Pion double charge exchange reactions in ^{12}C and ^{40,44,48}Ca

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Cross sections, $d^2\sigma/d\Omega dT$, on ^{12}C, ^{40,44,48}Ca are presented for inclusive (π^+,π^-) and (π^-,π^+) reactions at an incident energy of T_π = 290 MeV with the exit pions detected over an energy range of T_π = 175–255 MeV at an angle of 60°. These cross sections are found to vary systematically with reported proton-neutron differences in nuclear radial distributions.

[NUCLEAR REACTIONS ^{12}C, ^{40,44,48}Ca $(\pi^\pm,\pi^\mp)$; measured $d^2\sigma/d\Omega dT$, $T=290$ MeV, $\theta=60°$, nondiscrete final states; discussed the sensitivity to proton-neutron differences.]

The double charge exchange (DCE) reactions (π^+, π^-) and (π^-, π^+) require the two-nucleon transitions $2p\to 2n$ and $2n\to 2p$. It is possible that the DCE reaction can probe the importance of nucleon pair configurations as well as the mechanism for successive pion interactions with uncorrelated nucleons, an important aspect of multiple scattering models. Pion scattering in the kinematic region of quasi-free pion nucleon scattering (QFS) is dependent upon the average single particle features of the nuclear ground state, primarily in the surface region since nuclei are highly opaque to pions of intermediate energies.[1,2] The corresponding single charge exchange (SCE) scattering in the same kinematical region[3] may in addition distinguish between proton and neutron configurations. This should also be true for the inclusive $(\pi^\pm,\pi^\mp)$ reactions, but with the question of the predominant reaction mechanism unsettled there is room for particular nuclear structure features to show up in DCE. A comparative study of QFS, SCE, and DCE is therefore necessary and could help clarify some current problems in our understanding of the pion-nucleus interaction.[1,4] In this spirit we have completed QFS and DCE experiments on ^{12}C, ^{40}Ca, ^{44}Ca, and ^{48}Ca and we report here the pion charge and isotopic dependence of the DCE reaction in the continuum region.

Any two neutrons or protons in the nucleus can contribute to the DCE cross section by repeated SCE, $\pi+N$ scatterings ($\pi^-p\rightleftarrows\pi^0 n$ and $\pi^+n\rightleftarrows\pi^0 p$) and within this reaction picutre the nuclear structure involved is the same as for SCE. This DCE mechanism has been investigated for light nuclei using multiple scattering theory.[2] The multiple SCE mechanism would naturally accommodate DCE to discrete final states and the double analog transitions were believed to be strong since the elementary $2n\to 2p$ or $2p\to 2n$ transitions could occur within a given particle configuration. Recent experiments[5-7] have, however, indicated a more complex situation where the DCE reaction shows sensitivity to small admixtures of two-hole two-particle (2h-2p) core excitations besides the simple extra core configurations. Although these admixtures could be activated through the multiple SCE mechanism, one might raise the question whether the (π^-,π^+) and (π^+,π^-) reactions sample certain proton and neutron pair configurations in nuclei or are sensitive to gross nuclear properties such as proton and neutron distributions that differ from the average matter distributions. These possibilities are examined in the present study on the isotopic dependence of the inclusive $(\pi^\pm,\pi^\mp)$ DCE reactions.

The experiment was carried out with the EPICS channel and spectrometer system at LAMPF.[8] An

