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THEORY OF PION-NUCLEUS SCATTERING BELOW 1 GeV

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Abstract

We will review recent theoretical developments in the area of meson-nucleus interactions with an emphasis on the behavior of baryon resonances in nuclei.

1. Introduction

To begin, we want to indicate the connection of meson-nucleus scattering, a primary source of information about baryon resonances in nuclei, to an emerging area of theoretical physics: development of methods of nonperturbative QCD [1-3] that relate the properties of hadrons to condensates of quarks and gluons. Since properties such as mass change in nuclear matter (an effect that has been quantified empirically for the nucleon and the $\Delta_{33}(1232)$, and, in the strange sector, the $\Lambda(1115)$), the possibility of extending the same methods to study hadrons in nuclei naturally arises.

The method of QCD sum rules has in fact been applied to study the behavior of the nucleon in nuclear matter in recent years [4–6]. In the work of Drukarev and Levin [4], a theoretical estimate of the familiar two-quark condensate in nuclear matter was given, and it was shown that this condensate is appreciably modified from its free-space value. Others, particularly the four-quark condensates, are considerably less well known in nuclear matter. These have been the subject of study in models [7], but they may also be determined from meson-nucleus scattering data. For example, in [8], the mass of the Δ_{33} in the nucleus, first deduced from π scattering measurements [9], was used to obtain a value for the four-quark condensate indicating a significant correction to the factorized result. The coupling $g^{*}_{\pi N\Delta}$ provides even more information [8].

Since many new condensates arise at the four-quark level, one needs additional empirical information in order to apply QCD sum rules to nuclei. Modified values for the mass M_i^*, width Γ_i^*, and pion coupling $g_{\pi NN^*,i}^*$ to baryon resonances i, which may be obtained from meson and γ scattering on nuclei, are suitable for this purpose by extending Ref. [8] to higher-lying baryon resonances.

2. Meson-Nucleus Scattering Theory

How does one obtain the properties of baryon resonances from meson scattering? The basic element of scattering is the meson-nucleon (and, for photons, the γ-nucleon) scattering t-matrix, which may be divided into resonance $t_{res,j}$ and background t_{nr} parts for resonance j,

$$t = t_{nr} + \sum t_{res,j} \; . \quad (1)$$

The amplitude $t_{res,j}$ may be expressed in a Breit-Wigner form, characterized by a free-space elastic width (proportional to $g_{mNN^*,j}$), mass M_j, and total width Γ_j,

$$t_{res,j} = \frac{g^2_{mNN^*,j}}{(k+p)^2 - M_j^2 + iM_j\Gamma_j} \; . \quad (2)$$

Here k is the meson (m) and p is the nucleon (N) four momentum. The parameters have been determined empirically for numerous baryon resonances formed in π, kaon, and γ scattering from isolated nucleons. For the remainder of the talk, I shall deal mostly with π scattering and its relationship to nonstrange baryon resonances in nuclei. Similar considerations would apply to K^- scattering, which is an important source of information about strange resonances.

Scattering from the nucleus is often calculated from the optical potential, which is found by averaging the scattering amplitude over the nucleus. This has been done both phenomenologically [9] and microscopically [10,11] for π scattering in the region of the Δ_{33} resonance with considerable success. More recently, various attempts have been made to understand π scattering data above the Δ_{33} resonance, see e.g., Refs. [12–19]. Different groups have emphasized different approximations and methods, including semi-classical approaches [12,13,15], optical model approaches [14,16,17], and comparisons between them [14,16]. In contrast to the situation in the vicinity of the Δ_{33}, the off-shell behavior of the amplitude does not seem to be a very important consideration for the higher energies [19].

