Measurement of the ^{12}C(π, 2π) Reactions and Possible Evidence of a Double-Δ Excitation

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Cross sections, pion momentum spectra, and angular distributions for the reactions ^{12}C($\pi^-,\pi^+\pi^-$) and ^{12}C($\pi^-,2\pi^-$) at a bombarding energy of 292 MeV were measured with a 360° spectrometer. An enhancement of the cross-section ratio of ^{12}C($\pi^-,2\pi^-$) to ^{12}C($\pi^-,\pi^+\pi^-$) relative to that of the elementary cross sections was observed, and is discussed in terms of various nuclear-medium effects including a double-Δ production channel.

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Experimental data of pion-induced single-pion production on the nucleon are available for both the $p(\pi^-,\pi^+\pi^-)n$ (Refs. 1-4) and the $n(\pi^-,2\pi^-)p$ (Ref. 5) channels. It was found[6] that at energies not far from threshold the cross section for the former is more than an order of magnitude larger than for the latter [studied by the isospin equivalent $p(\pi^+,2\pi^+)n$ reaction[7]]. We will therefore refer to them as the "strong" and "weak" channels, respectively. For the deuteron, only inclusive measurements for ^{2}H($\pi^-,\pi^+\pi^-$)2n are available.[8,9]

The motivation to study these reactions on nuclei ranges from trying to understand inelasticities in the pion-nucleus interaction to using these reactions as tools to detect exotic phenomena. Cohen,[10] Cohen and Eisenberg,[11] Eisenberg,[12,13] Rockmore,[14,15] Bhalerao and Liu,[16] and Oset and Vicente-Vacas[17,18] studied the (π,2π) reaction using various approximations and calculated inclusive cross sections. It was also suggested[11-13] that these reactions could be used as a probe of pion-condensation-precursor phenomena or spin-isospin strength distribution in nuclei. Other exotic mechanisms such as double-Δ formation[19] or coupling to non-nucleonic degrees of freedom[11] were suggested as causing enhancement of the reaction cross sections. Calculations by Brown *et al.*,[19] based on a SU(4) quark model, showed that excitation of a double-Δ intermediate state in $T=0$ nuclei will cause $\approx 13\%$ of the double isobar pairs to decay into two pions. About 9% of these pion pairs are estimated to be in the weak channel (compared with[6] 3.8% for the free nucleon), since the $T=2$ intermediate double-Δ system would be favored. By studying the two channels on charge-conjugate nuclei, this high percentage could allow detection of such mechanisms. The calculations should be confronted with experimental data.

The only (π,2π) experiments on heavier nuclei, where the nuclear-medium effects could be significant, are the ones by Grion *et al.*,[20,21] who measured the strong-channel reaction ^{16}O($\pi^+,\pi^+\pi^-$), and some old emulsion data.[22] In this Letter we present results from large-acceptance measurements of both the ^{12}C($\pi^-,\pi^+\pi^-$) and ^{12}C($\pi^-,2\pi^-$) reactions with a 292-MeV π^- beam.

The experiment was carried out at the πM1 channel of Paul Scherrer Institute (PSI) (formerly SIN), using the modified CALLIOPE spectrometer.[23] The spectrometer consists of an 81-cm-diam circular dipole magnet. The beam (defined by monitoring scintillators) enters the magnet radially and hits a target positioned at the center. The magnetic field is surrounded by six detector assemblies allowing detection of the outgoing particles over almost 360° (Fig. 1). Each detector assembly contains multiwire proportional chambers (MWPC's) with two or four sets of XY planes to measure the position and direction of the detected particles, plastic scintillators to determine the energy loss (ΔE) and time-of-flight (TOF) information, and a liquid-fluorocarbon ($n=1.28$) threshold Čerenkov counter. The spatial resolution of the MWPC's was 0.8 mm FWHM for the horizontal X position and 3.0 mm for the vertical Y position. The resulting momentum resolution is also a function of the momentum and of the geometry of the detector and varies from 0.5 to 8 MeV/c. The plastic scintillators had a resolution of 0.7 nsec FWHM for the TOF and of 1 MeV FWHM in energy loss. The Čerenkov-counter efficiencies for the separation of electrons from pions up to 200 MeV/c were measured to be better than 98%.

