Possible way out of the (p, n) puzzle

M. Ericson

Institut de Physique Nucléaire, Université Claude Bernard Lyon I, Institut National de Physique Nucléaire et de Physique des Particules—Centre National de la Recherche Scientifique, Bvd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France
and Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland

(Received 30 November 1993)

The off-shell expansion of the s -wave πN amplitude suggests that the s -wave interaction of space-like pions with the nuclear medium is appreciably repulsive. This has consequences for the experiments aimed at the exploration of the spin longitudinal response or of the pion excess in nuclei. It may offer in particular an explanation for the (p, n) puzzle where the attraction from the pion exchange force has failed to appear.

PACS number(s): 24.70.+s, 25.40.Kv

In recent years, the behavior of the nuclear spin-isospin responses has confronted us with the following puzzle, which has attracted considerable attention both experimentally and theoretically. In the quasielastic domain, the attractive pion exchange force should appear as a collective effect in the spin longitudinal-isospin response with enhancement and softening. In the extreme case, this attraction can bring the pion energy down to zero, giving rise to pion condensation. While no such phase transition is expected to occur even at large densities, owing to the counter-effect of the short-range repulsive force, one expects that this phase transition has precursor effects at the normal density, in the form of a mild collectivity of the response [1]. Since a mild enhancement and softening are difficult to detect, Alberico *et al.* [2] have suggested to first search for the contrast between the spin longitudinal and spin transverse isospin response functions. In the latter, the particle-hole force is repulsive so that collectivity now produces a hardening and a quenching. The most recent experiment on this contrast [3] is the polarization transfer in (p, n) reaction which automatically selects the isospin response. It explores both the spin longitudinal and spin transverse response functions at a momentum $|\mathbf{q}| \simeq 1.72 \text{ fm}^{-1}$ and it gives their ratio as a function of the energy. From the distinct collective features of the two responses, this ratio, which is one in the free case, is expected to be larger than unity. Instead it does not surpass unity as appears in Fig. 1. No convincing explanation has been found for this discrepancy. The result of the (p, n) experiment has implications for the concept of a pion excess in nuclei which is put in doubt. It thus affects the influence of this excess in the deep inelastic experiments [European-muon-collaboration (EMC) effect or Drell-Yan process].

It is the aim of the present article to suggest a way out of this dilemma. It is not restricted to the (p, n) case but applies as well to the deep inelastic case. For illustration, I will focus on the case of the (p, n) experiment, with a fixed momentum transfer. The elementary NN amplitude that governs the longitudinal spin-isospin response contains the exchange of a virtual pion between the probe and the target. The assumption is that this amplitude remains unchanged when one nucleon is imbedded in the

nuclear medium. All previous theoretical descriptions implicitly make it. It is this hypothesis that I want to question in this work. My motivation is the strong interaction of pions, real or virtual, with the nuclear medium. Consequently, the pion exchange part of the NN interaction may undergo a medium renormalization. Let us discuss this point in more detail.

The interaction of the pion with the medium is not totally ignored in the previous theoretical calculations which are based on the RPA. They take into account the main part of this interaction, i.e., the part arising from the p -wave interaction of the pion with the nucleons. However the s -wave part is ignored. It is rather natural to omit this part, because the s -wave interaction is smaller than the dominant p -wave one for physical pions. The smallness of the s -wave interaction follows from that of the elementary s -wave πN amplitude. But this is true only for physical pions, and it results from an accidental cancellation between the sigma term and the effective range term of the s -wave amplitude, as will be recalled below. When the pions are off-shell, this cancellation does not apply and the s -wave amplitude can reach an appreciable value. The situation is analyzed in the following. For simplicity, I consider the case of

FIG. 1. Ratio of the longitudinal to transverse response for Ca measured in the (p, n) reaction (taken from Ref. [3]). The experimental points are from Ref. [3]. The dotted curve is the RPA calculation of Ref. [6].

isospin-symmetric infinite homogeneous nuclear matter. For the reasons mentioned above, only the s -wave interaction is relevant to my discussion. The pion self-energy Π is related, to leading order in the density, to the isospin-symmetric πN amplitude A^+ in the forward direction by $\Pi = -\rho A^+(t=0)$ where ρ is the nuclear density. The introduction of this self-energy modifies the pion propagator from its free space value to the in-medium expression

$$D(\mathbf{q}, q_0) = [m_\pi^2 + \mathbf{q}^2 - q_0^2 + \Pi(q_0, \mathbf{q})]^{-1}. \quad (1)$$

