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Energy dependence of the reaction $^{12}C(p,\pi^+)^{13}C$ to different final states

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Angular distributions have been measured for the reaction $^{12}C(p,\pi^+)^{13}C^*$ at several proton bombarding energies in the range 156–200 MeV. Distinct differences between single-particle and 2p-1h final states are observed in the energy variation of the angular distributions and total cross sections.

[NUCLEAR REACTIONS $^{12}C(p,\pi^+)^{13}C(Ex)$, $E_p = 156$–200 MeV, $Ex = 0.0$, 3.09, 3.68, 3.85, 6.86, 9.5 MeV; measured $d\sigma/d\Omega(\theta)$, $\theta = 25°$–$155°$.]

The (p,π^+) reaction has been studied extensively[1] because of intrinsic interest in the reaction mechanism and the hope that the high momentum transfer ($\gtrsim 470$ MeV/c) associated with this reaction might be used to investigate new aspects of nuclear structure. The primary attention in recent studies of the (p,π^+) reaction on nuclei has been focused on cases leading to single-particle final states, mainly because the relatively simple nuclear structure has been considered an advantage in attempts to establish the reaction mechanism. In some of these cases, detailed studies have been made of the energy dependence in the near-threshold region.[2] However, a basic understanding of the (p,π^+) reaction mechanism is still elusive, even with regard to a description of the dominant process. Calculations are in general plagued by theoretical uncertainties concerning the way momentum is shared by the constituents of the nucleus, the distortion of the outgoing pion, the role played by pion rescattering, and the residual state nuclear wave function at high momentum. The two theoretical approaches most often used to calculate differential cross sections are the distorted-wave Born approximation (DWBA) pionic stripping model[3,4] and the two-nucleon model (TNM).[5,6] The former uses a nonrelativistic reduction of the pseudoscaler πNN vertex as a one-body (nucleon) transition operator, whereas the latter, assuming the dominance of intermediate Δ propagation, used the transition potential of the $NN \rightarrow \Delta N$ process together with the $N\Delta\pi$ vertex as a two-body transition operator. For the $^{12}C(p,\pi^+)$ reaction, it has been found that these two different approaches can produce qualitatively similar fits to cross section angular distributions for single-particle final states at 185 MeV bombarding energy.[4,6]

One possible way to probe the nature of the reaction mechanism and impose further constraints on the two models is to study the energy dependence of transitions not only to single-particle but also to 2p-1h final states, since the different residual-state structures may enhance different aspects of the pion production mechanism. For example, whereas single-particle states can be excited by a simple stripping mechanism, the excitation of 2p-1h states requires a multinucleon mechanism. For the case of $^{12}C(p,\pi^+)$, data at 185 and 200 MeV indicate[7,14] that single-particle and 2p-1h final states are populated with about equal strengths.

In this paper, we present data on the energy dependence near threshold ($T_\pi^{\text{c.m.}} = 3.7$ to 46.6 MeV) of the $^{12}C(p,\pi^+)^{13}C$ reaction leading to specific final states: the well known $1p_{1/2}$, $2s_{1/2}$, and $1d_{5/2}$ single-particle states at $0.00(\frac{1}{2}^-)$, $3.09(\frac{1}{2}^+)$, and $3.85(\frac{5}{2}^+)$ MeV, and the 2p-1h states at 3.68 $(\frac{3}{2}^-)$, $6.86(\frac{5}{2}^+)$, and $9.50(\frac{9}{2}^+)$ MeV, whose dominant configurations are $[1p_{1/2} \otimes 2^+(1p_{3/2}^{-1}1p_{1/2})]$, $[1d_{5/2} \otimes 2^+ + 2s_{1/2} \otimes 2^+]$, and $[1d_{5/2} \otimes 2^+]$, respectively.[8-11] The experiment was performed with the variable-energy proton beam from the Indiana University Cyclotron Facility. At the lower bombarding energies, $T_p = 156$, 159, and 166 MeV, the positive pions were detected by using an opposing dipole ($D\bar{D}$) pion spectrometer.[12] At higher energies, $T_p = 170$, 174, and 200 MeV, a quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrograph[13] was used. The energy resolution of the QDDM was sufficient (63–120 keV) to resolve the close-lying doublet state at 3.68/3.85 MeV, and thus separate angular distributions for these states were obtained.

