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Compound nucleus (α,p) and (p,p') reactions on odd-A nuclei in the Ni region*

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Experimental compound nucleus cross sections are obtained for (p,p') and (α,p) reactions induced by 12 MeV protons and 15 and 18 MeV α particles on ^{55}Mn, ^{57}Fe, ^{59}Co, ^{61}Ni, and ^{63}Cu. The noncompound nucleus cross sections, estimated from the spectra from ^{64}Ni, are found to account for at least 20% of the total proton cross sections and also soften the spectra in the (p,p') cases. When these are subtracted off, good agreement in spectral intensities is found between experimental compound nucleus cross sections and predictions using Hauser-Feshbach calculations with Gilbert-Cameron level density parameters. No adjustable parameters were used. The slopes of the proton energy spectra from both (p,p') and (α,p) reactions are consistently flatter (i.e., decrease less rapidly with increasing proton energy) for odd-A than for even-even targets.

[NUCLEAR REACTIONS: ^{55}Mn, ^{57}Fe, ^{59}Co, ^{61}Ni, ^{63}Cu, ^{65}Cu (α,p), $E_\alpha = 15, 18$ MeV; ^{55}Mn, ^{57}Fe, ^{59}Co, ^{61}Ni, ^{63}Cu (p,p'), $E_p = 12$ MeV. Measured compound nucleus cross sections.]

INTRODUCTION

There has been an extensive program in the University of Pittsburgh Nuclear Physics Laboratory involving a separation of compound nucleus (CN) and noncompound nucleus (NCN) contributions to reactions exciting states in the high energy continuum region. Results have been presented on (p,p'), (p,α), (α,α'), and (α,p) reactions[1-3] on even-even target nuclei. In this paper, we apply the same separation method to odd-A nuclei in the Ni region with (α,p) and (p,p') reactions.

It has been noticed for some time that there are systematic differences between energy spectra of protons induced by reactions on odd-A and even-A nuclei. For example, Fig. 1 shows these energy spectra from (α,p) reactions on various targets. There are differences in Q values between odd-A and even-A nuclei, and there is a systematic difference in the energy at which the curves must be cut off because of structure which cannot be easily averaged over, but distinct from these matters there is a clear tendency for spectra from odd-A targets to vary less rapidly with energy. A similar effect is present in proton spectra from (p,p') reactions and will be discussed later. In (p,p') there are the added complications of isospin selection rules and pre-equilibrium reactions[4-6] which require consideration.

The method of separation between CN and NCN processes is based on the fact that in CN processes, the probability of proton emission is determined essentially by its competition with neutron emission, and that competition is extremely sensitive to the relative energies available for the two emission processes. These relative energies differ substantially from isotope to isotope of a given element, so that the proton emission probability may decrease by several orders of magnitude between proton rich isotopes in which proton emission is energetically favored and neutron rich isotopes where the situation is reversed. In the latter situation, protons from CN processes may be so rare as to be negligible relative to those from NCN processes. Since proton emission probabilities from NCN reactions vary slowly with mass number (A), a typical pattern in the Sn region is for the proton emission to decrease rapidly with increasing A among the light isotopes of an element and then remain constant among the heavy isotopes since CN processes are too small in cross section to contribute in the latter. In such situations, the proton spectrum from the heavy isotopes is taken to be the NCN contribution for all isotopes, and it may be subtracted from the measured spectra in the light isotopes to yield the CN contribution in them. This is the separation method we use.

The situation is somewhat less favorable in the Ni region because elements have fewer isotopes and CN proton emission is relatively more favored by the lower Coulomb barriers, so CN contributions to proton spectra are probably not completely negligible even in the heaviest isotopes. However, CN calculations indicate that that situation is approached in ^{64}Ni, ^{68}Zn, and ^{70}Zn, and proton spectra (including absolute cross sections) for those three isotopes were found to be essentially identical with one another contrary to CN predictions, so they were taken to be the approximate NCN contribution to be subtracted from spectra of lighter isotopes in obtaining CN spectra for the latter.[3]