A good event was defined by both hardware and an on-line front-end microprocessor demanding a coincidence between at least two detectors. Part of the large and dominant (π^-,π^-p) background was rejected by

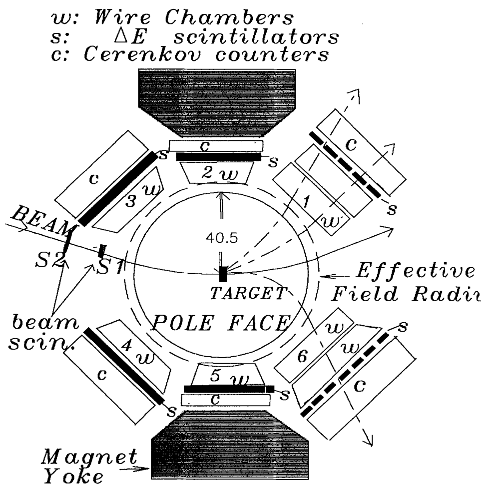

FIG. 1. Layout of the CALLIOPE spectrometer. The dashed lines represent scattered particles.

the front-end microprocessor, using TOF plus momentum cuts, thus reducing the system dead time. Events containing two pions in the same beam burst were rejected by a 64-element hodoscope positioned in the beam.[24] Particle identification was established by TOF vs momentum, ΔE signal vs momentum, and Čerenkov signal. By vertical ray tracing we required the event to originate at the target. We used CH_2 and ^{12}C targets, 3 cm wide and 1 g/cm^2 thick. The cross section for the $p(\pi^-,\pi^+\pi^-)n$ reaction was obtained by subtracting the normalized ^{12}C data from those of CH_2. Similarly, the cross sections for the two $^{12}C(\pi,2\pi)$ reactions were obtained by subtracting the no-target background from the ^{12}C spectra. The "no-target" background amounted to 20% and 12% for the strong and weak channels, respectively, presumably originating from scattering of the beam in the monitoring scintillator or by air.

The spectrometer acceptance was calculated from the magnetic-field measurements and the detector geometry. The acceptance was checked by measuring two reactions: (1) the $p(\pi^-,\pi^-)p$ elastic scattering and (2) the reaction $p(\pi^-,\pi^+\pi^-)n$, whose cross sections and angular distributions are known.[6,25] The measured angular distribution for reaction (1) agreed with the calculated spectrometer acceptance to within a few percent. The cross section for the second reaction was obtained by using the observation that it closely follows the three-body phase-space distribution.[1,2] The integrated cross sections for both reactions, normalized by the calculated acceptance and the detector efficiencies, 11.1 ± 0.3 mb and 500 ± 40 μb, respectively, agreed within 10% with the known values.[6,25]

For the purpose of studying the general properties of the results we compared the data obtained for both reaction channels on ^{12}C with a four-body phase-space

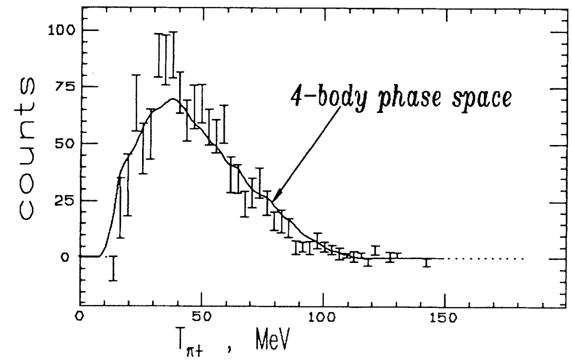

FIG. 2. Energy spectra of the outgoing π^+ in the reaction $^{12}C(\pi^-,\pi^+\pi^-)$, integrated over pion angles. The solid line represents the accepted four-body phase space.

Monte Carlo calculation for the $^{12}C(\pi,2\pi)p\,^{11}B$ reaction.[26] The phase-space distribution was folded with the experimental resolutions and filtered through the spectrometer acceptance, which was different for each of the two channels, due to the system asymmetry to negative and positive particles. The comparison was made between the filtered calculations and the measured data. The measured energy spectra and angular distribution for the strong channel $^{12}C(\pi^-,\pi^+\pi)$ followed closely the calculated four-body phase space, accepted by CALLIOPE for both signs of outgoing pions, as one can see in Figs. 2 and 3. Figure 2 shows clearly the cutoff momentum of the magnetic field. Figure 3 shows how the spectrometer acceptance dictates an oscillatory behavior corresponding to the six detectors of the system.

