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Search for enhancements due to pion condensation precursors in (p,p') reactions on ^{12}C

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Cross sections for the $^{12}C(p,p')$ reaction leading to the 1^+ states at 15.1 MeV ($T=1$) and 12.7 MeV ($T=0$) were measured at a bombarding energy of 402 MeV. These data, covering a range of momentum transfer q from 0.45 to 2.65 fm^{-1} ($0.6-3.7m_\pi$) provide a test of the effects, precursor to a pion condensate, predicted to be important for the $T=1$ state near $q=2-3m_\pi$. The cross sections for the two 1^+ states are very similar for large q, perhaps indicating that the precursor effects are small.

[NUCLEAR REACTIONS $^{12}C(p,p')$; measured $\sigma(\theta)$, $q_c \simeq (2-3)m_\pi$ 15.1 MeV $1^+T=1$ and 12.7 MeV $1^+T=0$ levels; $E_p=402$ MeV; precursor effects discussed.]

Migdal[1] and independently Sawyer[2] first called attention to a possible new phase of sufficiently large hadronic systems in which pions would have condensed from the vacuum. Subsequent theoretical work[3] showed that due mainly to repulsive nucleon-nucleon correlations the onset of this new phase could be expected only for systems with about twice the normal nuclear density; such densities presumably occur in dense astronomical objects and are possibly reached in heavy ion collisions.[4] Indirect indications for the existence of this "pion-condensed" phase in neutron stars are still controversial,[5] and given our present state of knowledge, evidence for the condensed phase obtained from heavy ion collisions is likely to be ambiguous. Fortunately, the condensation mechanism also implies,[6,7] even at normal densities, that there are so-called "precursor" effects: enhancements of the cross sections for nuclear transitions which carry the quantum numbers of the pion ($\Delta S=\Delta T=1$). These enhancements should be largest at momentum transfers of $2-3m_\pi$ ($m_\pi=140$ MeV/c $=0.7$ fm^{-1}).[8-13] Observation of such effects should also yield information on the effective short-range repulsive nucleon-nucleon interaction (value of the Migdal parameter g') which must be known to predict when pion condensation will occur.

Recent investigations of cross sections for magnetic electron scattering in ^{12}C (Refs. 10–12) and ^{13}C (Ref. 13) seem to indicate that the precursor effects are surprisingly large, corresponding to values of $g'=0.4-0.5$, compared to the values greater than 0.6 found from the low momentum properties of nuclear states. In view of these results it is then crucial to check the conclusions with a probe, such as inelastic proton scattering,[6,9,11,12] which couples more directly to the pion field than (e,e').[14]

The choice of bombarding energy is crucial in such experiments if we wish to relate the experimental results and theoretical predictions with confidence. For the validity of current reaction models, energies above 200 MeV seem necessary.[15-17] For example, the calculations of Comfort and Love[15] at $E_p=122$ MeV apparently indicate that precursor effects must be small in (p,p') transitions leading to the 1^+, $T=1$ state at 15.1 MeV in ^{12}C. Unfortunately, their calculations, while nicely reproducing the data for this state at low q, fail for the nearby 1^+, $T=0$ state at 12.7 MeV. As a result, one cannot have confidence that the reaction mechanism is well enough understood at energies as low as 122 MeV to merit an unambiguous conclusion. At higher energies, the problem is that reliable estimates of the spin-isospin dependent parts of the two nucleon t matrix are not available above about 600 MeV. For this reason, any conclusion drawn from data at 800 MeV (Ref. 16) has to be taken with caution. Unfortunately, while data are available at both higher[16] and lower[17] energies, no experiments have been performed in the energy range between 300 and 600 MeV where quantitatively reliable analyses seem possible.

We describe in this Communication the results of a $^{12}C(p,p')$ experiment carried out at $E_p = 402$ MeV. Data were obtained for the $1^+T=1$ state at $E_x = 15.1$ MeV and the $1^+T=0$ state at $E_x = 12.7$ MeV; the latter state, having $T=0$, should not exhibit large precursor effects[18] and so may provide a null test.

Protons from the synchrotron accelerator of the Laboratoire National Saturne (Saclay) bombarded a natural carbon target with a thickness of 18 mg/cm^2. Scattered protons were detected with a resolution of about 120 keV FWHM (full width at half maximum) in the energy loss spectrometer SPES I. The beam was monitored with a secondary emission chamber and a scintillation counter telescope. The absolute normalization of the monitors was obtained by counting the ^{11}C activity induced by bombardment of a carbon disk.[19] Spectra were obtained over the laboratory angular range from 6° to 32°; two magnetic field settings were necessary to cover the observed range of excitation $E_x = 0-17$ MeV.

In Fig. 1 is shown a part of the energy spectrum obtained at a momentum transfer of $2.4m_\pi$, near the peak of the expected enhancement. The cross sections of most of the observed states will be published elsewhere; here we shall focus only on the results obtained for the 15.1 MeV (1^+, $T=1$) and 12.7 MeV (1^+, $T=0$) levels shown in Fig. 2. The relative errors given there are purely statistical and include the contribution from the subtraction of the continuum; the uncertainty in the overall normalization is $\pm 6\%$. Our cross sections for the elastic scattering are in excellent agreement with data available at 425 MeV.[20]

The present results for the $T=1$ state resemble closely those obtained at 122 and 800 MeV,[16,17] while the data for the $T=0$ state differ greatly from that at 122 MeV. But the most striking feature of the 402 MeV data is the similarity of the cross sections for the two 1^+ states. It is then tempting to conclude that whatever processes cause the cross sections to differ from those predicted on the basis of the naive shell model, they are the same for the $T=0$ state (where precursor effects should be small) and for the $T=1$ state (where they should appear). Moreover, precursor effects are expected to depress the $T=1$ cross section at small q and to enhance it at large q; the observed differences are in the opposite direction. One can then argue that any precursor effects must be small if it is justified to use the $T=0$ state as a null test.

