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Pion-nucleus scattering and baryon resonances in the nuclear medium

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Pion-nucleus total cross sections are examined for pion laboratory kinetic energies between 400 MeV and 1 GeV. Modifications by the nuclear medium of the dominant $D_{13}(1520)$ and $F_{15}(1680)$ excited hadrons are investigated. Fermi motion and multiple scattering are found to broaden significantly the peaks in the cross section. Additional broadening as determined from a model of photon-nucleus total cross sections is found to further reduce the cross sections and increase the discrepancy between theory and data. The discrepancy, nearly energy-independent and of the order of 15–20 %, can be accounted for if one assumes the nuclear medium causes a 31–42 % increase in the strength of the pion-nucleon interaction in all channels.

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The properties of hadrons, including their masses and (for unstable hadrons) their widths, are expected to change when the hadron is embedded in nuclear matter. This effect has been quantified empirically for the nucleon and the $\Delta_{33}(1232)$, and, in the strange sector, for the $\Lambda(1115)$. For the Δ_{33}, a combination of medium effects [1–3] are required to reproduce pion- and photonucleus data. These include the binding of the nucleon, the mean field acting on the Δ_{33}, Pauli blocking, Fermi averaging and correlation corrections. The total of these effects can be phenomenologically described [4] as shifts in the mass and width of the Δ_{33}.

Measurements with energetic photons [5,6] have been used to extend the empirical study of baryon resonances in nuclei to some of the more highly excited states. In the case of photonuclear measurements, the prominent peaks for the $D_{13}(1520)$ and $F_{15}(1680)$ resonances, present for the free nucleon, have essentially disappeared for the finite nucleus target. This result is interpreted in Ref. [5] as the combined effect of Fermi averaging plus additional collision broadening that occurs when the baryon resonances propagate in nuclear matter; a somewhat more detailed model is presented in Ref. [6]. In contrast to the photonuclear measurements, similar measurements with exclusive electron scattering [7] find prominent peaks for these two resonances with a nuclear target. The fate of the more massive resonances when embedded in a nucleus is thus not yet clear.

The same set of baryon resonances couple both to photons and to pions, so that a combined treatment of pion and photon scattering can elucidate the behavior of baryon resonances in the nucleus. In the present paper we explore pion-nucleus scattering in the GeV region utilizing one [5] of the phenomenological models for the total photoreaction cross section. A more exact treatment of the photonucleus data along the lines of Ref. [3] is discussed later in this paper.

The couplings of the photon and the pion to the resonances differ markedly, and thus the details that govern the dynamics of photon- and pion-induced reactions will likewise differ. However, the same medium modifications of the resonances will be present in both cases. In addition, the pion at energies above the Δ_{33} is the second weakest of the strongly interacting hadrons (behind the kaon) so that resonances created by pions will find themselves in a nuclear medium of reasonable density [8,9].

In this paper we implement an isobar model of the pion-nucleon interaction for energies above the Δ_{33}. Within the scattering theory of Ref. [2], we examine pion-nucleus scattering. By working with the momentum-space optical potential [10], we are able to investigate within a covariant theory total cross section measurements and examine separately the effects of Fermi motion and multiple scattering. We here assume that the conventional second-order correlation corrections and mesonic-current corrections are negligible. We further incorporate the medium modifications of the excited hadrons as deduced from the photon total cross section data in Ref. [5]. We find an interesting discrepancy — the theoretical results lie consistently below the data. A possible explanation is that the coupling of the pion to the nucleon to form a resonance is increased inside the nucleus. A full understanding will require additional data utilizing both pion and electromagnetic probes.

