# Cusps in proton-induced reactions on intermediate-mass nuclei*

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Evidence for cusps is presented for the cross sections of inelastic proton scattering from $^{48}$Ti, $^{52}$Cr, and $^{56}$Fe as well as for the $^{48}$Ti$(p,n)^{48}$V reaction. Detailed statistical model calculations are compared with the experimental absolute cross sections.

[NUCLEAR REACTIONS $^{48}$Ti$(p,n)$, measured $\sigma(E,0)$, $E_p$=4.7–5.4 MeV. Compared data with statistical model calculations. Presents evidence for cusps in cross sections.]

In a recent publication, Mann, Dayras, and Switkowski[1] reported the observation of Wigner cusps in the $^{64}$Ni$(p,\gamma)^{65}$Cu reaction. They noted that although cusps had been observed for a number of reactions on light nuclei with the opening of neutron thresholds in proton-induced reactions, no cusps had been previously reported in charged-particle-induced reactions on intermediate mass nuclei. We would like to point out that a number of cusplike phenomena have been observed in inelastic proton yields near the thresholds for $(p,n)$ reactions.[2,3] While it is true that the authors of Refs. 2 and 3 did not emphasize the significance of the cusp behavior, it is appropriate now to examine the cusp nature of these reactions in the light of the renewed interest in this phenomena.

The threshold effect is expected to be most pronounced when the new channel opens suddenly, absorbing an appreciable amount of the total flux, and when the number of open channels which share the decreasing flux is small. The effect is expected to be especially pronounced for the emission of an $s$-wave neutron, since its transmission coefficient rises so rapidly with energy compared with higher $l$ values, as can be seen in Fig. 1. The $^{64}$Ni$(p,\gamma)^{65}$Cu reaction reported by Mann *et al.* is a particularly good example since at the low threshold energy of the $(p,n)$ reaction the open channels are mainly $(p,\gamma)$ channels and the high density of low-lying states in $^{64}$Cu makes the likelihood large that some of the states will be strongly populated by $s$-wave neutrons. The order of magnitude drop observed in the $(p,\gamma)$ cross section at the opening of the neutron threshold is a dramatic confirmation of the existence of the cusp.

The examples reported here of cusp behavior oc-

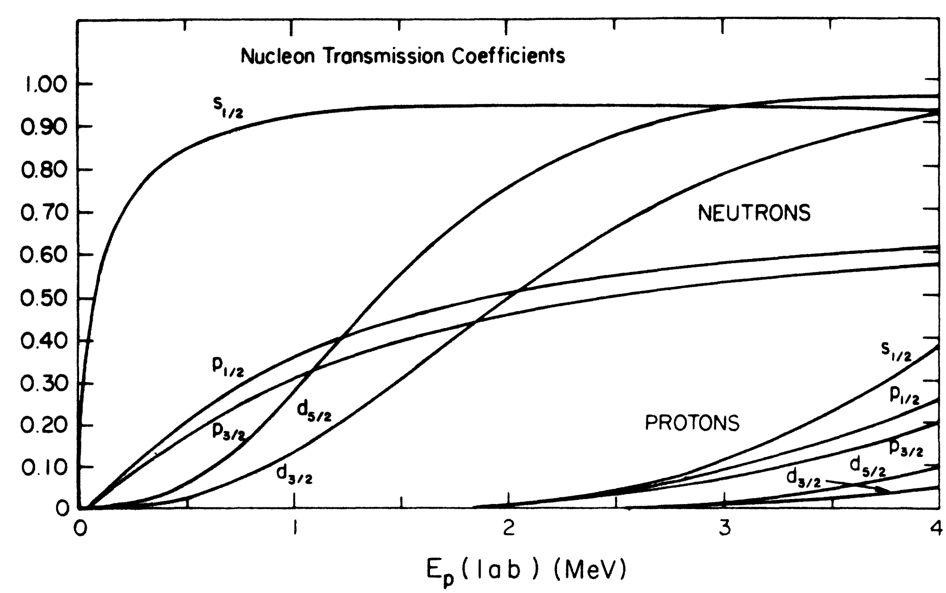


FIG. 1. The energy dependence of normalized nucleon transmission coefficients for the nucleus $Z=22$, $A=48$.

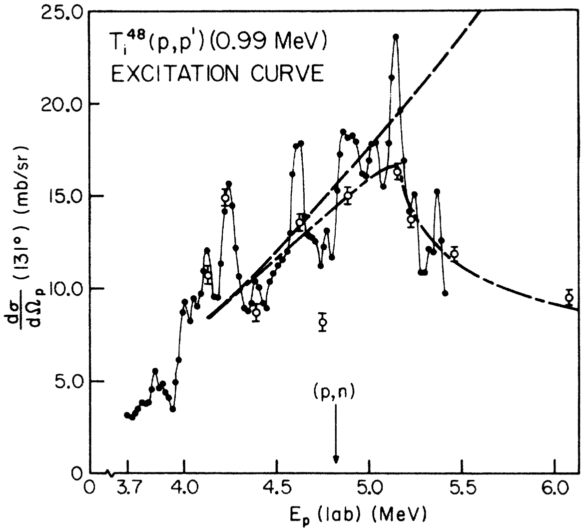


FIG. 2. The $^{48}Ti(p,p')$ (0.99 MeV) excitation curve. The solid line through the experimental points serves only to guide the eye. The dotted curves are calculations assuming differing numbers of open reaction channels.