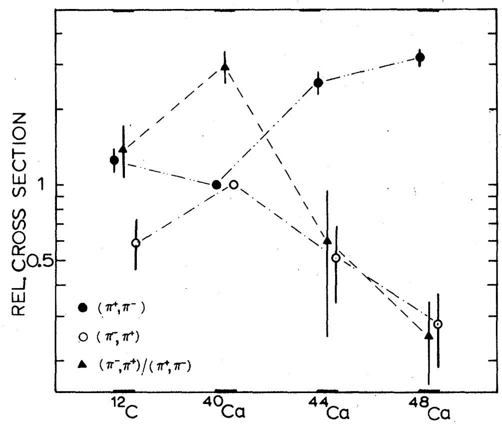

FIG. 1. The mean differential cross sections $d^2\sigma/d\Omega dT$ for pions emitted at $\theta = 60°$ over the energy range $T = 175$–255 MeV. The (π^+, π^-) and (π^-, π^+) cross sections are expressed relative to those of ^{40}Ca which are 4.3 ± 0.4 and 12.7 ± 1.6 μb/sr MeV; the $(\pi^+, \pi^-)/(\pi^-, \pi^+)$ ratios are also shown.

incident pion beam of π^+ or π^- at $T_\pi = 290$ MeV was used and the corresponding negative or positive pions emitted from the target were detected at $\Theta = 60°$. Electrons and muons were effectively discriminated against using particle-trajectories and time-of-flight measurements in conjunction with triggers from a gas Cherenkov counter. The spectrometer was set at a fixed field which accepted pions of energies between 175 and 255 MeV; the pion energy loss in the reaction is then in the region of the QFS (π, π') reaction. Particular attention was given to the nonuniform acceptance of the spectrometer which was measured by scattering pions from ^{12}C in the flat region of the QFS spectrum. The overall uncertainty in the absolute DCE cross section is estimated to be less than 10%, including the uncertainties from normalizing to the $\pi^\pm + p$ elastic cross section[9] and particle identification. Results on the (π^+, π^-) and (π^-, π^+) cross section using the entire energy acceptance ($\Delta T_\pi = 80$) are given in Fig. 1 where the errors given are the statistical uncertainties. The energy dependence of the DCE cross sections is shown in Fig. 2 where the large bin size (20 MeV) used was dictated by the limited statistics.

The spectra display a general increase with increasing pion energy loss (ΔT). These results are in agreement with previous measurements[10] which include the region of larger energy losses $\Delta T/T_0$; the measurements indicated moderate or little cross section variation with angle and nuclear mass. The energy dependence of the DCE cross section can be conveniently described by $\exp(\Delta T/t_0)$ with an average slope of $t_0 \approx 50$ MeV. Within the limited statistics there is room for detailed differences between the studied cases, but such ques-

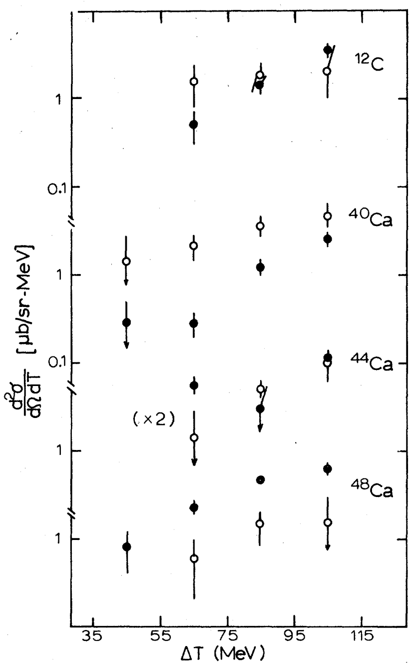

FIG. 2. Energy spectra for the (π^+, π^-) and (π^-, π^+) reactions (solid and open symbols) in ^{12}C and ^{40,44,48}Ca plotted vs the pion energy loss. The ^{44}Ca data shown have been multiplied by a factor of 2.

tions can be settled only by future experiments with improved statistics. The rest of the discussion will be based on the results of the integrated cross sections.