In doing so, we implicitly assume that the two 1^+ states would have the same cross sections in the absence of precursor effects. It is consistent with this assumption that the two states have almost identical $1p$-shell configurations. However, different components of the two-nucleon t matrix contribute to the two transitions and could lead to differences in the cross sections. Indeed, predictions for the two cross

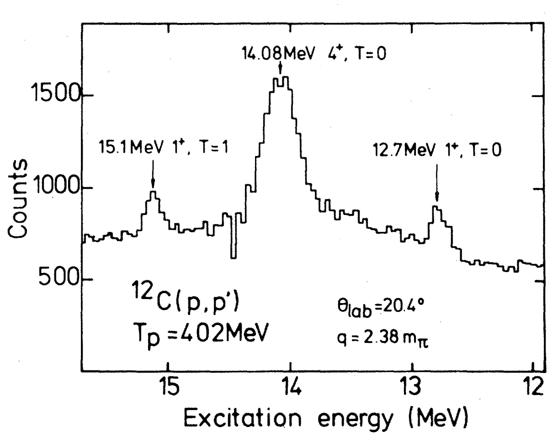

FIG. 1. Energy spectrum for the $^{12}C(p,p')$ reaction at $E_p = 402$ MeV and a laboratory scattering angle of 20.4°.

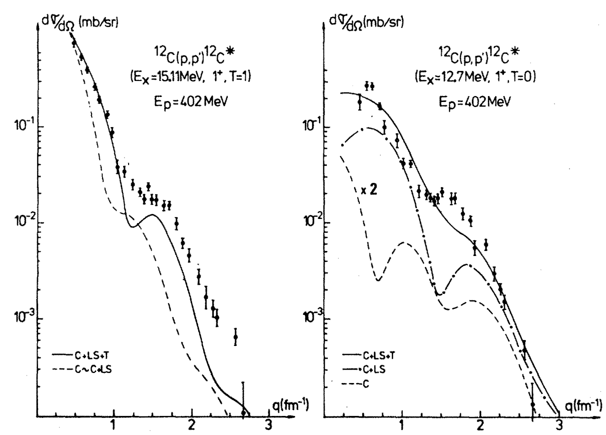

FIG. 2. Cross sections for the $^{12}C(p,p')$ reaction at $E_p = 402$ MeV leading to the 1^+ states at 15.1 MeV ($T=1$) and 12.7 MeV ($T=1$) (dots). The curves result from calculations reported in the text and show the cumulative contributions of the central (C), spin-orbit (LS) and tensor (T) components of the nucleon-nucleon interaction. The central contribution (C) for the 12.7 MeV excitation was multiplied by a factor 2.

sections at 122 MeV (Ref. 17) while qualitatively similar, differ in detail. Thus it could be, although it seems improbable, that the effects of the precursor phenomenon are hidden by a coincidentially equal and opposite difference in the "nonprecursor" cross sections. Multistep processes could also cause differences, but these processes are probably small at such high energies.[17]

Since it has been shown[21] that the addition of high lying configurations in the random phase approximation increases the cross sections for both 1^+ states at large q, it would be highly desirable to verify that these normal effects of high lying configurations are properly described, by reproducing the cross sections for other states and particularly that for the 1^+, $T=0$ state. A calculation for only the 1^+, $T=1$ state does not seem adequate when the observed effects are so small. To investigate the dependence of the cross sections on the spin and isospin variables, a distorted-wave impulse approximation (DWIA) calculation has been made at 402 MeV using a newly derived t matrix from Love and Franey.[22] Cohen-Kurath ($1p$-shell) wave functions were used, adjusted slightly to fit the low q electron scattering data. Figure 2 presents the fits of these calculations to the experimental data. The overall trend of the cross section for the 12.7 MeV state is reproduced while the predicted cross section for the 15.1 MeV state differs from the data in the direction expected if precursor phenomena are present. If one takes the results of this preliminary calculation seriously, it seems that precursor effects enhance the cross sections by at most a factor of 2 at high momentum transfers ($q \simeq 2$ fm^{-1}). However, these calculations do not include the effect of higher orbitals and cannot yet be considered as definitive.

In summary, then, we have measured the cross sections for the $^{12}C(p,p')$ reaction at 402 MeV over a range of momentum transfers from $0.6-3.7 m_\pi$ encompassing the values of q for which effects of precursors of a pion condensate should be seen for the 15.1 MeV(1^+, $T=1$) state. That the cross sections for the 15.1 MeV state and the 12.7 MeV(1^+, $T=0$) state are so similar can be taken as evidence that precursor effects are small, since they cannot occur in the important direct amplitude for a state with $T=0$. This conclusion is buttressed by the fact that the two states have nearly the same shell model configurations. But since different components of the nucleon-nucleon t matrix are important for the two transitions, one must confirm with more detailed calculations (e.g., inclusion of higher orbitals) that the cross sections are similar in the absence of precursor effects. We hope that these data, at an energy where accurate *a priori* calculations can in principle be made, will stimulate the necessary theoretical effort.

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Indeed, the sensitivity vanishes entirely in an infinite system.

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