Note that in the (p, n) experiment, the exchanged pion is appreciably off-shell ($q^2/m_\pi^2 \simeq -6$), with a spacelike character. In order to discuss the s -wave interaction of such a pion with the nuclear medium, we introduce the linear expansion of the off-shell πN amplitude. For the s wave, and in the static limit, it writes

$$A_s^+ = -\frac{\Sigma_N}{f_\pi^2} \left(1 - \frac{q^2 + q'^2}{m_\pi^2} \right) + \beta q_0^2 + (\dots), \quad (2)$$

where q and q' are the momenta of the incident and outgoing pion (with $q_0 = q'_0$ since we work in the static approximation) and Σ_N is the sigma commutator which has a value of about 45 MeV. The coefficient β is linked to the effective range of the s -wave amplitude. Its empirical value is such that the scattering length nearly vanishes. This cancellation explains the smallness of the s -wave self-energy (or optical potential) for on-shell slow pions. The form of the expansion (2) is governed by the Adler consistency condition. The amplitude should vanish when one pion is soft and the other on-shell. This constraint fixes the parenthesis multiplying the term in Σ_N on the right-hand side of Eq. (2), which will be important in my discussion.

The sign of the sigma term, positive, is such that the optical potential for soft pions ($q_\mu = q'_{\mu=0}$) is repulsive, with $\Pi(0) = \Sigma_N \rho / f_\pi^2$. In such a situation, the magnitude of the pion propagator is smaller than its free value. Let us now discuss what happens for spacelike pions that we take, for illustration, to be static, $q_0 = 0$. Using the expansion (2) for the πN forward amplitude, we obtain the corresponding, s -wave self energy Π_s

$$\Pi_s = \frac{\Sigma_N \rho}{f_\pi^2} \left(1 + \frac{2\mathbf{q}^2}{m_\pi^2} \right). \quad (3)$$

It is increasingly repulsive with increasing momentum. Of course the validity of the expansion (2) is questionable at the momenta that we are discussing. Nevertheless, the point is that the pion exchanged between the (p, n) probe and the target may undergo a repulsive interaction, not taken into account in the present descriptions, which could renormalize the elementary NN amplitude and therefore modify the measured cross section. To simulate a more realistic amplitude than the one given by the linear expression (2), and to avoid the infinite increase with momentum we introduce a form factor Γ multiplying the terms in q^2 in the expansion (2). Its value is unity at $q^2 = m_\pi^2$, so as to preserve the Adler consistency condition. We take a monopole form with a parameter which reproduces an isoscalar rms radius, $r_s = 1.26 \text{ fm}^{-1}$ [4],

and we write

$$\Pi_s = \frac{\Sigma_N \rho}{f_\pi^2} \left(1 + \frac{2\mathbf{q}^2}{m_\pi^2} \Gamma(\mathbf{q}^2) \right). \quad (4)$$

For the concrete numerical evaluation, we take a density typical for the peripheral (p, n) reaction $\rho = 0.4\rho_0$ (where ρ_0 is the normal nuclear matter density). With the ansatz of Eq. (4) we find that the static pion propagator at $|\mathbf{q}| = 1.72 \text{ fm}^{-1}$ is reduced in magnitude by 13 percent.

We have now to discuss how this translates into the NN amplitude, the one which governs the spin-longitudinal response. Besides the exchange of one pion, this amplitude contains a short range interaction that can be approximated by a delta function with a Landau Migdal parameter g' . The overall spin longitudinal amplitude is then proportional to the quantity

$$g' - \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2 - q_0^2} \Gamma_\pi^2(q^2), \quad (5)$$

where Γ_π is the form factor at the πNN vertex for which we take a monopole form with a mass parameter Λ .

