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Pion single charge exchange on ^{14}C

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Forward-angle differential cross sections for the isobaric-analog state in the $^{14}C(\pi^+,\pi^0)^{14}N$ reaction were measured at 100, 165, 230, and 295 MeV. The extracted excitation function is found to have a maximum near 200 MeV and its shape resembles that of the free πN cross sections. Impulse-approximation calculations with optical potentials linear in the nuclear density do not reproduce the trends of the data. Systematics of 0° cross sections with N and Z are presented.

The semimagic nucleus ^{14}C provides a unique opportunity for obtaining a complete set of pion-scattering measurements that are related by isospin invariance. The nuclear level spacings in the $A=14$ nuclei are the most favorable among the $T\geq 1$ nuclei, for studies of the $^{14}C(\pi^+,\pi^0)^{14}N$ isobaric-analog-state (IAS) and the $^{14}C(\pi^+,\pi^-)^{14}O$ double-isobaric-analog-state (DIAS) transitions. The separations of the IAS in ^{14}N are 2.31 MeV from the 1^+ ground state and 1.65 MeV from the 1^+ second excited state[1]. Population of these 1^+, $T=0$ neighbors requires spin transfer $\Delta S=1$. Such states typically have small cross sections in pion scattering at forward angles.[2] These features of ^{14}C, together with the currently available resolution of 3 to 5 MeV of the Los Alamos π^0 spectrometer, make it possible to obtain reliable forward-angle cross sections for the $^{14}C(\pi^+,\pi^0)^{14}N$ (IAS) reaction.

The isospin invariance properties of the pion-nucleus interaction have been explicitly adopted in recent theoretical work in which the pion optical potential is separated into isoscalar U_0, isovector U_1, and isotensor U_2 components.[3] The isovector term is most directly studied through (π^+,π^0) IAS transitions. Since DIAS transitions may proceed through two sequential operations of U_1 as well as directly through U_2, a full understanding of the role of the U_2 requires that U_1 also be well understood. To date, a unified study of U_0, U_1, and U_2 terms that takes into account the special sensitivities of each of the scattering and charge-exchange processes has not been carried out because of the lack of the appropriate IAS data on $T\geq 1$ nuclei.

As the first step in a unified study of U_0, U_1, and U_2, we present in this paper the 0° excitation function for the $^{14}C(\pi^+,\pi^0)^{14}N$ (IAS) reaction at 100-, 165-, 230-, and 295-MeV incident pion-beam energies. The data at 230 and 295 MeV represent the first measurement of forward-angle IAS differential cross sections with energies above the $\Delta(\frac{3}{2},\frac{3}{2})$ resonance. Measurements of the concomitant elastic and double-charge-exchange experiments at several of these energies are in progress.[4]

The experiment was performed with the π^0 spectrometer[5] mounted in the low-energy pion channel at the Clinton P. Anderson Meson Physics Facility. The spectrometer was set in its one-post configuration (horizontal scattering plane) at a 5° scattering angle. The distances to the first converter varied from 104 cm for the 100-MeV data to 154 cm for the 295-MeV data. With these configurations, the π^0 spectrometer spanned an angular range from 0° to 15°. A single converter in each photon detector was used for the experiments at 100, 165, and 230 MeV, while three converters were used in each photon detector for 295-MeV measurements. The energy resolution was about 4 MeV with one converter and about 5 MeV with three converters.

The target consisted of 9.12 g of carbon powder enriched to 82% (Ref. 6) in ^{14}C and pressed into two 5- by 5- by 0.6-cm nickel target cells, which had windows 25 μm thick. The ^{14}C target thickness was of 0.30 ± 0.02 g/cm^2. The pion flux was determined by the scintillator activation technique.[7]

During data analysis, the angular range of the π^0 spectrometer was subdivided into four bins. The variation of the spectrometer acceptance with π^0 energy, and the mean acceptance angle for each θ bin, were calculated by Monte Carlo simulation.[5] The effective solid angle at each energy was determined with use of CH_2 targets and the known $\pi^-p\rightarrow\pi^0n$ cross sections.[8]

Typical π^0 spectra are shown in Fig. 1. There is a clear peak at the expected energy of the IAS in all the spectra. The IAS peak areas were extracted by fitting the data with the instrumental line shapes and polynomial functions for the backgrounds. Line shapes were obtained by Monte Carlo simulation of the beam, target, and spectrometer conditions.[5] The statistical and fitting errors in the peak areas

