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On the s -wave repulsion of the pion-nuclear interaction

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Abstract. We show that, first, the relativistic mean-field approach of the pion-nucleus interaction, with the parameter values as proposed by Birbrair et al., is in contradiction with the pionic atom data. Second, pionic atom data do not admit any solution for a relativistic mean-field model, if the πNN coupling is assumed to be of pure pseudovector character (chiral limit). We conclude that, either there is a non-zero pseudoscalar part to the πNN coupling, or else the relativistic mean-field approach can not account for the observed s -wave repulsion.

1. Introduction

Pionic atom experiments show a strong repulsion (between 70 and 40 MeV at the nuclear center) in the s -wave part of the pion-nuclear interaction [1]. An s -wave repulsion of similar magnitude is also observed in π -nuclear elastic scattering experiments at low energies [2]. No satisfactory explanation has been given thus far for this pronounced phenomenon.

There exist in the literature two major ways of treating the pion-nuclear interaction at low energies. One is the (non-relativistic) multiple scattering approach due to M. and T. E. O. Ericson [3] and the other is the relativistic mean-field approach of Birbrair et al. [4, 5, 6]. All attempts to account for the s -wave repulsion within the multiple scattering approach have failed so far [7]. In the present work we address the question: *How does the s -wave repulsion fit into the relativistic mean-field approach?*

There is yet a third way which has been proposed to account for the s -wave repulsion, namely the conjecture that the Pauli principle, acting at the quark level, might prevent the π^- to penetrate the nucleus [8]. Unfortunately, no quantitative estimates are yet available within this scheme. One should also mention the elaborate approach of García-Recio et al. [9] which, however, suffers from large uncertainties in the real part of the s -wave potential due to off-shell extrapolations of the πN scattering amplitude.

2. The mean-field model of Birbrair et al.

The pion-nucleus interaction in this approach consists of two parts [4]. One is the direct interaction of the pion with static nuclear meson fields. There are two meson fields, one is the scalar field $S(r)$ and the other is a vector-isovector field (with the quantum numbers of the ρ meson); the latter vanishes for isoscalar ($N = Z$) nuclei. The second part of the interaction arises from the polarization of the nuclear ground state by the pion; a non-local gradient term as well as a local piece in the optical potential result from this part. The scalar meson field is assumed to be of the form

$$S(r) = S_\pi \cdot \frac{\rho(r)}{\rho_0}, \quad (1)$$

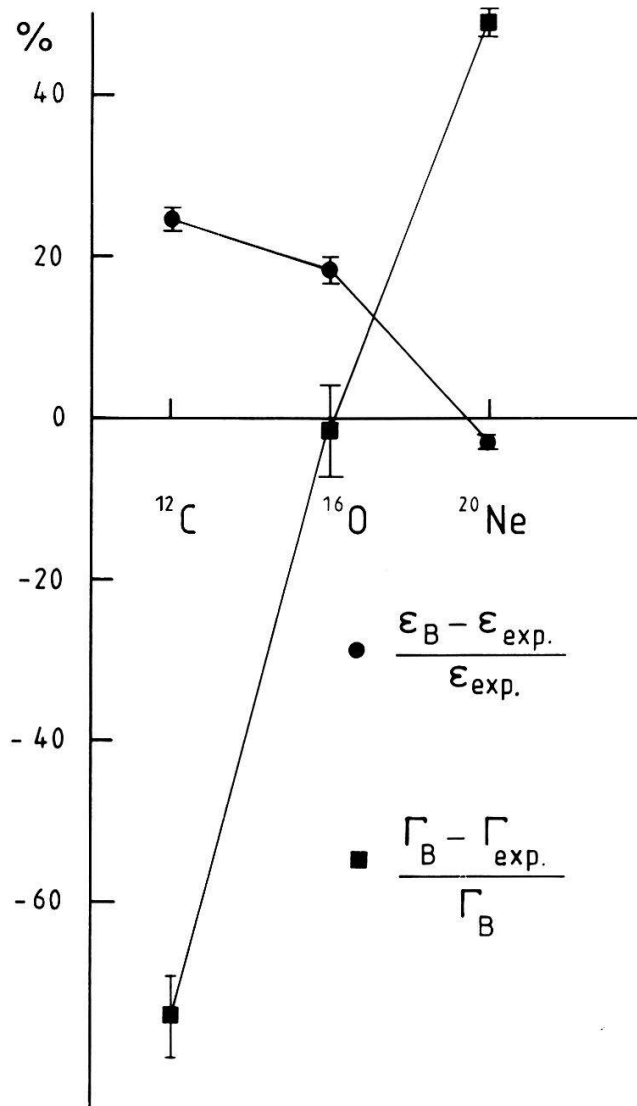


Figure 1

The relative difference, $(\epsilon_B - \epsilon_{\text{exp}})/\epsilon_{\text{exp}}$, between the 1s level shifts predicted by the Birbrair model and the measured shifts, for ^{12}C , ^{16}O and ^{20}Ne (in %): circular points. The relative difference, $(\Gamma_B - \Gamma_{\text{exp}})/\Gamma_B$, between the 1s level widths predicted by the Birbrair model and the measured widths, for ^{12}C , ^{16}O and ^{20}Ne (in %): square points.