The angular distributions of the (p,π^+) differential cross sections are shown in Fig. 1. The 185-MeV Uppsala data[14] are also included, except for the unresolved 3.68 and 3.85 MeV states, multiplied by a factor of 1.27 for normalization to overlapping IUCF data. For incident energies of 156 and 159 MeV, the 3.85-MeV angular distributions include a contribution from the 3.68-MeV state, since the two states could not be resolved by the $D\bar{D}$ spectrometer; however, the centroid

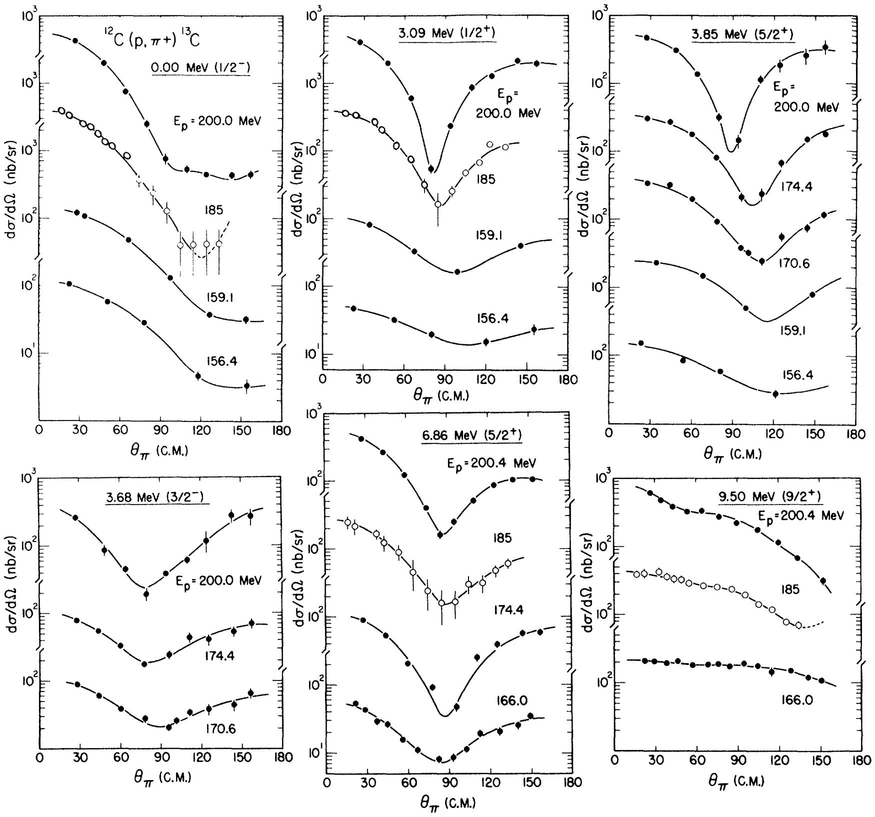

FIG. 1. Angular distributions at different bombarding energies leading to single-particle final states (top) and 2p-1h final states (bottom). The data at $T_p = 185$ MeV are from Ref. 14 normalized by a factor of 1.27. The data at $T_p = 200$ MeV are published in Ref. 17. The curves are best fits to the data using Legendre polynomials.

of the doublet corresponds closely to the 3.85-MeV state, indicating that the contribution of the 3.68 MeV state is less than 20%. In general, the structure in all the angular distributions becomes more pronounced as the energy increases. The solid lines displayed in Fig. 1 are χ^2 minimization fits with Legendre polynomials, including orders up to P_3 below 180 MeV and up to P_4 at higher energies. Only for the 9.50-MeV state at 200 MeV was P_5 necessary to obtain a good fit to the data. A significant distinction between the single-particle and 2p-1h final states is the fact that the characteristic minimum of the angular distributions in the case of the single-particle states shifts toward backward angles as the incident energy decreases, whereas for the 2p-1h states, little or no shift is observed. This contrast is especially clear for the two states of the same spin-parity ($\frac{5}{2}^+$) at 3.85 and 6.86 MeV.

In Fig. 2, the values of the momentum transfer $q_{\min}$ at the position of the minimum in the angular distributions are plotted versus the outgoing pion momentum P_π. Results for the ^{41}Ca ground state[2] are also included for comparison. It is observed that $q_{\min}$ varies linearly with P_π and has a similar slope for the 1d, 2s, and 1f single-particle shell orbits within uncertainties; the values of $dq_{\min}/dP_\pi$ from linear least squared fits are 0.74 ±0.08, 0.65 ± 0.08, and 0.82 ± 0.09, respectively.

