalized data of Switkowski *et al.* (1978*a*, 1978*b*). The calculation of the code HAUSER*4 is in good agreement with the data in that its values are only $\sim$30% high below the neutron threshold and $\sim$30% low above the neutron threshold. This corresponds to overestimation of the competition effect by a factor of $\sim$2. This is consistent with the fact that it overestimates the (p, n) cross section by $\sim$30% over the whole of our energy range. This is a very creditable performance for a code which uses global optical model parameters in the calculation of transmission functions in the particle channels. The agreement between our (p, n) data and those of Johnson *et al.* (1958), plotted as triangles in Fig. 1, is very good. Only one datum point from the work of Collé *et al.* (1974) fell in our energy range and it has not been plotted.

Our ^{64}Ni(p, γ)^{65}Cu data (Fig. 2) have very much finer resolution than those of Mann *et al.* (1975) and so provide a more stringent test of the ability of the code HAUSER*4 to describe the competition between the neutron and γ-ray channels. In particular the prediction concerning the competition cusps at the first two neutron thresholds is impressive. The absolute performance of the code is again very satisfactory. Over most of the energy range below the neutron threshold it is $\sim$50% high, but above the neutron threshold it is difficult to assess its degree of success because of the presence of the isobaric analogue resonance. However, the code does appear to underestimate the average cross section by about 50% and to overestimate the drop in the (p, γ) cross section by a factor of $\sim$2. Again, this is consistent with the fact that the code overestimates the (p, n) cross section, in this case by a factor of $\sim$2.

The absolute agreement between the theoretical and experimental ^{63}Cu(p, γ)^{64}Zn cross sections (Fig. 3) and ^{63}Cu(p, p$'$) cross sections (Fig. 4) below the neutron threshold is excellent, but once more the code overestimates the neutron cross section (Fig. 3), in this case by a factor of $\sim$1·5. The agreement between the present experimental data and those of Collé *et al.* (1974), plotted as triangles, and of Mann and Kavanagh (1975), plotted as squares, is most satisfactory.

From the astrophysical point of view, the success of the code HAUSER*4 must be assessed in terms of the oft-quoted requirement of reliability to within a factor of 2 in predicting cross sections. For the reactions reported here the code satisfies this criterion, but its (p, n) cross sections are consistently high and that of ^{64}Ni(p, n)^{64}Cu lies very close to the upper limit. The isotopes of Ni have a closed shell of 28 protons, and for all stable isobars with 28 neutrons HAUSER*4, with global optical model parameters, gave reaction cross sections which were near or above the upper limit (Kennett *et al.* 1981). These authors identified a parameter set which gave good agreement for all reactions on these nuclei and proposed its use with the unstable $N = 28$ nuclei. It would therefore be interesting to obtain cross sections for reactions on as many Ni isotopes as possible to see whether a similar approach is needed with $Z = 28$ nuclei.

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