where $\rho(r)$ is the nuclear density and $\rho_0 = 0.17 \text{ fm}^{-3}$ is an average center density; S_π is the strength parameter of the field. The Lagrange density describing the πNN interaction is assumed to consist of two parts [4]:

$$L_{\pi NN} = \frac{x}{1+x} ig \bar{\psi} \gamma_5 \vec{\tau} \psi \vec{\pi} + \frac{1}{(1+x)} \frac{g}{2m} \bar{\psi} \gamma_5 \gamma^\mu \vec{\tau} \psi \partial_\mu \vec{\pi}. \quad (2)$$

The first term in equation (2) is a pseudoscalar piece (mixing parameter x) while the second term is the pseudovector part. Nucleon and pion fields are denoted by ψ and $\vec{\pi}$, respectively, $\vec{\tau}$ is the nucleon isospin operator, g is the πN coupling constant and m is the nucleon mass. The essential parameters of the relativistic mean-field approach in the real part of the potential are thus S_π and x . In their second paper Birbrair et al. treat pion absorption and derive the corresponding modifications of the optical potential [5].

In their specific model Birbrair et al. have derived a value for S_π from the corresponding value of the nuclear scalar field for the nucleon, $S_N = -420 \text{ MeV}$, by scaling with the number of quarks ($S_\pi = \frac{2}{3} S_N$) [5]. They have then used pionic atom data to determine the pseudoscalar mixing parameter x , and find $x = -0.28$. Although the relativistic mean-field approach is a very interesting alternative to the multiple scattering theory, this particular model provides an extremely poor description of the 1s pionic atom data. This is illustrated in Fig. 1 where we have compared the 1s shifts (ϵ_B) and widths (Γ_B) predicted by the Birbrair model [5] with the directly measured values for ^{12}C [10], ^{16}O [11] and ^{20}Ne [12]. It is evident from Fig. 1 that the shifts are reproduced to no better than about 20% and the widths are off by factors of two. Clearly, the Birbrair model can not claim to account for the data nor to describe the s -wave repulsion (see also Sect. 4). This is perhaps not surprising since there is no motivation for choosing the value $S_\pi = -280 \text{ MeV}$ as a starting point in the analysis.

3. A mean-field model with zero pseudoscalar coupling?

Physically, the most interesting parameters of the mean-field approach are S_π and x . As mentioned before, they are at the same time the only essential parameters entering the problem. Since there is no compelling reason for choosing the above value for S_π , we would like to treat S_π as a free parameter, to be determined from pionic atom data. The mixing parameter x , on the other hand, is expected to be close to zero, since the chiral limit of QCD would require $x = 0$ [13]. Also experimentally, a value of x in the vicinity of zero is favoured: in threshold pion photoproduction on the nucleon a pseudovector interaction is clearly preferred [14]. We therefore make the approximation of the chiral limit ($x = 0$) and ask the question: is there *any* scalar meson field of the form of equation (1) which could describe the pionic atom data?

In the case of a vanishing pseudoscalar coupling the real part of the s -wave optical potential takes the form [5]

$$U_s(r) = S(r) + (2\bar{m}_\pi)^{-1} \cdot S^2(r), \quad (3)$$

where \bar{m}_π is the reduced pion mass. In equation (3) we have omitted the small term $\delta(r)$ (equation (4) of Ref. 5) whose contribution to $U_S(r)$ is everywhere less than 15 MeV. Figures 2 and 3 show $U_S(r)$ for various strength parameters S_π , for the nuclear density of the pionic atom ^{16}O . In the case of $S_\pi = -280$ MeV (Birbrair value) the two terms in equation (3) nearly cancel at the center of the nucleus and produce an overall attractive potential. In the range $-280 \text{ MeV} < S_\pi < 0$ the potential is attractive everywhere, while for $S_\pi < -280$ MeV a repulsive core develops inside the nucleus due to the $S^2(r)$ term in equation (3). One can show that for $S_\pi \leq -140$ MeV the minimum value of U_S is independent of S_π and equals $-\frac{1}{2}m_\pi c^2$ for all nuclei. Moreover, the 1s level shift is almost exclusively due to the real part of the *s*-wave potential. As an example we take the 1s level in pionic ^{16}O where the shift is found experimentally to be 15.4(1) keV, repulsive [11]. A repulsive shift implies $S_\pi < -280$ MeV. Because of the strong attraction at the minimum (-70 MeV) one has to go to extremely large negative values for S_π in order to obtain a repulsive 1s level shift as required by the experiment. A value $S_\pi = -1.4$ GeV is needed to reproduce the experiment.

