Scattering of 50-MeV π^+ from ^{12}C†

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We have measured the differential cross section for 50-MeV π^+ scattering to the ground state, 2^+(4.44 MeV) and 3^-(9.64 MeV) of ^{12}C. Both elastic and 2^+ data show a minimum at ~65°. Distorted-wave Born-approximation calculations yield excellent agreement with the inelastic data when the entrance and exit channels are distorted using a phenomenological optical potential which describes the elastic data.

The low-energy pion scattering problem has attracted a great deal of interest recently. The simple first-order optical models[1] that give qualitatively correct representations of the elastic scattering data[2] at πN resonance energies ($T_\pi \approx 120-250$ MeV) fail very badly at describing the low-energy ($T_\pi \approx 50$ MeV) data.[3,4] Below the resonance energy the nucleus is more transparent to the pion, and the elastic data seem to be much more sensitive to the nuclear-structure information imbedded in the optical model. Recent theoretical efforts[5-9] at including better kinematics and nuclear medium effects such as true pion absorption and NN correlations have shown considerable sensitivity to these phenomena.

Because of the above situation, it is of interest to study further the nature of the π-nucleus interaction through other processes. We have studied the scattering of 50-MeV π^+ from ^{12}C leading to excitation of the 2^+ and 3^- states at 4.44 and 9.64 MeV, respectively. Similar experiments[10] using other projectiles have led to a good phenomenological understanding of such inelastic processes using a reaction model based on the distorted-wave Born approximation (DWBA). Although this model has been shown to be reasonably valid at resonance energies[11] for ^{12}C, it has not been tested at low energies. If discrepancies with data are observed, they may lead to better understanding of the π-nucleus reaction mechanism or optical potential.

This experiment was run on the EPICS channel at Clinton P. Anderson Meson Physics Facility using a stack of two intrinsic germanium detectors[3,12] to stop the π^+ and measure its energy. The beam spot was about 7 cm wide and 20 cm high, and dispersed linearly in momentum (over ± 1% of the central value) in the vertical direction. Because of this large horizontal size, the detectors saw particles from angles $\theta \pm 3°$ for each angular setting θ of the apparatus. The measured ratio of beam particles ($\pi:\mu:e$) was about 1:0.5 :0.5 and approximately 5×10^5 π^+ per second hit the target with a 70-μA primary proton current.

One apparatus is shown schematically in Fig. 1. Three helical delay line proportional chambers[13] were used to determine the trajectory of particles triggering both germanium crystals to distinguish events not originating in the target (largely pion decay products) and to determine the initial momentum. Non–target-related background is significant, especially at forward angles. Scintillators surrounded the germanium crystals on four sides to tag particles not stopping in the stack. The beam currents were measured by two over-pressurized ion chambers downstream from the target. The targets were pressed natural carbon sheets of 99.9% purity;

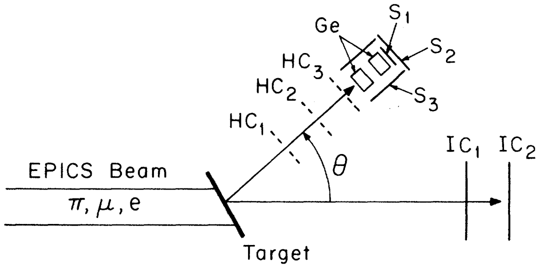

FIG. 1. A schematic drawing of the apparatus. *HC*1–*HC*3 are wire proportional chambers, Ge is the germanium detector, *S*1–*S*3 are scintillators, *IC*1 and *IC*2 are ion chambers.

thicknesses of 565 and 926 mg/cm^2 were used.

The background under elastic peaks is not related to the target and was measured to be about 1% of the normal elastic-peak amplitude. Inelastic peaks have this non–target-related background related to the elastic peak. This is due to processes within the germanium detector which produce a low-energy tail on every peak at about 2% of the full amplitude. This tends to obscure inelastic peaks if the ratio of elastic to inelastic events is very large. Figure 2 shows the energy spectrum at 40° which has an elastic amplitude forty times that for the 2^+ and is our worst case. At all angles ⩾ 30°, the peak area for the 2^+ state could be determined without difficulty.

The new measurement of the elastic angular distribution is shown in Fig. 3. As in our previous measurement,[3] the absolute normalization was determined by scattering 50-MeV π^+ from the hydrogen atoms in a polyethylene target and using these known cross sections[14] to fix the product of the angle-independent absolute constants. At each angle the new data are larger than our previous results. A large part of this difference can be attributed to a change in the π-p cross sections used for normalization. The old data should be about 20% larger, bringing it into agreement with the new data at forward angles; a 20–30% discrepancy still exists at back angles. We feel the greatly improved technique makes the present measurement more reliable. We estimate an error of ± 15% for the present normalization.

