Further study of π-^{12}C elastic scattering at 800 MeV/c

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We further examine the puzzling disagreement between data and calculations in pion-nucleus elastic scattering at 800 MeV/c by taking account of the dynamical modification of N^* resonances in nuclear medium and by improving the estimate of pion-absorption effects on the basis of a recent absorption measurement. The disagreement remains unexplained, though multinucleon absorption could be a possible explanation.

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Pion-nucleus elastic scattering differential cross sections at the pion laboratory momentum $p_{\rm lab}$ = 800 MeV/c [1] have been found to be consistently larger than those obtained by calculations [2–4]. In our previous work [4], we carefully analyzed various uncertainties involved in these calculations on the basis of the multiple-scattering theory. We established that the underestimate by the calculations amounts to 20–30 % throughout the scattering angles at which the measurement was made, and that the difference is larger than the combined experimental uncertainties and resolution. At this high energy, the multiple-scattering theory is expected to provide realistic results even in the lowest order, especially because of the long mean free path (about 3–4 fm) of the pion in the nuclei. Since the results should be most reliable in the forward direction, the persistent difference over the finite angles is thus quite puzzling.

We applied the multiple-scattering theory by constructing a π-nucleus optical potential and by using the Glauber theory. In these applications, the elementary πN amplitudes are assumed to be the same as those in free space. Though the standard off-energy-shell effects such as the nucleon-binding effect are expected to be insignificant at this energy, nuclear medium corrections to the πN amplitudes, which involve dynamical modification of nucleon resonances, could be significant. It is thus necessary to examine the medium effects since the puzzling disagreement may come from them. In a preceding paper [5], we investigated the dynamical modification of N^*'s in nuclear matter. Here, we examine consequences of the modification on the pion elastic scattering from a finite nucleus.

The largest uncertainty in our previous work [4] was in the estimate of pion-absorption effects. Since new absorption measurements on ^{4}He [6,7] have recently become available, we also reexamine the pion-absorption effects on the π-nucleus elastic scattering.

The following two items are discussed in this report: consequences of the N^*'s modification and the reexamination of the pion-absorption effects.

Around $p_{\rm lab}$ = 800 MeV/c, the πN D_{13}-wave resonance $N(1520)$ and the πN S_{11}-wave resonance $N(1535)$ are the important degrees of freedom in the πN interaction. In fact, these partial-wave amplitudes are a large portion of the total amplitude and dominate its energy variation [8].

In the preceding paper [5], we examined dynamical alteration of the resonances in nuclear matter and have evaluated its effects on the elementary πN interaction. For this, the modification of the N^* self-energies in nuclear medium is calculated in a resonance-hole model by inclusion of pion distortion, Pauli blocking, and nuclear binding. We now examine how such dynamical alteration affects π-nucleus elastic scattering by carrying out Fermi averaging so as to construct the π-nucleus optical potential. As in our previous work [4], we take the π-^{12}C scattering as an explicit example.

The forward-scattering t matrix is averaged in the Fermi-gas model to construct the optical potential:

$$\tilde{\tau}(\mathbf{k},\mathbf{k},E) \equiv \gamma(0)^{-1}\frac{3}{4\pi k_F^3}\int_{|\mathbf{p}|\leq k_F} d^3p\,\gamma(\mathbf{p})\tau(\mathbf{k}',\mathbf{k}',E')\ , \tag{1}$$

where $\gamma(\mathbf{p})$ is the Lorentz transformation factor for the t matrix [9]. The pion momentum $\mathbf{k}'$ and the πN total energy E' in the πN c.m. system are given in terms of the nucleon momentum $\mathbf{p}$ and the pion momentum in the laboratory system, in the standard manner [9]; the momentum $\mathbf{k}$ and energy E correspond to the pion scattering from the nucleon at rest (i.e., $\mathbf{p}$ = 0). [See Eq. (10) in the preceding paper for details of the t matrix in nuclear medium.]

Since the averaging over the Fermi motion smears out the energy dependence of the t matrix, the large modification of the πN amplitudes, which comes mostly from the pion-production suppression, is appreciably weakened, as shown in Fig. 1. Consequently, this modification changes the π-nucleus cross sections only slightly. The change is about a few percent in the case of the π-^{12}C differential cross section at $p_{\rm lab} = 800$ MeV/c, as illustrated in Fig. 2. This is of the same order of magnitude as that of the nuclear-correlation effect [4]. In these figures we show the results for the Fermi momentum $k_F = 1.02$ fm^{-1} instead of the value for the full nuclear-matter density $k_F = 1.36$ fm^{-1}, since the pion interacts with nuclei effectively at a density smaller than the nuclear-matter density. The k_F value used corresponds to a density a little larger than half the nuclear-matter density. The results are insensitive to an explicit value of k_F because of two competing effects: As k_F increases, the medium corrections become larger, but the smearing by the Fermi motion also becomes stronger. We confirmed the insensitivity numerically. Note that at $k_F = 0$ the free-space amplitudes (no Fermi averaging) must, of course, be recovered.