We assume that the pion-nucleus optical potential can be expressed in terms of a medium-modified pion-nucleon t matrix. We first divide the free-space t matrix into resonance and background parts,

$$t = t_{\mathrm{nr}} + \sum t_{\mathrm{res},j}, \tag{1}$$

where t_{nr} is the nonresonant background amplitude and $t_{\mathrm{res},j}$ is the resonant amplitude for resonance j. We write the resonant amplitude in a Breit-Wigner form,

$$t_{\mathrm{res},j} = \frac{g^2_{\pi NN^*,j}}{(k+p)^2 - M_j^2 + iM_j\Gamma_j} \tag{2}$$

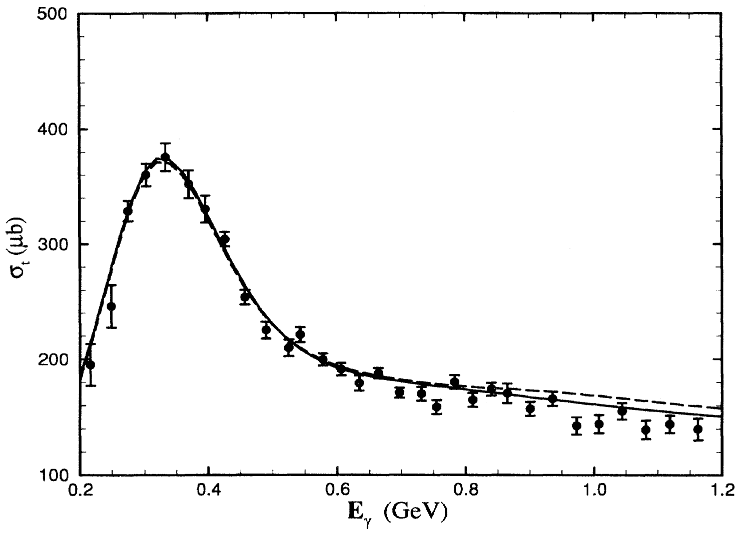

FIG. 1. The total cross section for photon-^{238}U scattering as a function of photon energy. The data are from Kondratyuk *et al.* The solid line is the result of the model presented there where eight resonances have enhanced widths. The dashed line is the result of their model with only three resonances having medium modified widths.

characterized by a free-space elastic width (proportional to $g_{\pi NN^*,j}$), a free-space mass M_j, and a free-space total width Γ_j. [The free-space mass of the $\Delta_{33}(1232)$ is shifted [5] by 15 MeV to help produce a better fit to the data with an energy-independent width.] Here k is the pion and p is the nucleon four-momentum. Next, in the spirit of [5,6], $t_{\text{res},j}$ is assumed to be modified in the medium by the Fermi motion of the nucleons plus additional collision broadening. Together, these effects explain the effective disappearance of the $D_{13}(1520)$ and $F_{15}(1680)$ resonances in photon total cross sections over the same energy region we are studying here. We choose the parametrization of Ref. [5] in which M_j are kept at their free-space values and examine the consequences for pion-nucleus reactions. The results of Ref. [6] are more detailed than those of Ref. [5] in that the former specifies medium modifications of M_j as well. In a future work, we will extend this to the model of Ref. [6].

In the model of Kondratyuk *et al.* [5], the resonant amplitude for forward Compton scattering on a nucleus is taken to be of the form of Eq. (1) with $g_{\pi NN^*,j} \rightarrow g_{\gamma NN^*,j}$. The resonance modifications in the nuclear medium are determined there from the total photon cross section on ^{238}U. To do this, the amplitude is first averaged over the motion of the nucleons and the free width is decreased by a Pauli blocking factor B_F. The masses of the resonances are left at their free values because the photon data do not exhibit any visible peaks from which they could be determined. The total free width of each resonance is then increased by adding a collision broadening contribution Γ^* until a fit to the photon total cross section for ^{238}U is obtained. The widths for eight resonances are modified in this fashion.

In our work, we have been able to simplify the model of Ref. [5] by making use of the observation that the photonuclear data sensitively determine only the medium modifications of the $\Delta_{33}(1232)$, the $D_{13}(1520)$, and the $F_{15}(1680)$. In Fig. 1 we compare the original model [5] with all eight resonances altered by the medium (solid line) to our version in which just these three resonances are modified (dashed line). The changes caused by the medium for the three-resonance model are exactly those prescribed in Ref. [5]. The difference between the models is quite small, justifying our choice.