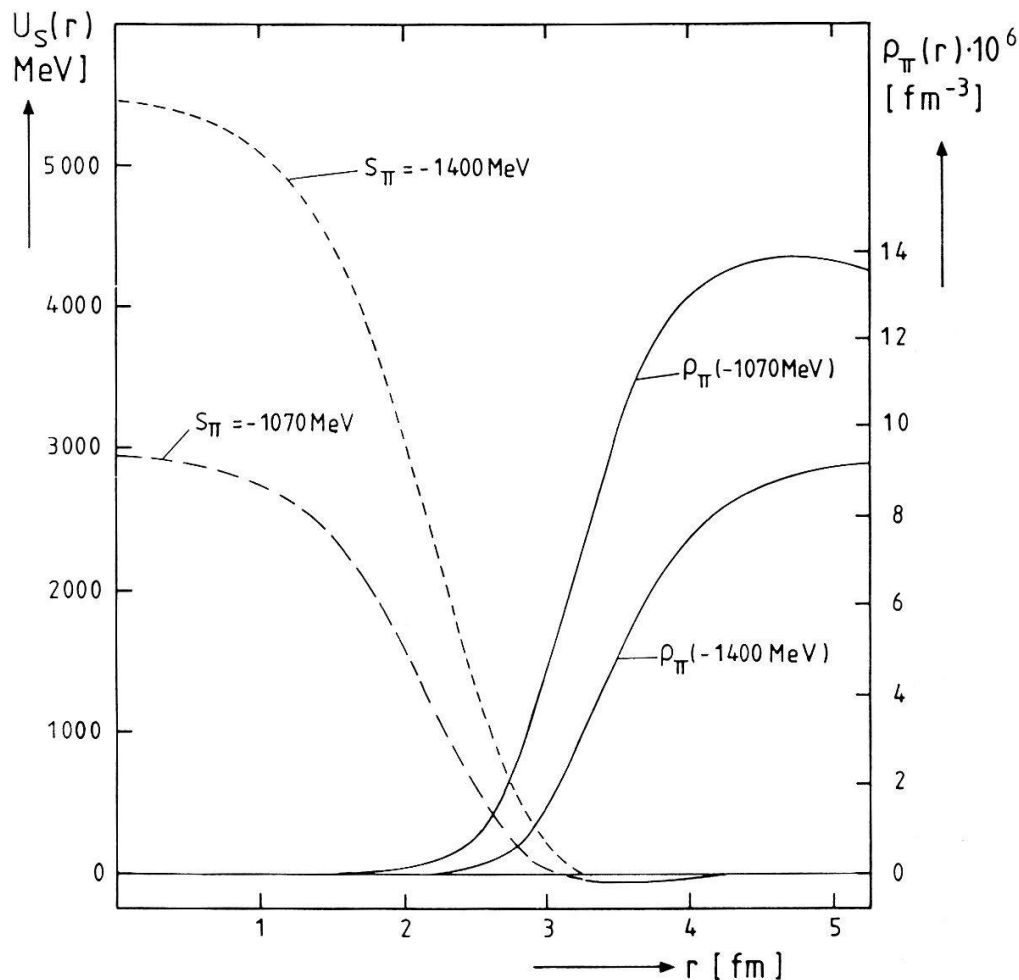


Figure 2

The ^{16}O effective *s*-wave potential $U_S(r)$ is shown for the two values $S_\pi = -1400$ MeV and -1070 MeV, respectively. These values correspond to the measured 1s level shift and zero level shift, respectively. The pion density distributions $\rho_\pi(r) = \psi^2(r)$ for the two potentials are also displayed (solid lines).