cur in the inelastic proton decay channels to the first excited $2^+$ states in $^{48}Ti$, $^{52}Cr$, and $^{56}Fe$. Unlike the $^{64}Ni(p,\gamma)$ reaction, the $^{48}Ti(p,p')$ reaction, for example, is characterized by a rather large $(p,n)$ threshold energy, 4.80 MeV. In this case there are several open inelastic proton channels as well as open $(p,\gamma)$ channels at bombarding energies corresponding to the opening of the $(p,n)$ channel. Despite the other open channels, a cusp-like behavior can be observed in the average cross section for the proton decay channel leading to the first excited $2^+$ state.

The energy dependence of the inelastic yield to the first excited state in $^{48}Ti$ is reported in Ref. 3 and shown in Fig. 2. The cross section is characterized by a resonancelike structure (isobaric analog states) superimposed upon a smooth background. The curves shown in the figure were computed using the statistical compound nucleus program BARBARA written by Sheldon and Gantenbein.[4] Details of the calculations are contained in Ref. 3.

While the drop in the cross section by about a factor of 2 is not as dramatic as that observed in the $^{64}Ni(p,\gamma)$ reaction, the cusp effect can be observed in both the experimental and the calculated cross sections. What is particularly interesting about the cusp is that it does not appear at an energy corresponding to the threshold of the $(p,n)$ channel but rather at an energy approximately 400 keV above the threshold. While at the opening of any reaction channel, flux will be removed from other channels, it is only at the opening of an $s$-wave neutron channel that one expects a precipitous drop in flux from all other channels. On examining the level structure of the residual nucleus $^{48}V$ one finds that the first possible $s$-wave neutron threshold occurs for the first excited $2^+$ state in $^{48}V$ at an excitation energy of 320 keV. In general the low-lying excited states for the odd-odd nuclei in the $f_{7/2}$ shell are high-spin states and consequently do not exhibit the cusp behavior. It is also interesting to note that the statistical compound-nucleus calculation agrees reasonably well with the energy-averaged experimental cross section.

In order to investigate in more detail the shape of the yield curves at energies near the openings of the various $p,n$ channels, detailed calculations were performed using Sheldon and Rogers[5] most current statistical-model program CINDY. An option of this program which includes an approximate determination of the Moldauer width-fluctuation correction as described in Ref. 5 was selected. The necessary neutron and proton transmission coefficients were computed using the global optical model parameters of Becchetti and Greenlees.[6]

The calculations indicate significant cusps in the $(p,p')$ cross section at $(p,n)$ thresholds corresponding to small but nonzero residual state spins $J_n$. This is expected since high $J_n$ values with $s$-wave neutron emission require high compound state spins which, for zero-spin targets, require high $l$ incident partial waves which have small transmission coefficients. At the other extreme, $J_n=0$ is expected to show only weak cusp behavior since only one compound state $J_c=\frac{1}{2}$ can contribute and even though it has a significant proton transmission coefficient it suffers from a small statistical weight $2J_c+1$. Which of the $J_n^\pi$ values $1^\pm$ and $2^\pm$ exhibits the strongest cusp depends on the detailed values of the transmission coefficients. The order of the calculated strengths of the cusps for these $J_n$ values can change as a function of neutron threshold energy.

The results of the calculations for the reactions induced by the proton bombardment of $^{48}Ti$, $^{56}Fe$, and $^{52}Cr$ were compared with the published cross sections of Seward (Ref. 2) and are shown in Fig. 3. The calculated cross sections are shown in the figures by a solid line; cusp behavior can be seen at the openings of the various $s$-wave decay channels for all three of the isotopes. Negligible cusp behavior was observed at the openings of the ground-state $(p,n)$ channel for any of the isotopes because of the large spin $J_n \geq 4$ of the ground states. For the experimental cross sections, detailed cusp behavior is obscured by the presence of isobaric analog resonances. In general, the agreement between the calculated cross sections and the average experimental cross sections is