We proceed to examine the direct interaction of N^* with a nuclear medium, which we describe phenomenologically by the spreading potential as in the Δ-hole model [10]. The spreading potential contains all unexplored effects, including NN^* direct interactions through meson exchanges (and perhaps more appropriately by quark exchanges at short distances). Because these effects contain much uncertainty and complications, their microscopic treatment would require a separate work, and so it is not carried out here (and in the preceding paper).

Although nothing definite is known about the spreading potential for N^*, the potential for Δ (only weakly energy dependent with the value of $V_{\rm sp} = V_R + iV_I \approx 40 - i40$ MeV [10,11]) may be used as a reference: We assume that the potential for N^* is energy independent with a value similar to that for Δ, while the magnitude of V_I of N^* might be larger since the phase volume for N^* is larger than that for Δ. Furthermore, the effect of the spreading potential is examined only for $N(1520)$. The spreading potential for the S_{11} resonance is disregarded in our study, because the S_{11}-wave amplitude depends more weakly on the energy than does the D_{13}-wave amplitude, and its effect is expected to be much smaller, especially after Fermi averaging. Note that the spreading potential tends to cancel the consequence of the pion-production suppression, as shown in Fig. 12 in the preceding paper.

We now combine the effects of the N^* self-energy modification and the N^*-spreading potential. As before, we smear out these effects by Fermi averaging to construct the optical potential. Figure 3 shows that the cross sections are affected a little by the combined effects when the strength of the N^*-spreading potential is similar to that of the Δ-spreading potential. Even if we take V_R from -100 to 100 MeV and V_I from 0 to -100 MeV (about twice as large as that for Δ), we find that the change

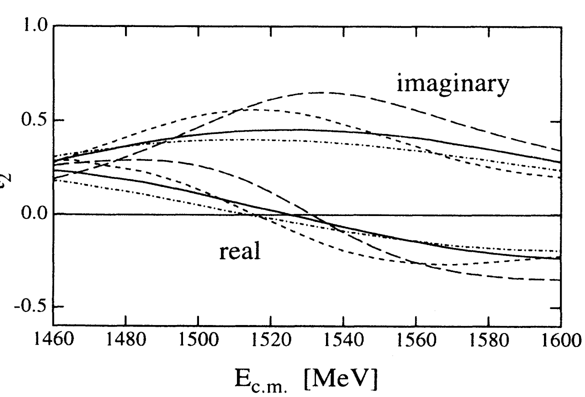

FIG. 1. The πN D_{13}-wave scattering amplitude in nuclear medium for $k_F = 1.02$ fm^{-1}. The solid and long-dashed lines are obtained by the isobar model with and without Fermi averaging, respectively. The dot-dashed and short-dashed lines are obtained by the free-space amplitudes given by Höhler [8], with and without Fermi averaging, respectively.

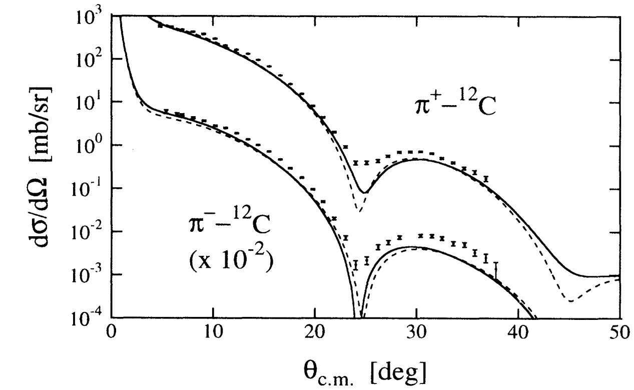

FIG. 2. The π-^{12}C elastic differential cross sections at $p_{\rm lab} = 800$ MeV/c. The solid curve is calculated by the use of the Fermi-averaged πN amplitudes that are affected by the modification of N^* self-energies in nuclear medium. The dashed curve is calculated by the lowest-order optical potential in impulse approximation (that is, neither higher-order, multiple-scattering effects, nor nuclear medium effects are included) [4]. The data are taken from Ref. [1].