This approximation cannot distort the shape of the spectrum obtained by the subtraction. If there is a CN contribution in ^{64}Ni, it will cause only an

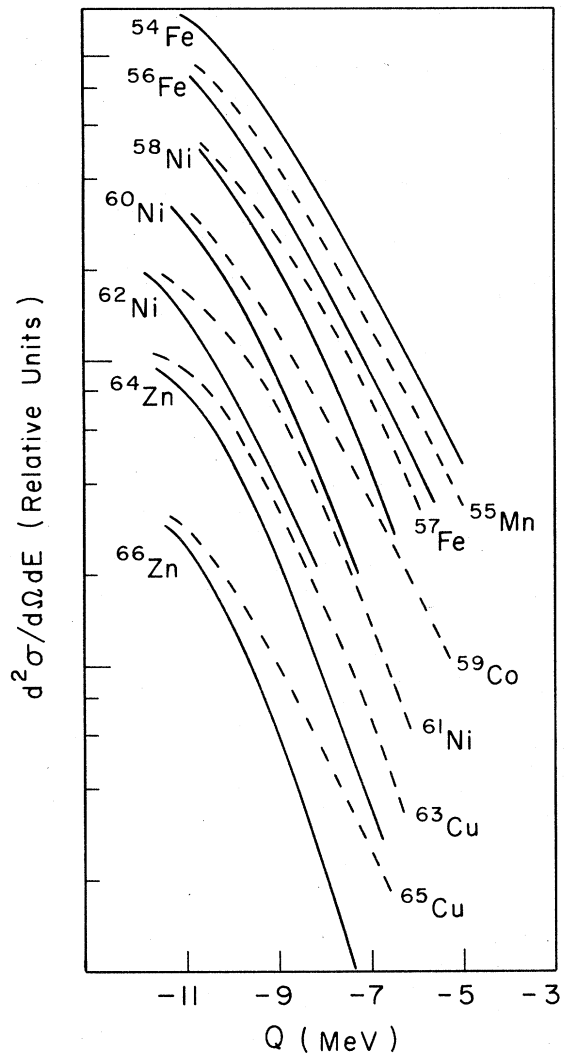

FIG. 1. Energy spectra of protons from (α,p) reactions on various nuclei.

additional subtraction of one CN spectrum from another of the same shape which does not alter the final shape. It will, of course, reduce the absolute cross section, but this is ordinarily not important relative to the uncertainties in the theory.

EXPERIMENTAL

The experimental methods have been described previously,[2] so they will be only briefly reviewed here. (p,p') and (α,p) reactions on nuclei in the Ni region were induced by 12 MeV protons, 15 MeV α particles, and 18 MeV α particles. The outgoing protons were observed with a detector telescope consisting of a 50 μm ΔE detector and a 2000 μm E detector. Particle identification was accomplished by gating the $E+\Delta E$ pulses with a discriminator fired by $E\times\Delta E$ pulses in a selected size range. All targets were of thicknesses between 1 and 2 mg/cm^2. Two detection angles, 75° and 135°, were used. Some of the proton spectra were checked by comparing with published data[4-7] and good agreement was found.

RESULTS AND ANALYSIS WITH CN THEORY

A. (α,p) reactions

A detailed discussion of the separation procedure and the Hauser-Feshbach calculations have been given in Ref. 3 where we reported the analysis of (α,p) reactions on even-even Fe, Ni, and Zn isotopes. Since the proton spectra from the ^{64}Ni(α,p) reactions were shown in that article to be more than 60% NCN in nature, they were used here as the NCN reaction cross sections in this region and were subtracted off to obtain the CN contributions. (Data from the same angle were used in the subtraction.) The resulting CN cross sections are shown in Fig. 2. As in the cases of even-even nuclei, since the shapes of proton spectra from different target are very similar to those from ^{64}Ni, the subtracting of NCN cross sections leaves the CN spectra essentially unchanged from the shapes of the total proton spectra. The net result, then, is just to decrease the spectra intensities.