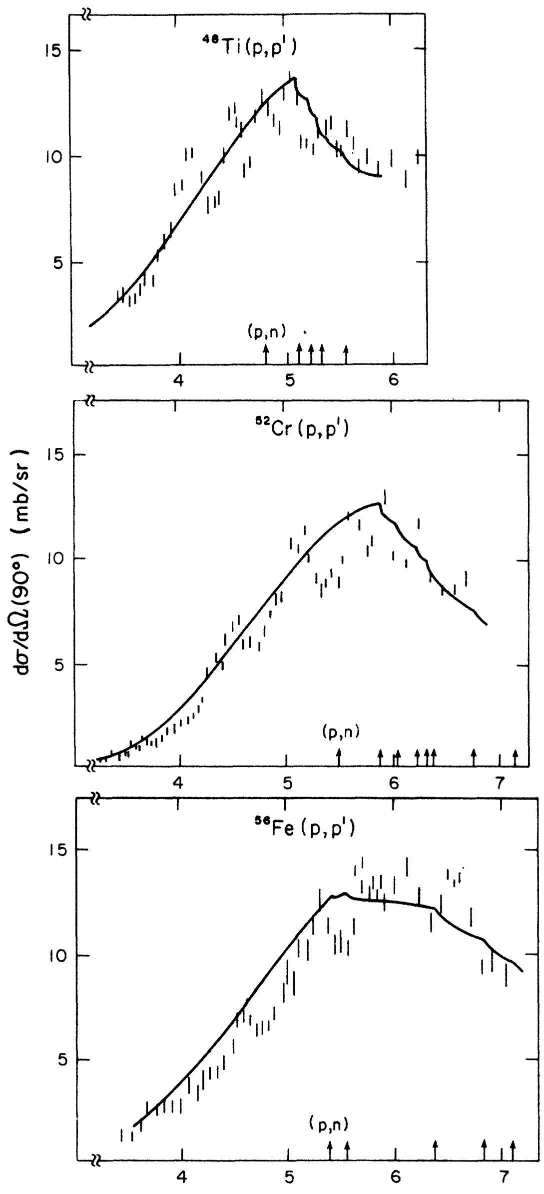


FIG. 3. The solid curves are statistical-model calculations for inelastic proton decay to the first excited $2^+$ states of the indicated nuclei. The arrows on the energy axis indicate the openings of various $(p, n)$ channels.

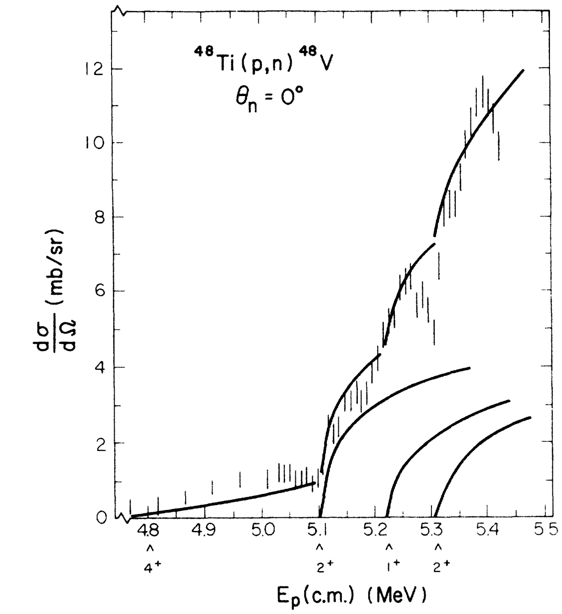


FIG. 4. The solid curve is a statistical-model calculation for the $^{48}Ti(p, n)^{48}V$ reaction using the same parameters as those for Fig. 3. The tick marks on the energy axis indicate the position of open $(p, n)$ channels.

quite good.

Since the region of the cusps in the cross section for the inelastic proton channel was obscured by the presence of analog resonances, it was decided to look at the neutron decay channel for one of the isotopes in order to verify the presence of the cusps and to test the statistical-model predictions. The analog-resonance decay through the isotopically forbidden neutron decay channel was expected to be sufficiently attenuated that the cusp behavior would show up in the neutron decay of the $T^<$ compound states. In addition, we were interested in observing how well the zero-free-parameter model predictions would agree with the shape and absolute cross sections for the measured neutron decay channels.

The absolute cross section for the reaction $^{48}Ti(p,n)^{48}V$ was measured at an angle of 0° with respect to the incident beam direction. Neutrons were detected using a Bonner sphere whose efficiency was determined at one energy using the known $^7Li(p,n)$ reaction cross section. The enriched (99.4%) $^{48}$Ti target had a thickness of 0.5 mg/cm$^2$. The measured cross sections have an absolute uncertainty of ±70% due primarily to target thickness nonuniformity and to the large uncertainty associated with the energy-dependent efficiency of the neutron detector.

The results of the $^{48}Ti(p,n)^{48}V$ reaction are shown in Fig. 4. The error bars on the experimental points are statistical only and reflect some background subtraction. Because of the large absolute uncertainty for the measured cross section, the data were normalized by a factor of 50% in order to compare with the calculated cross section. Three cusps are evident in the data corresponding to the openings of the $2^+$, $1^+$, and $2^+$ excited states of $^{48}$V. The opening of the $4^+$ ground-state channel results in a gradual increase in the cross section as characterized by $p$- or $d$-wave neutrons, as seen in Fig. 1.

The solid curve was calculated using the same parameters as were used to calculate the $(p,p')$ cross sections. In general, the agreement between the calculated cross section and the experimental cross section is good. The calculations reproduce the opening of the various channels both as to energy and shape. In summary, the statistic model used with the Becchetti-Greenlees parameters and incorporating the Moldauer level width-fluctuation correction produces a reasonable fit to the average energy behavior of the $(p,p')$ cross sections and to the cusps of the $(p,n)$ cross section for the cases studied.

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