Because of the momentum cutoff of the spectrometer, the enhancement beyond phase space of low-energy outgoing π^+ reported by Grion *et al.*[20] for the $^{16}O(\pi^+,\pi^+\pi^-)$ reaction was not detected.

We used the phase-space and acceptance calculations for these two reactions and the three-body phase-space and the corresponding acceptance calculations for

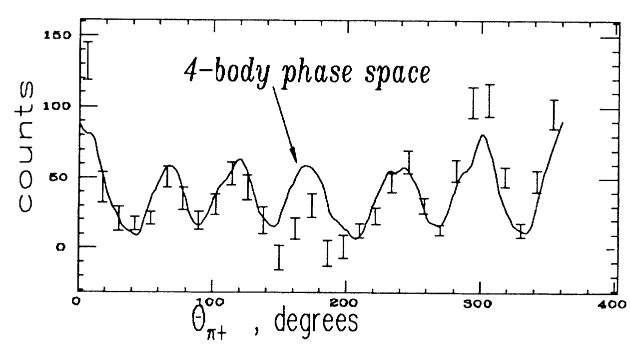

FIG. 3. Angular distribution of the outgoing π^+ in the reaction $^{12}C(\pi^-,\pi^+\pi^-)$, integrated over pion momenta. The solid line represents the accepted four-body phase space.

$p(\pi^-,\pi^+\pi^-)n$ in order to obtain total cross sections and the following ratios:

$$\sigma(^{12}C(\pi^-,\pi^+\pi^-))/\sigma(p(\pi^-,\pi^+,\pi^-))=2.06\pm0.23\,, \tag{1}$$

$$\sigma(^{12}\mathrm{C}(\pi^-,2\pi^-))/\sigma(^{12}\mathrm{C}(\pi^-,\pi^+\pi^-))=0.145\pm0.014\,. \tag{2}$$

While relying on phase-space calculations for the purpose of obtaining absolute cross sections may introduce significant errors, only those deviations from phase space which are different for the two reactions will affect the ratios. It is assumed that these differences are not large. We then use the known cross section $\sigma(p(\pi^-,\pi^+\pi^-)n)=475\ \mu\mathrm{b}$, extracted from the isospin analysis of Ref. 6, to obtain both $\sigma(^{12}\mathrm{C}(\pi^-,2\pi^-))=142\pm18\ \mu\mathrm{b}$ and $\sigma(^{12}\mathrm{C}(\pi^-,\pi^+\pi^-))=978\pm109\ \mu\mathrm{b}$. The errors reflect the combined statistical errors in the ^{12}C, CH_2, and no-target yields.

The cross section for the $^{16}\mathrm{O}(\pi^+,\pi^+\pi^-)$ reaction at $T_{\pi^+}=280$ MeV measured by Grion *et al.*[20] is $2250\pm350\ \mu\mathrm{b}$. In order to compare the results of the two experiments we note that the ^{16}O results are expected to be lower by 40% due to the lower energy (as seen from the elementary cross-section behavior) and higher by 20% due to the heavier mass (assuming $A^{2/3}$ dependence). There appears, therefore, to be a significant discrepancy of about a factor of 3 between the two results. A possible source for that may be the way the data were extrapolated for integration over 4π. Grion *et al.* measured differential cross sections at three angle combinations, fitted the results with polynomials, integrated over the polar angle, and then multiplied by 2π assuming azimuthal symmetry. The fraction of phase space covered in the present work is 43 times larger and the integration is based on a four-body phase-space distribution. An attempt to integrate the subset of the ^{12}C data that coincides with the above experimental setup resulted in $900\pm350\ \mu\mathrm{b}$, indicating that the above discrepancy is not a local enhancement effect.