The predictions with Hauser-Feshbach calculations using level density parameters from Gilbert-Cameron[8] and Dilg[9] are also shown in Fig. 2. These sets of parameters are both derived by level counting techniques. The calculations are simple with respect to isospin consideration because the α particle has $T=0$. For further information on these calculations, the readers are referred to Ref. 3. Figure 2 shows that the predictions obtained using Gilbert-Cameron parameters are nearly always higher in the peak region of the spectrum than those using Dilg's parameters. For both 15 and 18 MeV data, the spectral intensities are well predicted by calculations using Gilbert-Cameron parameters except for ^{55}Mn, and the predictions using Dilg's parameters are much inferior in all cases. The latter conclusion was not obvious for even-even nuclei where predictions from both sets of parameters are about equally compatible with the data. The larger discrepancy for the ^{55}Mn case, though it can be explained by inaccuracy of level density parameters, may be an indication that the ^{64}Ni(α,p) spectrum is not a good representation of the NCN contribution because ^{55}Mn and ^{64}Ni are too far separated in mass. On the other hand, the locations of the peaks in CN spectra are predicted to better than 0.5 MeV for both sets of parameters. This is not surprising since the peak positions are somewhat independent of the level density parameters and mainly determined by the energy depen-

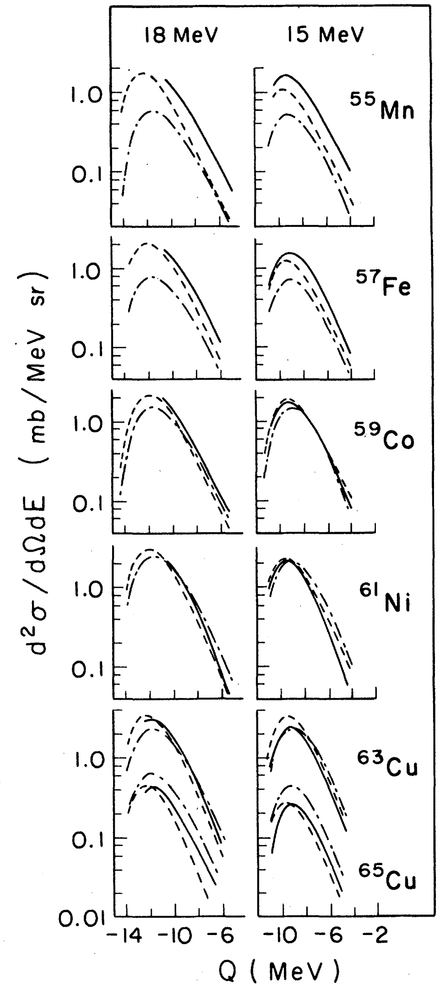

FIG. 2. Compound nucleus cross sections from (α,p) reactions with 15 and 18 MeV incident energies. Solid curves are the experimental data. Dashed curves and dash-dotted curves are from calculations using level density parameters from Gilbert-Cameron and Dilg, respectively.

dence of the proton transmission coefficient which, in this experiment, is calculated by proton optical model parameters taken from Perey.[10]

B. (p,p') reactions

In (p,p) reactions, the separation method must be reconsidered because of the excitation of the $T_>$ levels in the CN (we refer to this as CN-$T_>$). According to isospin coupling rules, they cannot decay to $T_<$ levels in the residual nucleus by neutron emission and must therefore decay exclusively by proton emission. In that this process is unaffected by neutron-proton competition, it may be thought of as an NCN process, but unfortunately it does not have the NCN property of slow variation with A. It varies rather as $1/(2T+1)$ and among the Ni isotopes that fraction varies by a factor of 3 between ^{58}Ni and ^{64}Ni. However, this problem is not as serious as it may appear since the ordinary CN contribution in ^{58}Ni is so large that uncertainties in what is to be subtracted are not very important.