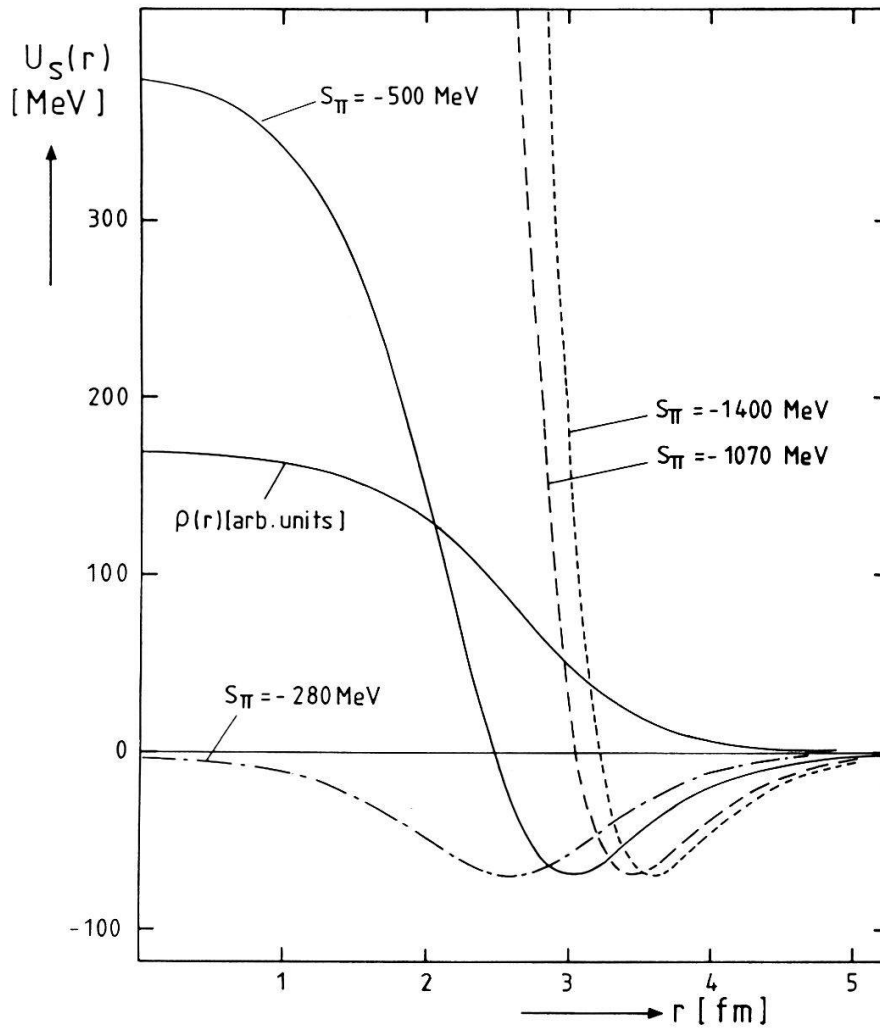


Figure 3

The ^{16}O effective s -wave potential $U_s(r)$ is shown for various values of S_π . Note the constant value of U_s at the minimum (-70 MeV), and the repulsive core for $S_\pi < -280$ MeV. The nuclear density $\rho(r)$ is also displayed.

This corresponds to an effective potential $U_s(0) = 5.5$ GeV(!) (see Fig. 2). Since such a large value is unphysical we reach the conclusion that the potential of equation (3) admits no solution for any negative value of S_π .¹⁾ We can also rule out any positive value for S_π . For this purpose we refer to our very recent work [15] in which we show that the $1s$ level shifts of all $N = Z$ nuclei can be described, at the 1% level, by a real s -wave potential of the form

$$U_s(r) = -\frac{2\pi}{\bar{m}_\pi} [\bar{b}_0 \cdot \rho(r) + \frac{1}{2} \bar{B}_0 \cdot \rho^2(r)], \quad (4)$$

where \bar{b}_0 and \bar{B}_0 are uniquely determined from the atom data. The values for \bar{b}_0 and \bar{B}_0 are such that any positive S_π is ruled out. This then means that pionic atom data do not admit any model with zero pseudoscalar coupling.

¹⁾ It is amusing to note that $U_s(r)$ with $S_\pi = -1.4$ GeV would still have more than enough attraction to account also for the (attractive) $2p$ level shift of ^{16}O ; no additional p -wave piece would be needed.

4. Conclusion

In this work we have investigated the possibility of using the relativistic mean-field approach of Birbrair to describe the low-energy pion-nuclear interaction. One motivation for this is the failure of the standard multiple scattering approach to explain the observed *s*-wave interaction. Another motivation is the need for treating the interaction relativistically [1]. The present results can be summarized as follows:

- (i) The relativistic mean-field model with $S_\pi = -280$ MeV and $x = -0.28$ does not describe the pionic atom data.
- (ii) In any relativistic mean-field model it is essential to have a non-zero pseudoscalar piece in the πNN coupling ($x \neq 0$), otherwise it cannot account for the pionic atom data.

Recently we have succeeded in obtaining a 'perfect' description of the $1s$ level shifts for all isoscalar nuclei in terms of two essential potential parameters [15]. The improvement as compared to the Birbrair model (Fig. 1) is at least an order of magnitude. The implications of these new results in terms of the relativistic mean-field approach are discussed in a forthcoming publication [16].

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