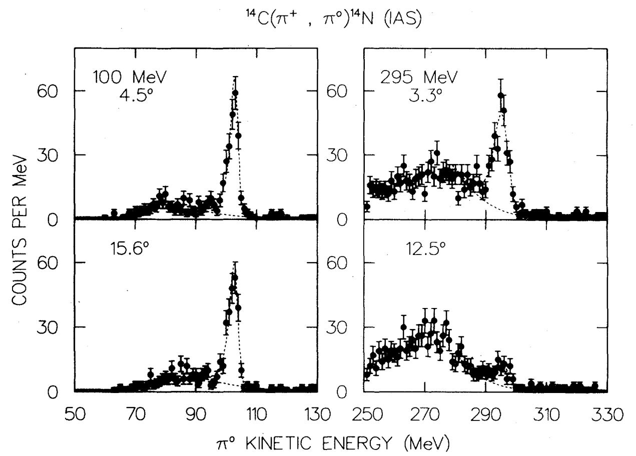

FIG. 1. Measured π^0 spectra for the $^{14}C(\pi^+,\pi^0)$ reaction at 100- and 295-MeV incident beam energy. The dashed lines show the fits to the data used to determine the IAS peak areas.

varied from 7 to 20%, and the overall normalization error is 15% at each energy.

Extrapolations of the 0° cross sections were performed by fitting the measured angular distributions with shapes given by the distorted-wave impulse-approximation (DWIA) calculations discussed below. These calculations predict only a small rise in the cross section between the most forward-angle data point (3° to 4°) and 0°. The largest extrapolation is at 295 MeV, where the ratio $\sigma(0°)/\sigma(3.3°)$ is 1.05. The extracted 0° cross sections, $\sigma_{IAS}(0°)$, are shown in Fig. 2

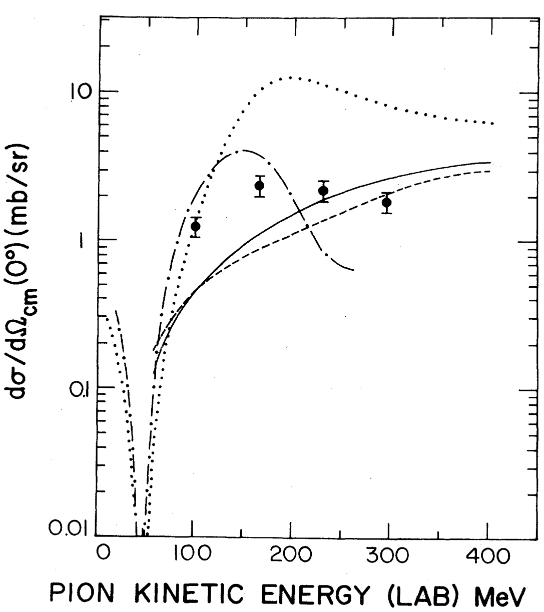

FIG. 2. Comparison of the measured 0° cross sections with theoretical calculations. The dot-dot curve represents the free πN laboratory cross sections. The solid and dashed curves are first-order DWIA calculations using Skyrme III and harmonic oscillator models for the transition densities, respectively, as discussed in the text. The dash-dot curve includes the medium corrections of Ref. 16.

TABLE I. Reduced (π^+,π^0) IAS cross sections. Values are the measured $\sigma_{IAS}(0°)/(N-Z)A^{-4/3}$ (mb/sr) in the center-of-mass system.

Target	Beam energy (MeV) 100	165	230	295
^{7}Li	12 ±2[a]	54 ±8[a]	39 ±6[b]	32 ±5[b]
^{13}C	13 ±2[a]	55 ±10[a]		
^{14}C	21 ±3[c]	40 ±6[c]	37 ±6[c]	31 ±5[c]
^{15}N		44 ± 11[a]		
^{18}O		45 ± 10[a]		
^{120}Sn	18 ±4[a]	55 ±5[a]		

[a] Reference 11. [b] Reference 12. [c] This experiment.

and are given in Table I.