To throw further light on this question, the measured spectra for ^{64}Ni, shown in Fig. 3, were separated into NCN and CN-$T_>$ portions. As a guide to this separation we have (1) the calculated CN-$T_>$ spectrum shown in Fig. 3, (2) the NCN contribution derived from pre-equilibrium theories by other authors also shown in Fig. 3, and (3) an independent demonstration[11] that NCN is predominant in this reaction at proton energies above 7 MeV. There is the complication that the calculated CN-$T_>$ contribution in this region is larger than what is observed, but this is readily explainable by isospin mixing. Vaz, Lu, and Huizenga[12] have estimated that this reduces the CN-$T_>$ cross section by a factor 0.5 ± 0.2, which would bring it into good agreement with the low energy portions of the observed spectra. When this adjustment is made, the observed ^{64}Ni spectra are readily explained as a sum of CN-$T_>$ and NCN parts.

One method for using the ^{64}Ni spectrum to correct observed spectra from other nuclei would be to subtract the NCN contribution directly, and multiply the CN-$T_>$ contribution by the ratio of $1/(2T$

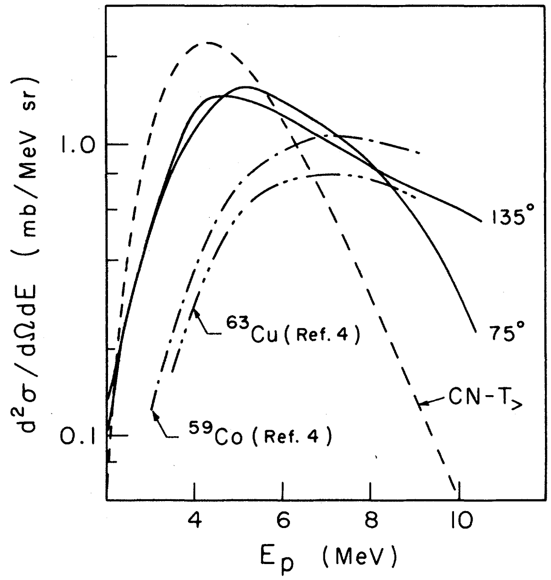

FIG. 3. Decomposition of proton spectra from ^{64}Ni-(p,α) induced by 12 MeV incident protons and observed at 75° and 135°. CN is mainly the $T_>$ compound nucleus cross section calculated with Gilbert-Cameron parameters. Precompound curves are those used in Ref. 4 for ^{59}Co and ^{63}Cu(p,p') reactions with 13 and 12 MeV incident energy, respectively. Both of them were observed at 90° laboratory angle.

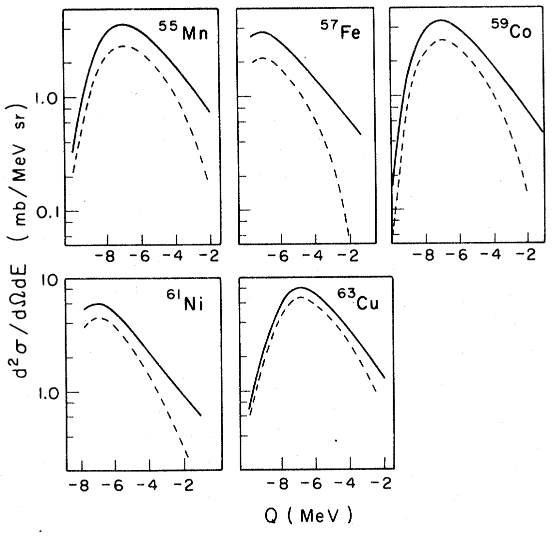

FIG. 4. Proton spectra observed at 135° are shown in solid curves. The compound nucleus cross sections obtained after subtraction of the ^{64}Ni spectrum are shown by the dashed curves.

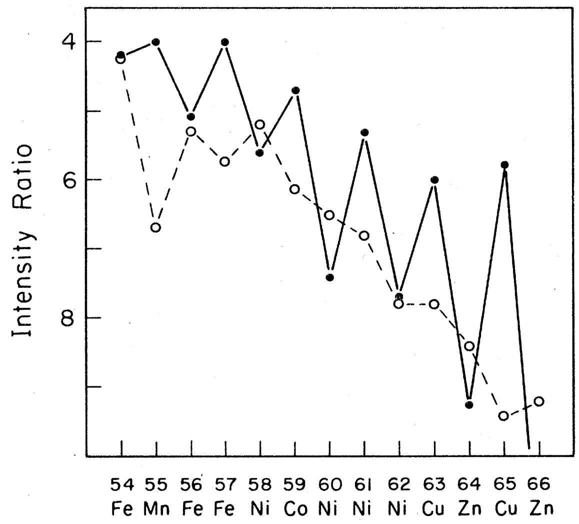

FIG. 6. Ratio of spectral intensities at ($Q=-11$ MeV)/($Q=-8$ MeV) for protons from (α,p) reactions in various nuclei (solid lines). Measurements are averaged between 75° and 135°. Dashed lines connect ratios calculated from CN theory.

