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Isospin dependence of the Δ-spreading potential

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The ratio of near-resonance inclusive $\pi^{\pm}$ scattering cross sections from the isotopic pair $^{16,18}O$ is shown to be consistent with an isospin dependence of the Δ-spreading potential determined by intermediate coupling to the pion absorption channel.

[NUCLEAR REACTIONS $^{16,18}O(\pi^{\pm}, \pi^{\pm\prime})$ inclusive scattering; test isospin dependence of Δ-nucleus interaction.]

The scattering and absorption of intermediate energy pions by nuclei are dominated by formation and propagation of the Δ isobar. Analyses of pion scattering from light "closed-shell", isoscalar nuclei (i.e., ^4He, ^{12}C, ^{16}O) have shown that Δ propagation in the nuclear medium is modified significantly from that in free space by strong Δ-nucleus interactions.[1] For example, the rough equality of the inclusive pion inelastic scattering and total annihilation cross sections implies that the Δ has a nuclear damping or spreading width arising from the $\Delta+N\to N+N$ process roughly equal[2] to the free space width arising from decay $\Delta\to\pi+N$:

$$\Gamma_{Abs}\approx\Gamma\approx 100\text{ MeV}. \tag{1}$$

Here, Γ is the free space decay width and Γ_{Abs} is the nuclear matter value of the spreading width due to pion absorption out of the Δ "doorway." Since the absorption process requires the presence of another nucleon, Γ_{Abs} is roughly proportional to the local nuclear density. It is important to stress the direct connection between the partial Δ-decay widths and the partial inclusive pion reaction cross sections.

Ashery[3] reported, at the Vancouver conference, data for inclusive scattering of 165 MeV $\pi^{\pm}$ from the isotopic pair $^{16,18}O$. These data display a qualitatively surprising feature. Namely, while the cross section ratio R_- for $^{18}O(\pi^-,\pi^{-\prime})/^{16}O(\pi^-,\pi^{-\prime})$ is larger than one ($R_-\sim 1.22$) as expected, the ratio R_+ for $^{18}O(\pi^+,\pi^{+\prime})/^{16}O(\pi^+,\pi^{+\prime})$ is less than one ($R_+\sim 0.84$). The most naive expectation would be that, since the π^+n elastic cross section is much smaller than that for π^+p, R_+ should be slightly larger than one. However, this expectation is based implicitly upon the assumption that free Δ decay in the nucleus (equivalently, quasifree πN scattering) controls the dynamics. We have seen above [Eq. (1)] that this is not correct. The purpose of this short note is to demonstrate that the isotopic dependence of Γ_{Abs} leads naturally to the observed behavior. This was indicated qualitatively by Lenz and Moniz.[1]

The nuclear absorption of π^+ mesons takes place predominantly through the process

$$\pi^+pn\to\Delta^{++}n\to pp\,. \tag{2}$$

Consequently, π^+ scattering occurs mostly from the nuclear protons, but the intermediate Δ^{++} spreading potential is proportional to the neutron density. The proton densities in ^{16}O and in ^{18}O are essentially the same, but the neutron density in ^{18}O is substantially larger. Therefore, the in-medium π^+p scattering amplitude will be more spread in ^{18}O than in ^{16}O, leading to an effectively weaker amplitude at the resonance energy and thus to a smaller inclusive cross section. This decrease in the cross section is somewhat offset by the associated increase in the pion mean free path and by the comparatively weak scattering from the "extra" neutrons.