It is natural to start examining the data with respect to the DCE reaction mechanism based on multiple SCE from individual necleons where the effective number of protons or neutrons contributing to the (π^-, π^+) and (π^+, π^-) would determine the magnitude of the cross section. A large phase space factor will be realized only for nucleon knock-out processes each having a finite Q value. A finite pion energy loss in DCE ($\Delta T \approx 75$ MeV in our case) thus limits the number of scatterings. This effect, combined with the strong attenuation in the nuclear interior due to true pion absorption, tends to limit the inclusive DCE reactions of small or moderate energy loss to the nuclear surface. The multiple SCE mechanism would predict a DCE cross section that varies smoothly with the number of neutrons or protons on the surface; simple arguments[10] lead to (π^-, π^+) and (π^+, π^-) cross sections proportional to $Z(Z-1)A^{-2/3}$ and $N(N-1)A^{-2/3}$. Such a systematic $A(N, Z)$ dependence is not seen in the data.

The rapid change of the DCE cross sections in the calcium isotopes is one conspicuous trend of the data (Fig. 1) that may signal the influence of nuclear structure. There are indications from other experiments that the neutron distributions in the calcium isotopes ($N \neq Z$) extend outside ($\Delta r > 0$) the average matter distribution, which in turn extends outside the proton distribution ($\Delta r < 0$). The matter distribution is a natural reference for comparing the (π^+, π^-) and (π^-, π^+) cross section since the attenuation is symmetric with respect to proton and neutron interactions apart from the difference in incident and exit energies. The effective number of protons and neutrons that contribute to the (π^+, π^-) and (π^-, π^+) is sensitive to a finite difference Δr, particularly if the reaction is surface peaked. Proton and neutron distribution differences as claimed on the basis of other studies[11,12] could thus give rise to the type of reciprocal (π^+, π^-) and (π^-, π^+) cross section variation as seen for the calcium isotopes.

The results for ^{40}Ca, together with ^{12}C, indicate a difference in the (π^+, π^-) and (π^-, π^+) cross sections while a reaction symmetry might have been expected for these self-conjugate nuclei. It is then interesting to note that there are indications that these nuclei have asymmetric proton-neutron components in their ground state configurations; nucleon pickup experiments[13,14] show a substantial proton excess in the 2h-2p core excitations $1p_{3/2}^{-2}\, 1p_{1/2}^{\;2}$ and $(2s1d)^{-2}(1f2p)^2$ of ^{12}C and ^{40}Ca. Such configurations could contribute because they are related to radial distribution differences in the nuclear ground state[11] resulting in the effects mentioned above, or because of the two-particle correlations of these configurations. Apart from (π^+, π^-) in ^{44,48}Ca, the DCE cross sections actually vary as the core-excitation strenghts measured in pickup experiments.[13,14]

There are other effects to consider in the interpretation of the DCE cross sections such as the phase space available for nucleons knocked out due to the DCE reaction. It will depend on ΔT and on nucleon binding energies (E_B), i.e., the DCE cross section would increase with increasing ΔT and decreasing E_B where E_B is a nuclear parameter with a particularly small value for two-proton removal from ^{40}Ca. It could cause the $(\pi^-, \pi^+)/(\pi^+, \pi^-)$ cross section ratio to exceed unity and more precise energy spectra at small ΔT are needed to assess the importance of such effects. Nuclear peculiarities could also show up if a significant fraction of the DCE reactions results in low-energy charge-exchanged nucleons that have to go into partially filled nuclear orbits. Blocking effects could then be experienced for DCE just as seen for QFS in certain regions of energy loss. This could cause the DCE cross section to vary systematically for cases such as (π^+, π^-) in the calcium isotopes with the strongest effect for DCE at very small ΔT. Any attempt at a quantitative interpretation of the data must consider these and similar factors as well as the nuclear structure effects discussed that give rise to proton-neutron asymmetries with the predictable effects on the (π^-, π^+) and (π^+, π^-) cross sections.

In summary, the reported DCE cross sections at moderate energy losses ($\Delta T = 35$—115 MeV) show deviations from a smooth $A(Z,N)$ variation. We find a certain correlation between these cross sections and possible differences in proton-neutron nuclear ground state distributions and nucleon pair correlations. More data are needed with better precision to assess the role of other effects and confirm the trends found here.

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