We next apply the isobar model to pion-nucleus total cross sections taking the resonance medium modification from our version of the results of Ref. [5]. We first adjust $g_{\pi NN^*,j}$ to fit the free pion-nucleon elastic amplitudes taken from [11]. However, since the energy-independent widths that are used in Ref. [5] do not reproduce exactly the measured pion-nucleon total cross section, we add to the background amplitude in Eq. (1) the difference between the amplitude as determined from [11] and the amplitude that results from the sum of the three parametrized resonances. In Fig. 2 we compare the pion-nucleon total cross sections determined from the data [11] (solid line) to the calculation in which the three resonant channels of interest are replaced by the parametrized Breit-Wigner form with the masses and total widths from Ref. [5]. Our procedure of including the difference between these two curves as part of the background amplitude produces a model that, in the absence of any medium modifications, makes no error due to the lack of an exact fit to the two-body amplitude in the resonant channels. We extend the resonant channel amplitudes off the energy shell by utilizing a separable form,

$$\langle \kappa' | t_{JLI}(\omega_\alpha) | \kappa \rangle = \frac{v(\kappa')}{v(\kappa_0)} \langle \kappa_0 | t_{JLI}(\omega_\alpha) | \kappa_0 \rangle \frac{v(\kappa')}{v(\kappa_0)}, \tag{3}$$

where κ_0 is the on-shell momentum, i.e., the momentum corresponding to the center-of-momentum energy ω_α. We use Gaussian functions for the form factor $v(\kappa)$ with a range of 1 GeV. We find that the predicted total cross sections for pion-nucleus scattering do not depend on the functional form chosen for the form factor nor do they depend on the range chosen for the form factor.

Using the off-shell pion-nucleon amplitude discussed in Eq. (3), we have calculated the pion-nucleus total cross sections utilizing the momentum-space optical potential approach developed in [10]. Our theoretical calculations are presented in Fig. 3 as a function of pion laboratory kinetic energy for π^+ on ^{12}C. The medium-dashed line is the result of the calculation in the absence of collision broadening. For purposes of comparison, the result for twelve free nucleons, $6[\sigma(\pi^+p)+\sigma(\pi^+n)]$, is shown as the dot-dashed line. We

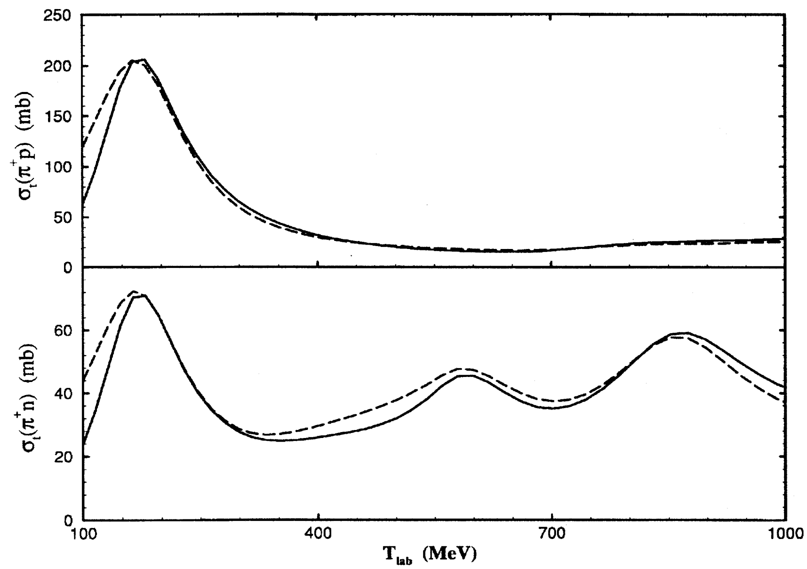

FIG. 2. Total cross sections for pion-nucleon scattering. The solid line is the result of the phase shift analysis of Arndt. The dashed line replaces the $\Delta_{33}(1232)$, the $D_{13}(1520)$, and the $F_{15}(1680)$ channels by the Breit-Wigner form with parameters as taken from Kondratyuk *et al.*

see that the combined effect of Fermi averaging (performed exactly by the computer code ROMPIN [10]) and multiple scattering decreases the cross section and, to a great extent, removes the bumps visible in the dot-dashed line. The effect of Fermi averaging alone is seen in the Born approximation to the momentum-space result, given as the short-dashed curve in Fig. 3. By comparing this to the dot-dashed curve, we see that the Fermi motion broadens the resonances and significantly smooths the energy dependence of the cross section; effects of multiple scattering change the results from the short-dashed curve to the medium-dashed curve. Note that the momentum-space calculation falls below the data [12,13] by about 20%. A qualitatively similar discrepancy has been seen [1,14,15] in the elastic angular distribution [16] for 800 MeV/c pions on ^{12}C. A mechanism that uniformly increases the optical potential over the energy range examined will be able to approximately fit all the data that currently exist.