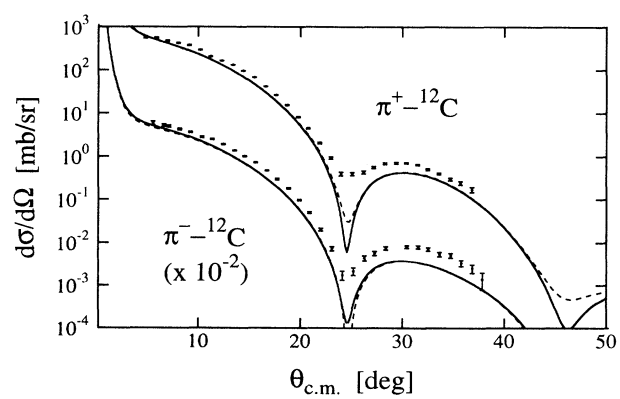

FIG. 3. The π-^{12}C elastic differential cross sections calculated by the use of the Fermi-averaged πN D_{13}-wave amplitude that are affected by the N^* self-energies modification of Fig. 2 and also by the spreading potential. The spreading potential, $V_{\rm sp} = V_R + iV_I$, is taken to be $V_R = 40$ MeV (solid line) and -40 MeV (dashed line) with $V_I = -40$ MeV.

is so small that we must conclude that the puzzling disagreement between the data and the calculations remains unexplainable by these effects. We note that a recent analysis, by Alberico *et al.* [12], of photonuclear experiments at 0.2–1.2 GeV [13] suggests an effective width of $N(1520)$ to be as large as 265 MeV. This seemingly large effective width is still within the range of our examination described here. (The effective width is a consequence of both of the N^* self-energy and the spreading potential in our formulation.)

The largest uncertainty in our previous study [4] was in the estimate of pion-absorption effects. We reexamine the effects here in light of new absorption measurements in ^{4}He on two-nucleon processes at $p_{\rm lab} = 1\,{\rm GeV}/c$ [6] and on two- and four-nucleon absorption at $T_\pi = 500$ MeV [7]. We first discuss the 1 GeV/c data in detail.

The new measurement at $p_{\rm lab} = 1\,{\rm GeV}/c$ is of angular distributions of (π^+, pp) and (π^+, pn) cross sections. By integrating the distributions, we extract the integrated cross sections as approximately 210 μb and 40 μb, respectively. Let us estimate the integrated cross sections, using a simple model with the π-deuteron-absorption data [14], and compare the estimates with these extracted values.

The reactions are classified according to the isospin of the nucleon pair as follows:

$$\pi^+ + pn(T=0) \to pp\,(T=1),$$
$$\pi^+ + pn(T=1) \to pp\,(T=1),$$
$$\pi^+ + nn(T=1) \to pn\,(T=0 \text{ or } 1).$$

We use a contact interaction form of the two-nucleon-absorption operator to analyze the first process [4] and thus to determine the interaction strength B from the deuteron data [14]. From the tabulated Legendre polynomial coefficients of the differential absorption cross-section data, we extract the cross section of $\pi^+ + d \to p + p$ to be 0.070 mb at 1 GeV/c, which yields ${\rm Im}B = -0.15$ fm^4. Here, we assume that the three reactions listed above have the same interaction strength. The π-nucleus potential that is due to pion absorption then becomes $5B\rho^2$, because the number of the appropriate nucleon pairs in ^{4}He is 5: three pn $(T=0)$ pairs, one pn $(T=1)$ pair, and one nn $(T=1)$ pair. Note here that the nuclear density ρ is normalized to unity.

Together with this value of ImB, we construct the π-nucleus optical potential on the basis of the multiple-scattering theory including the πN scattering contributions, as in our previous work [4]. Once it is constructed, the optical potential can provide the information not only of the pion elastic scattering from nuclei but also of the (two-nucleon, in our case) absorption and quasielastic scatterings [15]. In this way, we calculate the $^4{\rm He}(\pi, NN)$ cross sections by ignoring the nucleon distortion caused by the final-state interactions.

The cross sections thus estimated come out to be 180 μb and 45 μb for $^4{\rm He}(\pi^+, pp)$ and $^4{\rm He}(\pi^+, pn)$, respectively. They are in rough agreement with the above-quoted cross sections that we extracted from the ^{4}He data [6]. The rough agreement suggests that our simple model would not be too unreasonable.

In our previous work, we found that a strong pion-absorption potential is needed to resolve the puzzling discrepancy between the elastic scattering data and the calculations at 800 MeV/c: $B = 1.3 - i1.3$ fm^4 was needed for the π-^{12}C data if the absorptive part of the potential was in the commonly used form of $\frac{1}{2}A(A-1)B\rho^2$. The procedure we have followed here, however, requires a redefinition of B by the use of a different coefficient: the total number of appropriate pn and nn pairs instead of the total number of nucleon pairs, $\frac{1}{2}A(A-1)$. For ^{4}He, the factor is 5 (as above) instead of 6. Since for ^{12}C it is 51 instead of 66, the needed value that should be compared with is larger by the factor of 66/51, $B = 1.7 - i1.7$ fm^4.