Some of these calculations modeled π scattering using the *free* π-nucleon scattering amplitude. While there is general quantitative agreement among the different approaches in this approximation, the experimental data generally disagrees with them. Experience with the Δ_{33} and the failure to explain π scattering using free-space amplitudes, suggests modified values, M_i^*, Γ_i^*, and $g^*_{\pi NN^*,i}$. A recent study within a conventional many-body approach [18] found it very difficult to calculate medium effects reliably as the energy is raised. A more phenomenological approach to determining them was taken in

Ref. [19], where an effort was made to combine γ- and π-nuclear data in the GeV energy region. I will next discuss the data within the context of the theory of Ref. [19] as applied to π scattering from ^{12}C. This results were obtained from a limited data set of total cross sections [20,21] and angular distributions [22]. The recent release of the new KEK angular distribution data [23] at several energies provides a basis for testing the conclusions of this theory.

3. Analysis of γ-Nucleus and π-Nucleus Scattering Data

The problem of determining the properties of the baryon resonances above the Δ_{33} is more complicated than it is for the Δ_{33} itself because at the higher energies the resonances are overlapping. Consequently, one needs to consider all sources of information available. Photonuclear reactions are complementary to π scattering, since the resonances couple differently to the γ and π. The most direct way to determine $g^{*}_{\pi NN^*,i}$ is of course to use π beams, although photopion production could also provide this information.

Measurements of total cross sections with energetic γ up to 1 GeV have already been used for an empirical study [24,25] of the more highly excited baryon resonances in nuclei. The prominent peaks for the $D_{13}(1520)$ and $F_{15}(1680)$ resonances, present for the free nucleon, were found to disappear in the γ-nuclear measurements. This result is interpreted in Ref. [24] as the combined effect of fermi averaging, Pauli blocking, plus additional collision broadening. The resonance modifications in the nuclear medium were determined there from the total γ cross section on ^{238}U. The resonant amplitude for forward Compton scattering was taken to be of the form of Eq. (2) with $g_{\pi NN^*,j} \rightarrow g_{\gamma NN^*,j}$. The masses of the resonances were left at their free values because the γ data do not exhibit visible peaks from which they could be determined; the total widths Γ^{*}_{i} for eight resonances were then determined by varying a collision broadening term until a fit to the total cross section was obtained.

Although the baryon resonances couple differently to γ and to π, the in-medium masses and widths (resonance proper self energies) that enter into the scattering amplitude of Eq. (2) are the same for both. This is because the proper self energy characterizes the resonance and not the projectile, and also because the π, as well as the γ, can penetrate nearly to the center of ^{12}C. Note that the π, at energies above the Δ_{33}, is the second weakest of the strongly interacting hadrons (behind the K^+) [16]. Medium modifications to the self-energies of the baryon resonances are thus incorporated in Ref. [19] in the spirit of Refs. [24,25]; that is, $t_{res,j}$ is assumed to be increased by the fermi motion and collision broadening. Several simplifications have been made to the model of Ref. [24], which are described further in Ref. [19]. The physical origin of resonance broadening is presumably the additional decay channels available to a resonance created in the medium. Pion production and absorption are two examples of channels that can contribute to the decay of the resonances in the nucleus. 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 larger radial size of these resonances [26].

The results of Ref. [19] were obtained using the covariant theory of Ref. [11], but here we use the eikonal theory of Ref. [16]. The two approaches may be considered identical for the purposes of this talk. Fermi motion is included, but the conventional second-order and meson-current corrections that do not contribute to Γ_i^* are assumed to be negligible.

First of all, the amplitude of Eq. (2) is fixed by adjusting $g_{\pi NN^*,j}$ to fit the free π-nucleon elastic amplitudes of Ref. [27], and the total cross sections are then calculated from these using the eikonal theory. The results are presented in Fig. 1 as a function of laboratory kinetic energy for π^+ on ^{12}C and compared to data [20,21,23]. (The new KEK data [23] were not available when the study of Ref. [19] was made.) The dashed line is the result of the calculation in the absence of collision broadening, showing the combined effect of fermi averaging and multiple scattering. When the collision broadening is added, as determined from the γ total cross section in Ref. [24], the dash-dotted curve is obtained. Although the increase in widths has a noticeable effect on the predicted cross sections, the result is strikingly small and has the wrong sign above 500 MeV. Changes in the masses of the resonances will have very little additional effect since the resonances in the model are quite broad.