A very crude calculation suffices to demonstrate the effect. We calculate the ratios $R_{\pm}$ for backward inclusive scattering, where the large momentum transfer guarantees that "quasielastic" nucleon knockout dominates. Ignoring refinements due to recoil and nonlocal effects, the inclusive cross section has the semiclassical form

$$\left.\frac{d\sigma}{d\Omega}\right|_{\pi A}=\int d\vec{r}\,\rho(r)e^{-L(\vec{r})}\left.\frac{d\sigma}{d\Omega}\right|_{\pi N},\quad \int d\vec{r}\,\rho(r)\equiv A \tag{3}$$

where $L(\vec{r})$ is the optical path length in units of the mean free path

$$L(\vec{r})=L(\vec{b},z)=\int_{-\infty}^{z}dz'/\lambda(b,z')\,. \tag{4}$$

The free-space πN scattering amplitude has the resonant form

$$f_{\pi N}(0)=-\frac{k\sigma_R}{4\pi}\frac{\Gamma/2}{E-E_R+i\Gamma/2}\,, \tag{5}$$

where σ_R is the cross section at resonance ($\sigma_R^{\pi^+ p} \approx \sigma_R^{\pi^- n} \approx 3\sigma_R^{\pi^+ n} \approx 3\sigma_R^{\pi^- p} \approx 200$ mb). Several modifications of Eqs. (3)–(5) are needed for our calculation of the isospin effects. First, we must explicitly decompose the scattering into contributions arising from protons and from neutrons. Second, the Breit-Wigner resonant denominator must be modified to reflect the strong medium corrections to the Δ propagator described above. In scattering from protons (which occurs mostly for π^+) we take the density-dependent width

$$\Gamma \rightarrow \Gamma_T^p(r) = \left\{\Gamma - \Gamma_P\left[\frac{\rho_p(r)}{\rho_0}\right]^{1/3}\right\} + \Gamma_{\mathrm{Abs}}\left[\frac{\rho_n(r)}{\rho_0}\right]. \quad (6)$$

Here, ρ_0 is the central proton density in ^{16}O. The important point is that, as discussed earlier, the spreading width due to π^+ absorption is proportional to the neutron density. In addition, the Δ decay width is quenched because of the Pauli-principle blocking of final nucleon states. We have taken this as proportional to the local Fermi momentum and will comment below on other choices for the density dependence. The form given by Eq. (6) for the total in-medium width has been shown in semiclassical approximation[4-6] to reproduce rather well the results of far more detailed calculations.[2] For scattering from neutrons, the proton and neutron labels in Eq. (6) should be exchanged. The pion mean free path is calculated in the usual way, giving

$$\frac{1}{\lambda} = \sum_{i=n,p} \rho_i(r)\sigma_R^i \frac{(\Gamma/2)[\Gamma_T^i(r)/2]}{(E-E_R)^2 + [\Gamma_T^i(r)/2]^2}. \quad (7)$$

In principle, the resonance position E_R should also be density dependent, but this would not affect the qualitative results. Finally, an additional optical absorption factor is included to take account of annihilation and charge exchange of the scattered pions. The charge exchange is negligible. The absorption mean free path is given by $\lambda_{\mathrm{Abs}}^{-1} \equiv (\Gamma_{\mathrm{Abs}}/\Gamma_T)\lambda^{-1}$ and is included in $L(\vec{r})$ by the replacement $\lambda^{-1} \rightarrow (\lambda^{-1} + \lambda_{\mathrm{Abs}}^{-1})$. Putting this together, we have the expression

$$\left.\frac{d\sigma}{d\Omega}\right|_{\pi A} \propto \int d\vec{r}\, e^{-L(\vec{r})}\left\{\frac{\rho_p(r)\sigma_R^{p2}}{(E-E_R)^2 + [\Gamma_T^p(r)/2]^2} + \frac{\rho_n(r)\sigma_R^{n2}}{(E-E_R)^2 + [\Gamma_T^n(r)/2]^2}\right\},$$

$$L(\vec{r}) = \int_{-\infty}^{z} dz'/\tilde{\lambda}(b, z'), \quad (8)$$

$$\frac{1}{\tilde{\lambda}(r)} = \rho_p(r)\sigma_R^p \frac{(\Gamma/2)[\Gamma_T^p(r) + \Gamma_{\mathrm{Abs}}^n(r)]/2}{(E-E_R)^2 + [\Gamma_T^p(r)/2]^2} + (p \rightleftharpoons n).$$