We now add the collision broadening of the three dominant resonances as determined from the photon total cross section in Ref. [5]. The physical origin of the broadening of the resonances is presumably the opening of additional decay channels when the resonance is created in the medium. Pion production and absorption are two examples of channels that can contribute to the decay of the resonances in the medium. Another possibility is that the heavier resonances, once produced in the nucleus, immediately decay because they find themselves in direct contact with many nucleons due to the increased radial size of these resonances [17].

The result of collision broadening in pion scattering, as determined from the photonuclear data [5], is given as the solid curve in Fig. 3. We see that although the increase in widths has a noticeable effect on the predicted cross sections, the result is strikingly small and further reduces the theoretical predicted cross sections. Changes in the masses of the resonances will have very little additional effect since the resonances in our final model are quite broad. The most interesting feature is not the effects of the medium modifications *per se*, but rather the large discrepancy that stands out in comparing the solid curve in Fig. 3 with the data [12,13].

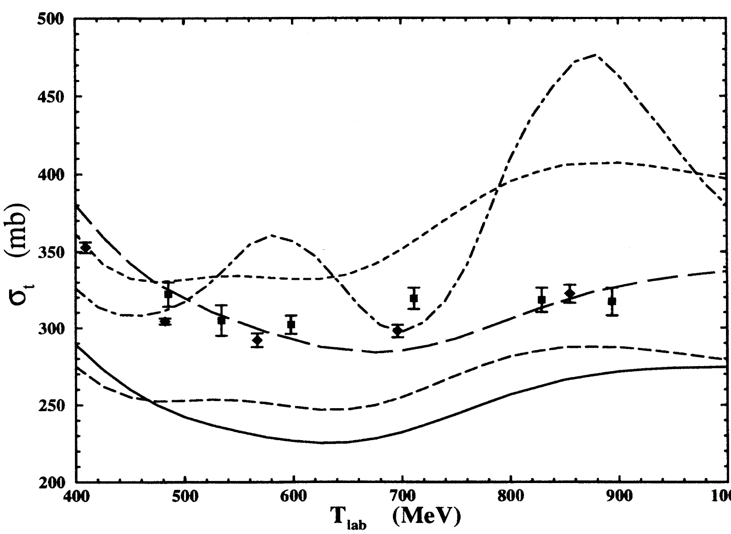

FIG. 3. The total cross section for pion-^{12}C scattering as a function of pion kinetic energy. The data are from Crozon *et al.* and Clough *et al.* The dot-dashed curve is the result of taking 12 times the spin-isospin average of the free two-body amplitude; the short-dashed curve is the result of Fermi averaging the free amplitude (the Born approximation to the optical potential); the medium-dashed curve is the result of solving the optical potential in Klein-Gordon equation; the solid curve adds the additional collision broadening as determined in Kondratyuk *et al.*; and the long-dashed curve is the result with collision broadening but with the pion-nucleon interaction increased by a phenomenological 42%.

The discrepancy between the data and the complete theory including the collision broadening (solid curve) is about 20% and is approximately energy independent. If we go to the opposite extreme and neglect the additional broadening that we have taken from the fit to the photon total cross section [5], we still find a discrepancy of roughly 15%. Such a discrepancy could indicate a failure to include some important piece of the reaction mechanism. However, we expect that the reaction channels, such as true absorption and pion production, are dominated in this energy region by the resonances themselves, so that these effects are included automatically in our phenomenological description of collision broadening taken from photonuclear data. A simple and possible explanation is that the coupling constant of the pion to excite resonances in the nucleus is modified in the medium. To simulate this, we find that a phenomenological increase of the pion-nucleon amplitude of 42% will reproduce the data as is shown by the long-dashed curve in Fig. 3. The result pictured includes the increase in width of the resonances as taken from the photonuclear data, but no additional increase in width that one might expect from an increased coupling constant. In a doorway model where the inelastic channels are coupled to the elastic channel only through the resonance channel, an increase in amplitude would be proportional to an increase in the square of the coupling constant. This model would then correspond to a 20% increase in all coupling constants, including those in the nonresonant channels. If we neglect the broadening of the resonances taken from the photon data, we find the data indicate a 31% increase in the in-medium amplitudes or a 15% increase in all the coupling constants.