+1) between that nucleus and ^{64}Ni before subtraction. This would amount to a tacit assumption that isospin mixing is the same in all nuclei.

The simpler alternative chosen was to subtract the ^{64}Ni spectrum directly. This leaves a difference spectrum which contains all of the ordinary CN contribution plus some small contribution from CN-$T_>$. Since the two contributors have the same shape, the spectral shape is not affected, and the only problem is in the absolute cross section. This may be applied to the theoretical curves to be compared, with the added advantage that the effect of varying the isospin mixing parameter may be explicitly displayed.

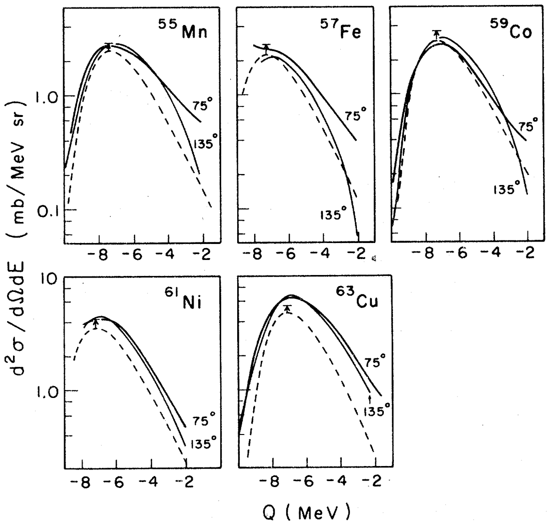

FIG. 5. Compound nucleus cross sections for (p,p') induced by 12 MeV protons (solid curves). The dashed curves are calculations using Gilbert-Cameron level density parameters. They represent the $T_<$ contributions and the arrows show the adjustment for CN-$T_>$ contributions assuming no isospin mixing.

The measured proton spectra from (p,p') reactions on various odd-A target nuclei are shown in Fig. 4, and the dashed lines there show the result of subtracting off the ^{64}Ni spectrum.

In Fig. 5, we show the cross sections obtained from the subtraction process of Fig. 4 (solid lines) compared to Hauser-Feshbach calculations (dashed lines) based on level density parameters from Gilbert-Cameron.[8] They represent only the ordinary (i.e., $T_<$) CN cross sections, and the arrows show the extent they will be increased if the adjustment for CN-$T_>$ contributions are taken into account assuming no isospin mixing.

The deviations between the curves for 75° and 135° in Fig. 5 cannot be real for CN processes. Near the high energy end of the spectra they may be explained by uncertainties in the smoothing processes since the actual spectra in that region are characterized by several distinct peaks. Otherwise these deviations can probably be ascribed to experimental error.

In general the agreement between theory and experiment is as good as would ordinarily be expected from a statistical theory. It should be noted that no arbitrary or adjustable parameters were used in the analysis. It might also be noted that there

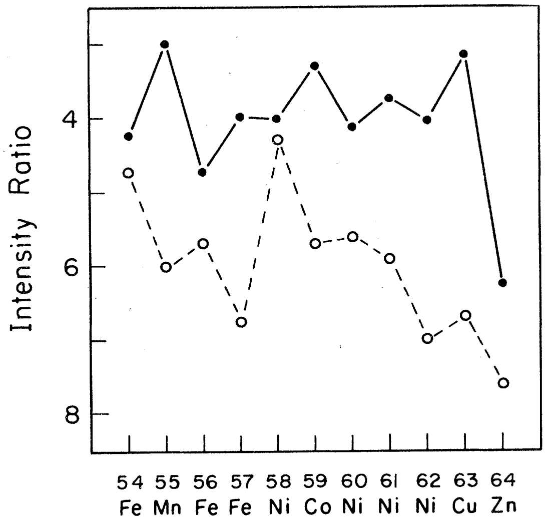

FIG. 7. Ratio of spectral intensities at ($Q = -6$ MeV)/($Q = -3$ MeV) for protons from (p,p') reactions in various nuclei (solid lines). Measurements are averaged between 75° and 135°. Dashed lines connect ratios calculated from CN theory.