The parameters characterizing the in-medium Δ width are taken from the detailed Δ-hole calculations[1,2]: $\Gamma_{\mathrm{Abs}} = 90$ MeV, $\Gamma_p = 40$ MeV. Hüfner and Thies[6] found surprisingly good agreement for both the magnitude and shape of a variety of pion inelastic spectra using similar parameters. The proton density was taken as a harmonic oscillator distribution with root-mean-square radius $\bar{R}_p = 2.71$ fm. The same distribution was taken for the neutrons in ^{16}O, while the ^{18}O neutron density was given by the harmonic oscillator distribution with $\bar{R}_n = 2.81$ fm.[7] The resulting values for the backward inclusive ratios are

$$R_- = 1.32, \quad R_+ = 0.87. \quad (9)$$

The results are not sensitive to reasonable modifications of the nuclear densities or of the density dependence of the Pauli width reduction (Hüfner and Thies[6] used a density-independent reduction, while the Δ-hole calculations support a reduction directly proportional to the density). The essential point made by this very crude calculation is that the qualitative behavior seen in the ratio of the π^+-^{18}O and π^+-^{16}O inclusive cross sections can be ascribed to the isospin dependence of the Δ spreading potential. This in turn supports the basic picture of the very important role played by intermediate coupling to the pion annihilation channel.

Clearly, several related experiments could be performed to test the model. Other isotopes, such as $^{40,44,48}Ca$, could be studied. The inclusive pion absorption cross sections on $^{16,18}O$ should be measured. The model invoked here clearly makes sense only if the π^+-^{18}O absorption cross section is substantially larger than that for π^+-^{16}O. The energy dependence of $R_\pm$ should be measured, since the model predicts that R_+ should approach unity as one leaves the resonance region. More detailed calculations are needed for producing reliable quantitative predictions of the energy dependence.

Note added in proof. In a recent report (TAUP 831-80), Navon *et al.* report in more detail their experimental results[3] for $\pi^\pm$ scattering and absorption on $^{16,18}O$. They find π^+ total absorption cross sections of 216 ± 34 mb for ^{16}O and 267 ± 41 mb for ^{18}O. Further, they measured R_+ at 315 MeV (i.e., beyond the resonance), with the result $R_+ = 1.03$. As discussed in the last paragraph, both of these results support the model discussed above. Navon *et al.* also attribute the small value of R_+ at resonance to a coupling between absorption and scattering channels. Note, however, that the large suppression of R_+ from unity in our model does not arise from increased optical absorption of the π^+ elastic channel wave function in ^{18}O. Indeed, pion annihilation leads to less optical absorption near resonance in our model, in contrast to standard second-order optical-potential approaches.

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[1]For a review, see F. Lenz and E. J. Moniz, M.I.T. Report No. CTP-834, Comm. Nucl. and Part. Phys. (to be published).

[2]M. Hirata, J. H. Koch, F. Lenz, and E. J. Moniz, Ann. Phys. (N.Y.) 120, 205 (1979); M. Hirata, F. Lenz, and K. Yazaki, *ibid.* 108, 116 (1977).

[3]D. Ashery, in *Proceedings of the Eighth International Conference on High Energy Physics and Nuclear Structure, Vancouver*, edited by D. Measday and A. Thomas, Nucl. Phys. A335, 385 (1980).

[4]F. Lenz, in *Proceedings of the Seventh International Conference on High-Energy Physics and Nuclear Structure, Zurich*, edited by M. Locher (Birkhauser, Basel, 1977), p. 175.

[5]E. J. Moniz, in *Theoretical Methods in Medium-Energy and Heavy-Ion Physics*, edited by K. McVoy and W. Friedman (Plenum, New York, 1978), p. 603.

[6]J. Hüfner and M. Thies, Phys. Rev. C 20, 273 (1979).

[7]We have taken the difference in neutron and proton root-mean-square radii to be 0.1 fm. This is an average of the values quoted by S. Iversen *et al.*, Phys. Lett. 82B, 51 (1979), and by C. Lunke *et al.*, *ibid.* 78B, 201 (1978).