The combination of values of the parameters $g' = 0.45$ and $\Lambda = 900 \text{ MeV}$ accounts reasonably well, up to $|\mathbf{q}| \simeq 2 \text{ fm}^{-1}$, for the experimental momentum dependence of the amplitude of Franey and Love [5] at the incident energy ($\simeq 500 \text{ MeV}$) of the (p, n) experiment (note that this value of g' which appears in the particle-particle interaction has no reason to coincide, and it does not, with the Landau-Migdal parameter of the particle-hole interaction which has a larger value of $\simeq 0.6$). With this set of parameters I find that, at $|\mathbf{q}| = 1.72 \text{ fm}^{-1}$ and in the static case, the medium modification of the pion propagator discussed above reduces the modulus of the amplitude by a factor 0.58. There is a magnification of the reduction effect in the amplitude because of the large cancellation between g' and the pion term (this cancellation makes the reduction factor quite sensitive to the parameters g' and Λ). The longitudinal cross section at small energy is therefore reduced by the square of this number, i.e., by 0.34. This result applies to static pions. For nonstatic ones, the spacelike character decreases somewhat, but not much, and I find nearly the same factor up to the maximum energy involved in the (p, n) experiment, which is 160 MeV. We have to see how the reduction of the amplitude affects the longitudinal response. What enters in the experimental quantities is the product of the square of the NN amplitude by the longitudinal response. In Ref. [3] this response was extracted in the hypothesis that the NN amplitude is unchanged. If there is a reduction of the modulus of the amplitude by medium effects, then the genuine longitudinal response is that of Ref. [3] divided by the square of the reduction factor. The experimental points should thus be multiplied by a factor $\simeq 3$.

This evaluation is quite rough, and it could be improved in several aspects. First, the penetration of the probe could be exactly accounted for. Second, the treatment of the short range part of the NN amplitude should be improved and a better description of the role of the pion reached. Alberico and Gersten [6] have shown that a folding of the pion exchange interaction with a short

range correlation function produces an excellent fit to the free double spin flip amplitude. A similar treatment could be applied here with a medium modified pion propagator. In this case, the pion exchange part and the short range piece would undergo a medium renormalization. However, the resulting treatment would still not be fully quantitative, and an uncertainty will remain in the renormalization factor of the longitudinal strength. The basic weakness in this problem is that we do not know the exact off-shell behavior of the s -wave self-energy. The linear expansion (2) only gives the trend at small momenta but we do not know how well our ansatz of Eq. (4) describes validity at the momentum $|\mathbf{q}| = 1.72 \text{ fm}^{-1}$. Moreover, the linear relation between the optical potential and the πN amplitude is only an approximation which is invalidated by correlations. Nevertheless, the possibility that the s -wave interaction becomes appreciably repulsive for space like pions must be taken seriously. Let us accept this possibility and discuss its consequences.

First, in this interpretation, the problem in the ratio between longitudinal and transverse responses is blamed entirely on the longitudinal one. The transverse one is not affected and follows the standard description. This is indeed the case as shown in Fig. 2 where the separate responses are compared to the RPA treatment of Ref. [7]. While the transverse response follows the theoretical curve, the longitudinal one does not. A uniform increase of the experimental strength puts the data more

in line with the theoretical prediction. The comparison can be performed with the RPA response. The theoretical factor of 3 seems too large. A somewhat smaller factor of 2.2 gives a better agreement with theory in the peak region. Note that this is a reasonable number, in view of the large uncertainty of the theoretical prediction. The comparison can also be performed with the free response, with a similar quality of fit (in this case a smaller factor of 1.8 is needed), since the two response functions differ in magnitude but not much in shape (in particular they peak at nearly the same energy).

This leads to my second comment. If the interpretation proposed here of the (p, n) puzzle is correct, it will be difficult to detect the precursor effects of pion condensation in the spin longitudinal response, if they exist, with hadronic probes. Indeed for peripheral reactions, the collectivity of the longitudinal response shows up as an increase in strength but with no visible softening, as is apparent in Fig. 2 from the comparison between the RPA and the free response (this is not the case if the full nuclear interior is explored; then there is a softening of the response). But since the renormalization factor due to the s wave is not accurately known there is no way to distinguish between the free and the collective response with peripheral probes.