seems to be a consistent tendency for the experimental spectra to fall off less rapidly with increasing energy than the calculated spectra in the high energy region. This could, of course, be due to an abnormally low NCN cross section in ^{64}Ni leaving some NCN contributions in the solid curves of Fig. 5. However, it is worthy of note that this problem did not occur in similar studies with even-even target nuclei, and it may be related to the discussion in the following section.

SYSTEMATIC DIFFERENCES BETWEEN EVEN-EVEN AND ODD-*A* TARGET NUCLEI

We now return to the question of the systematic differences in spectral shape between even-even and odd-A target nuclei as discussed in the Introduction in connection with Fig. 1. For (α,p) this is demonstrated in Fig. 6, which shows the spectral intensity ratios between ($Q = -11$ MeV)/($Q = -8$ MeV) (solid line). We see a clear and completely consistent alternation between odd-A and even-even nuclei. The dashed curve shows the theoretical predictions, and we see that there is nothing in the theory that predicts this alternation.

Figure 7 shows a similar treatment for (p,p') using the spectral intensity ratios between ($Q = -6$ MeV)/($Q = -3$ MeV). Again we see a consistent alternation in the data between odd-A and even-even targets, but here the situation is somewhat complicated by the fact that NCN processes are important in that region of the spectrum. An attempt was made to see if the alternation survives when the NCN contribution is subtracted as discussed previously, but the inconsistencies in results for 75° and 135° which are evident in Fig. 5 were larger than the effect under discussion. The Hauser-Feshbach calculations, shown by the dashed line in Fig. 7, give no indication of an explanation for the alternation. Figure 8 shows the ratio of observed to calculated ratios from Figs. 6 and 7. The low values for odd-A targets in (p,p') show the effect pointed out at the end of the last section.

In summary, there is a consistent difference between proton spectra from both (α,p) and (p,p') reactions from odd-A and even-even target nuclei; spectra from the former are flatter (intensity decreasing less rapidly with increasing energy) and spectra from the latter are steeper. There is nothing in the CN theory to explain this difference. One strange aspect of this problem is that in (α,p) reactions, odd Z-even N and even Z-odd N target nuclei behave similarly even though the former produce even-even, while the latter produce odd-odd, residual nuclei.

These conclusions should be considered tentative until confirmed by further study, but a reasonable effort was made in this work to avoid systematic differences between the two types of target nuclei. Measurements of these were interspersed and runs on several separate days were averaged before making comparisons. Results are somewhat more reliable for (α,p) than for (p,p') because of background problems and stronger angular distributions in the latter.

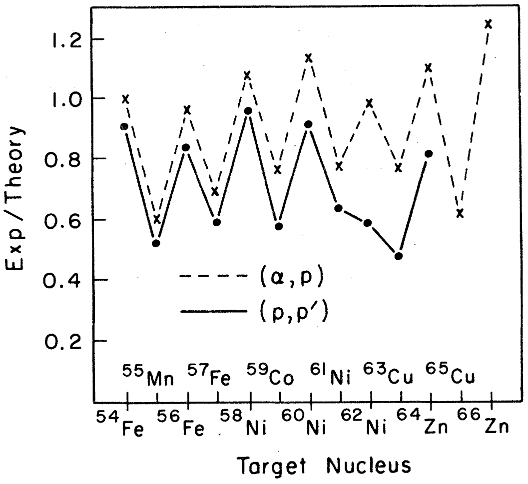

FIG. 8. Ratio of observed to calculated points in Figs. 6 and 7.

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