At 800 MeV/c, the Legendre coefficient tabulation [14] yields the π^+-deuteron-absorption cross section to be 0.135 mb, which corresponds to ${\rm Im}B = -0.24$ fm^4, only one-seventh of the needed ImB value. (Note that in our previous work [4], we cited Im $B = -0.35$ fm^4, a rough estimate based on 0.2 mb.) The large value of ImB could be accommodated only if the pion absorption should be highly isospin dependent: The absorption on the $T=1$ nucleon pair should be at least 10 times larger than that on the $T=0$ pair. In view of the above success of our simple model in pion absorption, we consider the strong isospin dependence highly unlikely even if the difference in the incident pion momenta were to be taken into account.

There are differences among the observed angular distributions of $^2{\rm H}(\pi^+, pp)$, $^4{\rm He}(\pi^+, pp)$, and $^4{\rm He}(\pi^+, pn)$ [6], but they would be too small to be attributed to such strong isospin dependence. The pion-absorption effects thus seem to be too small to resolve the puzzle when the two-nucleon absorption is assumed.

Let us apply the preceding examination to the data at $T_\pi = 500$ MeV (or, 624 MeV/c) [7]. Using again the tabulation [14], we obtain the π^+-deuteron-absorption cross section to be 0.370 mb at this energy. The cross section corresponds to ${\rm Im}B = -0.54$ fm^4. Adding the ρ^2 term with this ImB to the potential, we repeat the calculation of the $^4{\rm He}(\pi, NN)$ cross sections. We find 1.3 mb and 0.3 mb for $^4{\rm He}(\pi^+, pp)$ and $^4{\rm He}(\pi^+, pn)$, respectively. The former is in agreement with 1.14 ± 0.11 mb that is reported in Ref. [7] as being a likely lower limit. The agreement with the data again verifies that our procedure is basically sound (see below, however).

Reference [7] also reports the four-nucleon-absorption cross section of 2.5 ± 0.6 mb, possibly as an upper limit. Sorting out various processes in pion absorption requires a reliable treatment of the final-state interactions, while Ref. [7] uses a plane-wave impulse approximation. Consequently, these quoted cross sections should be treated as estimates, as our preceding analysis should be, which also neglects the final-state interactions. Nevertheless, the four-nucleon-absorption cross section reported is quite large, and when we computed ImB by including the two-nucleon- and all multinucleon-absorption processes, the effective ImB was much larger than our preceding estimate based on the two-nucleon absorption. The multinucleon-absorption processes may indeed be quite significant, as was suggested theoretically some time ago [16,17]. A reliable, quantitative assessment of the processes is most urgently needed.

In summary, we have examined the effects of nuclear-medium modifications of the πN resonances to pion elastic scattering at 800 MeV/c, by using the isobar models for D_{13} and S_{11} resonances, i.e., $N(1520)$ and $N(1535)$. The modifications are mainly results of the pion distortion in the $\pi\Delta$ channel for $N(1520)$ and of Pauli blocking in the ηN channel for $N(1535)$. While they are prominent at a fixed πN energy in nuclear matter, they largely diminish in finite nuclei because of the Fermi averaging. The consequence of the modifications is only a few percent in the π-^{12}C differential cross sections, which is about the same amount as that of the nuclear-correlation effect [4]. Furthermore, even if the N^*-spreading potential of a rather large magnitude is assumed, the calculated cross sections do not reach the magnitudes of the data.

The recent π-^{4}He-absorption data confirmed our estimate, based on the assumption of pion absorption by a pair of the nucleons. We thus conclude that the two-nucleon absorption does not resolve the puzzling disagreement between the data and the calculations [1–4]. The strength of multinucleon-absorption processes, which contribute additively, may be quite significant at this energy range and could be a possible explanation of the disagreement. A reliable, quantitative assessment of the processes is thus urgently needed.

Before closing, we make relevant comments: In our previous work [4] and in this work, we have examined various effects to find for a resolution of the puzzle and have found none strong enough to explain it (possibly apart from multinucleon-absorption processes). Certainly, a possibly logical explanation is that many or all of the effects might be contributing constructively to fill the gap. We cannot exclude this possibility, of course, but we think it unlikely. Another possible logical explanation is that the original experimental uncertainties [1] were underestimated. Differential cross sections of the π-^{12}C elastic scattering have been measured recently with better precision for 0.5–1 GeV/c at KEK and are being analyzed [18]. We hope that the new data may clarify this possibility. Last, we must emphasize that the puzzle we have addressed here is quite similar to that in K^+ scattering [19], involving a similar magnitude of discrepancy at a similar energy. The latter puzzle has been attributed to swelling nucleons [20] and to a smaller rho-meson mass in the nuclei [21]. If clarified, the puzzle here would affect the K^+ puzzle as well.

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