The most interesting feature is not the effect of the medium modifications *per se*, but rather the large discrepancy that stands out in comparing the dash-dotted curve with the data. The discrepancy is about 20% and is approximately energy independent. This could indicate a failure to include some important piece of the reaction mechanism. However, we expect that the reaction channels 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 γ-nuclear data.

A particularly intriguing possibility is that the coupling of the π to the resonances is modified in the nucleus. In the eikonal theory, a phenomenological increase of the π-nucleon interaction in the medium by 20% will reproduce the older data, as is shown by the solid curve in Fig. 1. This would correspond to a 10% (20% in the theory of Ref. [10]) increase in the π-nucleon-resonance coupling constant, $g_{\pi NN^*,j}$, in all (including

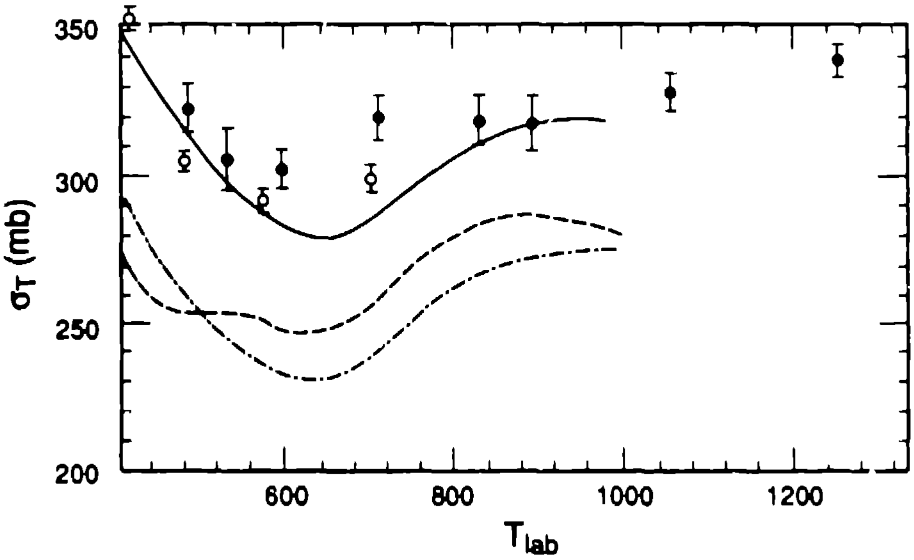

Fig. 1. Total cross section for π on ^{12}C. Data are from Refs. [20,21] and the calculations are described in the text.

nonresonant) channels and would constitute a significant additional piece of information for constraining the four-quark condensates in nuclei. This situation is reminiscent of what has been seen [28] in K^+-nucleus scattering, where one also finds the theoretical cross sections lying consistently about 20% below the data, and suggesting [29] an increased coupling of mesons to the nucleon.

To check the consistency of the theory of Ref. [19], we have compared it to the recent KEK data [23]. There are two points to make: (1) the angular distributions are generally improved by the 20% renormalization, but the minima in the theory are generally too deep. Note that the minima depend strongly on the real part of the amplitude [30] and are therefore particularly sensitive to the masses of the resonances in the nucleus; (2) if the KEK total cross sections are taken seriously, the coupling constant enhancement may be energy- (or resonance-) dependent and, in particular, will have to be reduced below 600 MeV where the Δ_{33} begins to dominate.

4. Conclusions

Baryon resonance properties in nuclei, which can be deduced from meson and γ scattering from nuclei, provide an empirical probe of four-quark condensates in nuclei. Pion scattering data, including angular distributions taken recently at KEK, are consistent with a substantial broadening of resonances and an enhanced π coupling to the more massive baryon resonances in nuclei. Before one can make a more quantitative determination of the properties of baryon resonances above the Δ_{33}, additional data is needed. A simple but indirect approach for obtaining the information is to fit the properties of the resonance appearing in Eq. (2) to elastic scattering as in [9] for the Δ_{33}. A more direct and promising type of experiment is to detect the outgoing π or γ in coincidence with the proton arising from decay of excited baryon resonances [31].

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