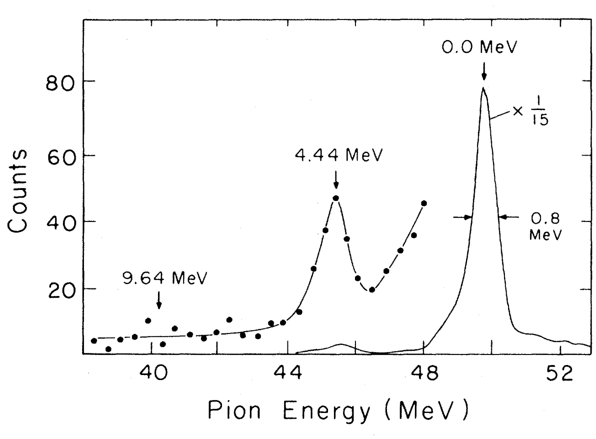

FIG. 2. The pion energy spectrum at $\theta_{\mathrm{lab}} = 40°$. The elastic peak is scaled down by a factor of 15. The 9.64-MeV state was not observed at angles smaller than 110 deg.

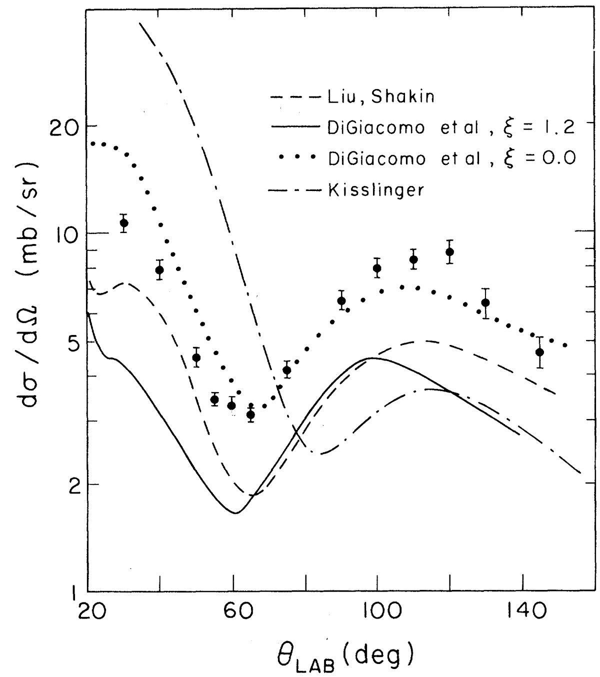

FIG. 3. The elastic data with relative errors compared to theories. The Kisslinger model with free-πN information (dot-dashed curve); Liu and Shakin (Ref. 6) (dashed curve); DiGiacomo *et al.* (Ref. 5), $\xi = 0$ (dotted curve), $\xi = 1.2$ (solid curve). ξ is the strength parameter for the Lorentz-Lorenz part of the second-order optical potential.

In Fig. 3 are shown three theoretical predictions for the angular distribution. The Kisslinger model using free-πN information[1] is compared to recent calculations by Liu and Shakin[6] and DiGiacomo *et al.*[5] The latter two calculations, while much more comprehensive than the Kisslinger treatment, approach the problem emphasizing quite different physical content. In broad terms, we may say that Liu and Shakin emphasize a careful treatment of the *first-order* optical potential, and include also true π absorption in a phenomenological way; on the other hand, DiGia-

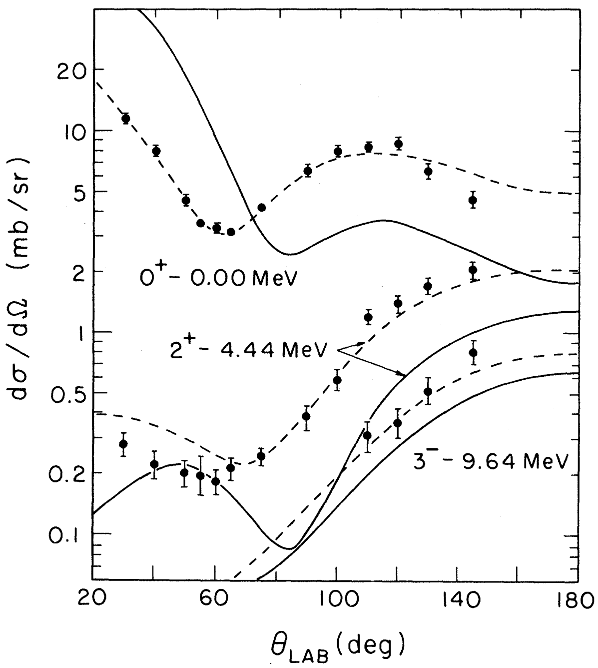

FIG. 4. The elastic and inelastic data with relative errors (see text). All calculations use the Kisslinger potential. Those based on free-πN information are solid curves. The phenomenological fit to the elastic data is a dashed curve, as are the DWBA predictions for the inelastic data using this best-fit elastic optical potential.

como *et al.*[5] shows the importance of *second-order* terms such as Pauli and short-range correlations as well as true π absorption. It may be that a detailed calculation involving all of these effects, carried out to second order, will be necessary to explain the data, since all effects appear to be important.