Notice that the reduction of the elementary process on the nucleons affects as well the EMC or Drell-Yan effect. It is believed that the virtual pion around a nucleon contributes to its structure function through the Sullivan process [8] shown in Fig. 3. An increase of the pion number in the nucleus would manifest itself as an increase in the structure function. This was the proposed interpretation [9] for the original EMC effect [10]. Later data [11] showed a much smaller effect than the initial one. The s -wave repulsion, which is not included in the existing calculations, produces a reduction of the in-medium pion propagator and, hence, of the elementary Sullivan process. The reduction factor for the pionic contribution to the structure function is the squared renormalization factor of the pion propagator, taken this time at the normal density and properly averaged over the momentum of the exchanged pion. This reduction could counterbalance the effect of an eventual increase in the pion number. The same remark applies to the Drell-Yan process. Here also the enhancement of the sea quarks in the nucleus due to a pion excess has failed to appear [12].

I want to stress the following important point. The agreement between theory and the new experimental re-

FIG. 2. The longitudinal response (a) and transverse one (b) of Ca, measured in the (p, n) reaction [3] compared to the free (dotted) and to the RPA response of Ref. [6] (continuous). The black points are those of Ref. [3] while the crosses are obtained after multiplication by a factor 2.2.

FIG. 3. The pion contribution to deep inelastic scattering (Sullivan process).

sponse of Fig. 2(a) cannot be considered satisfactory. But this is to be expected because the renormalization effect discussed here is not the complete story. The repulsive s -wave interaction does not only renormalize the elementary amplitude and hence the strength but it also enters in the RPA equations by a modification of the particle-hole force, reducing the p -wave attraction. This is similar to the influence of the delta resonance where both the renormalization of the strength and the renormalization of the force are present. In this work, I have discussed only the strength renormalization. As for the effect in the residual force, it implies that the RPA theoretical curve should also be modified. It is not clear how much of the p -wave attraction will survive and what will remain of the enhancement and softening of the response (and thus of the pion excess) after introduction of the s -wave repulsion. It is even possible that the residual force in the spin longitudinal channel becomes repulsive. The expected softening could turn into a hardening. In fact, the experimental data seem to support this possibility, as is apparent in Fig. 2(a): the experimental response peaks at a higher energy than the free one (the uniform

renormalization introduced previously does not modify the peak position). A complete description is under investigation. A combination of strength renormalization and modification of the residual interaction by the s -wave interaction may lead to a satisfactory agreement between theory and experiment. Note that when the exchanged pion gets closer to the mass-shell the s -wave repulsion decreases and the p -wave attraction can fully exert its influence which leads to collectivity with a softening effect. This is the case, for instance, on the pion branch, which is a high energy collective state, mixture of pion and Δh states.

Finally, the question is how the interpretation presented here of the (p, n) data could be confirmed and whether the s -wave repulsion for spacelike pions shows up in other types of experiments. A possibility is in the weak interactions which are strongly influenced by pionic effects owing to PCAC. This possibility is presently being investigated.

I am grateful to T. Ericson, J. Delorme, and G. Chanfray for useful discussions and comments.

-
- [1] W. M. Alberico, M. Ericson, and A. Molinari, *Phys. Lett.* **92B**, 153 (1980).
 - [2] W. M. Alberico, M. Ericson, and A. Molinari, *Nucl. Phys.* **A379**, 429 (1982).
 - [3] X. Y. Chen *et al.*, *Phys. Rev. C* **47**, 2159 (1993).
 - [4] J. Gasser, H. Leutwyler, and M. E. Sainio, *Phys. Lett. B* **253**, 260 (1991).
 - [5] M. A. Franey and W. G. Love, *Phys. Rev. C* **31**, 488 (1985).
 - [6] W. M. Alberico and A. Gersten, CERN Report No. TH.3730, 1983 (unpublished).
 - [7] M. Ichimura, in *Proceedings of the Fifth French-Japanese Symposium on Nuclear Physics*, 1989, edited by K. Shimizu and A. Hashimoto (unpublished).
 - [8] J. D. Sullivan, *Phys. Rev. D* **5**, 1732 (1972).
 - [9] C. W. Llewellyn Smith, *Phys. Lett.* **128B**, 107 (1983); M. Ericson and A. W. Thomas, **128B**, 112 (1983); E. L. Berger, F. Coester, and R. B. Wiringa, *Phys. Rev. D* **29**, 398 (1984).
 - [10] J. J. Aubert *et al.*, *Phys. Lett.* **123B**, 275 (1983).
 - [11] M. Arneodo *et al.*, *Phys. Lett. B* **211**, 493 (1988).
 - [12] D. M. Alde *et al.*, *Phys. Rev. Lett.* **64**, 2479 (1990).