It is of interest to compare $\sigma_{IAS}(0°)$ for ^{14}C with the trends seen in other nuclei; the strong absorption model[9] predicts that the scaling factor of cross sections with respect to nuclear size and neutron excess in $(N-Z)A^{-4/3}$. The ratios $g=\sigma_{IAS}(0°)/(N-Z)A^{-4/3}$ of the available IAS cross sections[10-12] are given in Table I. The model is expected to be most accurate at the resonance energy of 165 MeV. The data at this energy, which are for targets ranging in neutron excess from 1 to 20, yield a nearly constant value $g=49\pm5$ mb/sr. The value of g is lower at energies above and below the delta resonance. At 100 MeV, a value $g\simeq13$ mb/sr describes quite well the data for most nuclei.[10] Compared to this, the value 21 ± 3 mb/sr for ^{14}C at 100 MeV seems anomalously high. We have no explanation of this discrepancy at the present time.

The DWIA calculations presented in Fig. 2 were made with a modified version of the computer code DWPI.[13] Only the first-order optical potential (linear in the nuclear density ρ) of Ref. 3 was used. The isoscalar and isovector parameters characterizing this potential were determined from the elementary πN phase shifts.[8] The two calculations in Fig. 2 differ in the choice of transition density distributions ρ_{tr} for the $(1p_{1/2})^2$ excess neutrons. One is based on a Hartree-Fock calculation with the Skyrme III force[14] to determine the $1p_{1/2}$ wave functions, while for the other calculations we used simple harmonic oscillator wave functions with an oscillator parameter[15] of 1.66 fm. The ground-state densities used to generate the distorted waves for both DWIA calculations were taken from elastic electron-scattering results.[15]

The DWIA calculations do not reproduce quantitatively the measured excitation function. The experimental $\sigma_{LAS}(0°)$ increases from 100 to 200 MeV, but, contrary to the theoretical curves, does not rise thereafter. The trend is, in fact, very similar to that of the elementary πN charge-exchange cross sections.[8] The data are about a factor of 10 below plane-wave impulse-approximation calculations, indicating that nuclear distortions are very important. The monotonic increase in the DWIA excitation functions can be understood jointly in terms of the rapid increase in the elementary cross section below 200 MeV and the increased penetration of the pion above the resonance energy. Differences in the magnitudes of the two transition densities in the tail region are reflected in the differences in the DWIA cross sections. One can see that the experimental energy dependence of the 0° cross sections cannot be accounted for simply by changes in the transition density.

The underprediction of the 0° cross sections below 200 MeV is characteristic of the failure of many first-order calculations.[3,9–11] Some success in accounting for such discrepancies has been obtained in recent work in which the effects of nucleon binding and Pauli blocking are explicitly considered in the theoretical construction of the distorted waves.[16] It is found that the absorption in low partial waves can be considerably reduced, resulting in increased cross sections at the lower pion energies. Results are illustrated for ^{14}C in Fig. 2, where the distorted waves generated by the model have been used within an otherwise conventional DWIA calculation. No energy shift has been included in the transition t matrix. Although arguments may be made for such a shift,[16] its use raises the cross sections above 200 MeV.

Alternatively, higher-order corrections to the DWIA may also be made by inclusion of ρ^2 terms in the optical potentials.[3] We have made such a calculation at 165 MeV and find an increase of about a factor of 2 in the 0° cross section, as required by the data. It will be interesting to determine whether the energy dependence can be correctly reproduced by inclusion of the ρ^2 terms.

In summary, the measurements of the $^{14}C(\pi^+,\pi^0)^{14}N$ IAS transition have provided the first evidence that $\sigma_{IAS}(0°)$ has a peak near 200 MeV. The ratios $\sigma_{IAS}(0°)/(N-Z)A^{-4/3}$ were extracted for nuclei ranging from $A=7$ to 120, and found to be remarkably constant at 165 MeV. At 100 MeV, this ratio for ^{14}C is higher by nearly a factor of ~ 2 compared to the other nuclei. First-order DWIA calculations do not reproduce the shape or magnitude of the excitation function, which resembles the free πN cross sections. Specifically, the predicted increase in cross section above resonance energies is contrary to the measurements. Corrections in the distorted waves caused by binding and blocking effects produce better agreement with the trends of the data. The data presented here, together with the corresponding elastic- and DIAS-scattering data now being measured on ^{14}C, should provide the strongest possible constraints for study of second-order processes. These processes must be understood before the theory of IAS and DIAS transitions can have a firm foundation.

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