The inelastic data for the 2^+ and 3^- states are shown in Fig. 4 along with two DWBA calculations for each state made using the code DWPI.[15] A standard phenomenological nuclear deformation ($\beta_2=0.56$, $\beta_3=0.40$)[10] was used to describe the excitations. The Kisslinger potential was used to distort the incoming and outgoing channels. Lacking a prescription for the energy dependence of the phenomenological parametrization, the entrance and exit channels were distorted in the same way. Coulomb excitation was included. The solid curves in Fig. 4 are results using a Kisslinger potential constructed from free-πN information. The inelastic prediction for the 2^+ state disagrees with the data regarding the position of the minimum in the same way as does the elastic case. It is again predicted to be too far backward by about 20°; the data are larger than the theory by a large factor.

A question of some interest is whether the elastic and inelastic measurements can be described by a consistent theoretical treatment. We first fit the elastic data (using program FITPI)[16] by allowing the parameters b_0 and b_1 to vary freely. A good fit to the elastic data is obtained with qualitatively the same b_0 and b_1 as in the previous measurement. Both sets of parameters (see Table I) require a strongly repulsive real s wave (Reb_0) and unitarity is slightly violated in the s wave [because of the sign of Im(b_0)]. Since the unitarity violation is small, it may not be statistically significant. The elastic-fit parameters were then used in DWPI to calculate the inelastic cross sections. The resulting predictions (dashed curves, Fig. 4) give an excellent representation of the data, both in magnitude of the cross section and in position of the minimum.

From the above, it is fair to conclude that the DWBA gives a very good account of the inelastic ^{12}C data at 50 MeV. A similar situation has been found at higher energies.[11]

At present, the theoretical situation regarding low-energy π-nucleus scattering is unclear. Several authors have confirmed the importance of kinematic effects such as Fermi motion, nucleon

TABLE I. The best-fit values of the complex parameters b_0 and b_1 in units of fm^3 for the Kisslinger model are given, with their percentage errors, for the present data and that of Ref. 3. In both cases, unitarity is violated only in the $l=0$ partial wave. The magnitude $|\eta_0|$ for this partial wave is given, as are the χ^2 per degree of freedom N for each fit. The best fits are also compared to the free-πN predictions.

Data	χ^2/N	Reb_0	Imb_0	Reb_1	Imb_1	$\lvert\eta_0\rvert$
Present work	22/13	−3.59 ± 2%	−0.60 ± 68%	7.09 ± 2%	1.66 ± 48%	1.06
Ref. 3	7.2/6	−2.74 ± 2%	−1.04 ± 13%	5.87 ± 2%	2.99 ± 10%	1.10
Free-πN	···	−0.83	+0.51	7.89	1.04	0.71

binding and "angle transformations," as well as large effects due to true meson absorption, Pauli correlations, and ρ-meson exchange. Because of the large contributions from all of these sources, it is imperative that a systematic calculation simultaneously including all of these effects be carried out. This will hopefully clarify the situation considerably.

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Resonances Below the $n = 3$ Doubly Excited States of Helium*

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Some features have been observed for the first time around 69 eV in the electron-impact differential excitation cross section of the bound state $2\,^3S$ of helium, measured in the forward direction. The main feature, which involves a variation of about 2.8×10^{-21} cm^2 sr^{-1} in the cross section, may be assigned to the negative-ion state $3s\,^23p\,(^2P)$ thus lying at about 68.98 ± 0.07 eV; a second feature is observed at about 69.67 ± 0.08 eV. The detection of these resonances has a special interest because the decay of these He$^-$ states involves the three electrons concerned in the collision process.

The $n=2$ region (around 60 eV) of the doubly excited states of helium was investigated by many techniques which lead to an accurate knowledge of these states.[1] Associated with the first members among them, at least two negative-ion resonances were observed by various electron-impact techniques, as summarized by Schulz[2] and by Hicks et al.[3] In the $n=3$ region (around 70 eV) however, few data are available; Madden and Codling[4] determined the energy values of the optically allowed series $3sn'p\,(^1P)$, but for the other levels some theoretical data and very little experimental data are available.[5] No detection nor theoretical prediction of He$^-$ resonances was reported so far in this region. The energy diagram presented in Fig. 1 summarizes these data for the lower-lying levels of He and He$^-$ in both regions. The features around 69 eV which are reported in the present work bring a new interest on this region and raise questions about configurations of new He$^-$ states with three electrons in the $n=3$ shell. Furthermore, what is novel in the observations of these He$^-$ states is that their decay into the $2\,^3S$ channel involves all three electrons which participate in the collision.

These features have been observed in the inelastic electron scattering by helium. They appear as a perturbation around 69 eV in the differential excitation cross section of the bound state $1s2s\,(^3S)$, measured in the forward direction.