Theoretical calculations of the cross section for the strong channel performed by Eisenberg[13] without enhancement due to precursor phenomena for pion condensation ($\epsilon=1$) are in rough agreement with the experimental results. Rockmore[15] predicts 115 μb for the weak-channel cross section, a value which is within the experimental range, but these calculations were done without any distortion mechanism. The inclusion of distortion suppresses the predicted cross section by almost an order of magnitude. The calculations by Oset and Vicente-Vacas[17] predict much larger cross sections: 3600 μb for the strong channel and 450 μb for the weak channel [calculated for the charge symmetric $^{12}\mathrm{C}(\pi^+,2\pi^+)$].

The result of Eq. (2) is 66% larger than the free ratio [Eq. (3)]. This enhancement may be attributed to nuclear-medium effects which we briefly discuss. The initial-state interaction $p(\pi^-,\pi^0)n$ followed by $N(\pi^0,2\pi)N$ cannot contribute to the weak channel and would thus reduce rather than enhance the ratio. Absorption of the outgoing pions would also tend to reduce the ratio as absorption at low energies is stronger for π^- than for π^+. The strong channel $^{12}\mathrm{C}(\pi^-,\pi^+\pi^-)$ followed by a (π^+,π^-) double-charge-exchange reaction could act in the right direction but the (π^-,π^+) reaction leading to a $^{12}\mathrm{C}(\pi^-,2\pi^+)$ final state would be just as likely to occur but was not observed.

What effect would the controversial excitation of a double-Δ system have? We assume two possible contributions to the $(\pi,2\pi)$ reaction on a $(2N)$ pair: the quasifree and the double-Δ mechanism. We denote the cross sections to all final states in these two mechanisms by σ_{QF} and $\sigma_{\Delta\Delta}$. For the quasifree process we know[6] that

$$\frac{\sigma(n(\pi^-,2\pi^-)p)}{\sigma(p(\pi^-,\pi^+\pi^-)n)}=0.086\pm0.018\,, \tag{3}$$

$$\frac{\sigma(p(\pi^-,\pi^+\pi^-))}{\sigma(n(\pi^-,2\pi^-+\pi^-,\pi^-\pi^0)+p(\pi^-,\pi^-\pi^0+\pi^-,\pi^+\pi^-+\pi^-,2\pi^0))}=0.45\pm0.027\,, \tag{4}$$

where the cross-section values are extracted from the isospin analysis fit of Ref. 6 at 292 MeV. For $\sigma_{\Delta\Delta}$ Brown *et al.*[19] and Wirzba[27] calculated the transition probabilities for all channels using spin and isospin Clebsch-Gordan coefficients, counting the relevant nucleon pairs and assuming equal probability of finding nucleon pairs in a given spin-isospin state. For a heavy $N=Z$ nucleus they find that $\approx9\%$ of all pion pairs will be in the weak channel. Applying these calculations to ^{12}C the pion production yield is 10.6% and 18.1% for the weak and strong channels, respectively. From these values and from Eqs. (2)-(4) we obtain, by adding the two mechanisms incoherently,

$$\frac{\sigma_{\pi^-,2\pi^-}}{\sigma_{\pi^-,\pi^+\pi^-}}=\frac{0.086\times0.45\sigma_{QF}+0.106\sigma_{\Delta\Delta}}{0.45\sigma_{QF}+0.181\sigma_{\Delta\Delta}}=0.145\pm0.014\,. \tag{5}$$

From Eq. (5) we obtain $\Gamma=\sigma_{\Delta\Delta}/\sigma_{QF}=0.30\pm0.14$. This result shows a possible role for the double-Δ mechanism in the $(\pi,2\pi)$ reaction. The stability of this value was tested by assuming 30% contribution of five-body phase space to the acceptance. The resulting modified cross sections are still consistent with Eqs. (1) and (2). This procedure increases the value of Γ to $\Gamma=0.47$, and hence a somewhat larger contribution from the double-Δ mechanism.

In conclusion, we measured the cross sections for the $^{12}C(\pi^-,\pi^+\pi^-)$ and $^{12}C(\pi^-,2\pi^-)$ reactions. The ratio of cross sections for the two reactions is different from the corresponding ratio on the free nucleon and may be interpreted as a signature for double-Δ excitation. More refined calculations and treatment of nuclei where the attenuation and structure effects may be easier to handle, such as ^{4}He, may lead to more conclusive results. Also, other medium effects which may modify the cross-section ratio in a similar way should be considered.

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