The discrepancy found here is reminiscent of what has been seen [18] in kaon-nucleus scattering. There one also finds that the theoretical cross sections lie consistently, and of the order of 20%, below the data. A possible explanation there [19] also could be an increase in the coupling of mesons to the nucleon. An alternative explanation which might also apply here would be a combination [20] of meson exchange currents [21] and correlations when a nonstatic approach to their calculation is used. The role of two-body correlations, meson exchange currents, and true absorption, although we believe them to be small for the pion-nucleus data, deserve a more careful investigation.

From a theoretical point of view, the modification of baryon properties in nuclear matter is an interesting and fundamental problem. One of the most promising developments in nuclear physics in recent years has been the realization that hadrons can be studied using methods of nonperturbative QCD [22], where masses and coupling constants can be related to the quark and gluon condensates [23,24]. Hadronic masses in nuclear matter have also been studied [25–27]. In the pioneering work of Drukarev and Levin [25], an estimate of the quark condensate in nuclear matter was given. Some of these condensates, particularly the four-quark condensates, are poorly known. The properties of the Δ_{33} in the nucleus are a promising source of information on these [28] condensates. Other sources of information, for example from higher-lying hadrons such as those discussed above, would be of great importance.

Although we have argued that reaction channels should be largely accounted for by the collision broadening, we have estimated what the effect of true absorption of the pion would be in the quasideuteron model [15] assuming that it is not resonance dominated. Our result is that it would contribute at most 5% to the total cross section, too small to account for the observed problem. Further investigations are needed to establish the actual contribution of such corrections to the observed discrepancy. A more dynamically motivated model for the photoinduced reaction is clearly needed to more cleanly separate the medium-modified resonance propagators (needed for the analysis of pion scattering) from other effects such as an enhanced photon-induced background [3]; such a model must, of course, maintain the established picture of the Δ_{33} that has come from microscopic models such as those in Refs. [1,2]. An enhanced photonuclear background would require less broadening, and the coupling constant enhancement we find would then lie between the 15% and 20% indicated above. In any case, we expect that the collision broadening would tend to *increase* the renormalization we have here found for energies above the Δ_{33}.

Very little data on pion-nucleus scattering exists in the GeV region. A few new measurements of pion elastic scattering that could be of help are presently being analyzed at LAMPF [29] and KEK [30]. A number of additional measurements that would clarify the situation suggest themselves: (1) total and total reaction cross sections on other nuclei to see whether the disagreement we find for carbon is a universal phenomenon; (2) measurement of elastic differential cross sections at sufficiently finely spaced intervals to identify structure in energy variation of the minima of the angular distributions; (3) measurement of single charge exchange [including (π,η) reactions], which would help separate isospin-dependent effects. Other measurements, for example partial reaction cross sections, would be desirable in order to rule out the unlikely possibility that the deficit we identify could be explained by unexpectedly large or exotic background reactions having nothing to do with the baryon resonances. Such measurements could be made in the low-energy region (pion kinetic energies up to 575 MeV) at LAMPF and at higher energies at KEK and at the AGS at Brookhaven.

In summary, we have shown how a model for the medium modifications of the hadron resonances can be taken from photon total cross section measurements and applied to pion-induced reactions. The result is a prediction for pion total cross sections that lie about 15–20 % below the data. This discrepancy can be easily and naturally explained by a renormalization of the coupling constant for pion-nucleon-resonance coupling by 15–20 %. This renormalization would be the dominant medium modification; the medium broadening of the resonances affects the cross sections but is too small and of the wrong sign to account for the difference between the theory and the data.

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