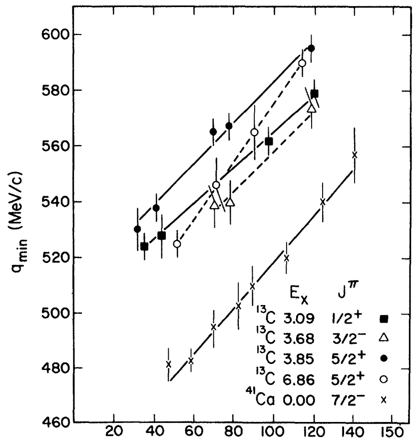

FIG. 2. Momentum transfer at the position of the minimum in the angular distribution versus outgoing pion momentum. The straight line drawn for each state is the result of a linear least-square fit.

For the 2p-1h state at 6.86 MeV the slope is steeper (1.06 ± 0.11) than for the single-particle states. The slope for the other 2p-1h state at 3.68 MeV has a rather large uncertainty (0.72 ± 0.22), and little can be inferred about its behavior relative to the single-particle states.

The most striking difference between the single-particle and the 2p-1h states lies in the energy dependence of the total cross sections shown in Fig. 3. The total cross sections were derived from the a_0 coefficient of the Legendre polynomial fits in Fig. 1. For the three single-particle states, the total cross section rises rapidly near threshold due to phase space and barrier penetrability effects for the outgoing pion, and then more slowly than predicted by penetrability arguments at higher energies.[2,15] The excitation functions for the 2p-1h states at 3.68 and 6.86 MeV are in general steeper than those for the single-particle states in the same energy region. The difference is most pronounced between the two states of the same spin and parity ($\frac{5}{2}^+$) at 3.85 and 6.86 MeV. The large change in pion energy (factor of 10) over the bombarding energy range (20% in proton energy) covered by the data suggests that pion rescattering effects may contribute significantly to the energy variation observed for the 2p-1h states. A recent experiment at LAMPF[16] shows that the pion inelastic scattering to the 4.44-MeV (2^+) state in ^{12}C has a strong and very broad enhancement around $T_\pi = 220$ MeV.

Compared to the two lower-energy 2p-1h states, the 9.50-MeV ($\frac{9}{2}^+$) state shows a quite different character in its excitation function as well as in its angular distribution. The energy variation of the total cross section for this state is more like, although slightly flatter than, that for the single-particle states. The strong enhancement for this state may be partly due to its high spin, which would be favored because of the large angular momentum mismatch in the (p,π^+) reaction. It is interesting to note that this state is thought to have a stretched neutron configuration. This is deduced from the large π^-/π^+ ratio observed in pion inelastic scattering.[10] Thus it appears that the excitation of 2p-1h states in the (p,π^+) reaction depends significantly on the details of the nuclear structure of the final states.

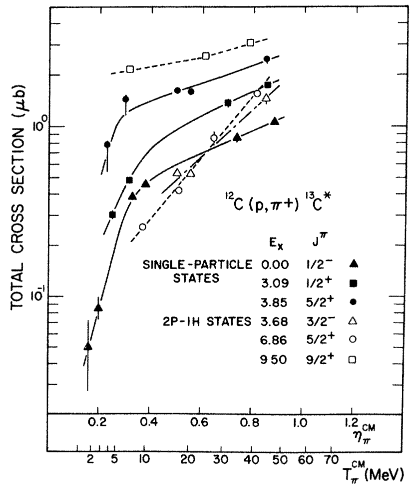

FIG. 3. Energy dependence of the total (angle-integrated) cross section versus pion center-of-mass momentum $\eta_\pi^{c.m.}$ (in units of $m_\pi c$). The lines are guides for the eye. The points for the ground state at the two lowest energies are from Ref. 15. The two low-energy 3.85-MeV state points have larger error bars, reflecting the uncertainty in the subtraction of the unresolved 3.68 MeV state (see text).

In summary, the data presented here on the energy dependence of the (p,π^+) reaction leading to both single-particle and 2p-1h final states in ^{13}C show distinct differences between these states. Such data should provide useful tests of microscopic models of the reaction process. So far, most theoretical calculations for the ^{12}C (p,π^+) reaction have been made only at one incident energy ($T_p = 185$ MeV). Calculations to match the present data on the energy and state dependence of the reaction would be instructive.

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