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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

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

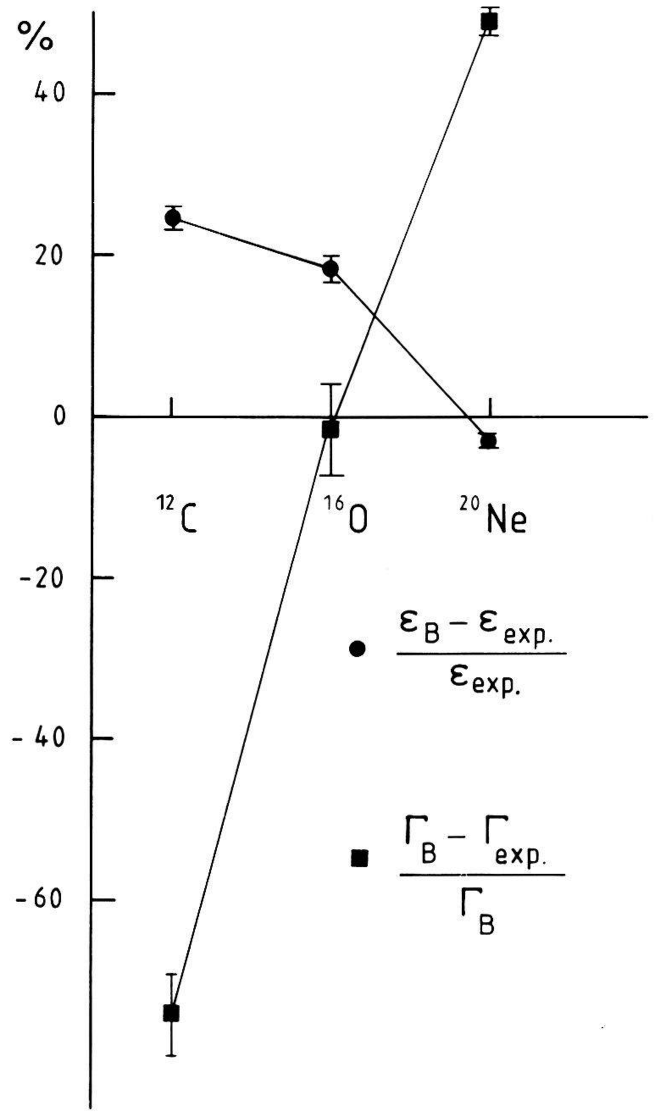

Figure 1
The relative difference, $(\varepsilon_B - \varepsilon_{exp})/\varepsilon_{exp}$, between the 1s level shifts predicted by the Birbrair model and the measured shifts, for ^{12}C, ^{16}O and ^{20}Ne (in %): circular points. The relative difference, $(\Gamma_B - \Gamma_{exp})/\Gamma_B$, between 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 $\rho_0 = 0.17\,\mathrm{fm}^{-3}$ 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]:

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

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, $S_N = -420\,\mathrm{MeV}$, 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 $S_\pi = -280\,\mathrm{MeV}$ 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]

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

where $\bar{m}_\pi$ 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 $S_\pi \leqslant -140$ 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.

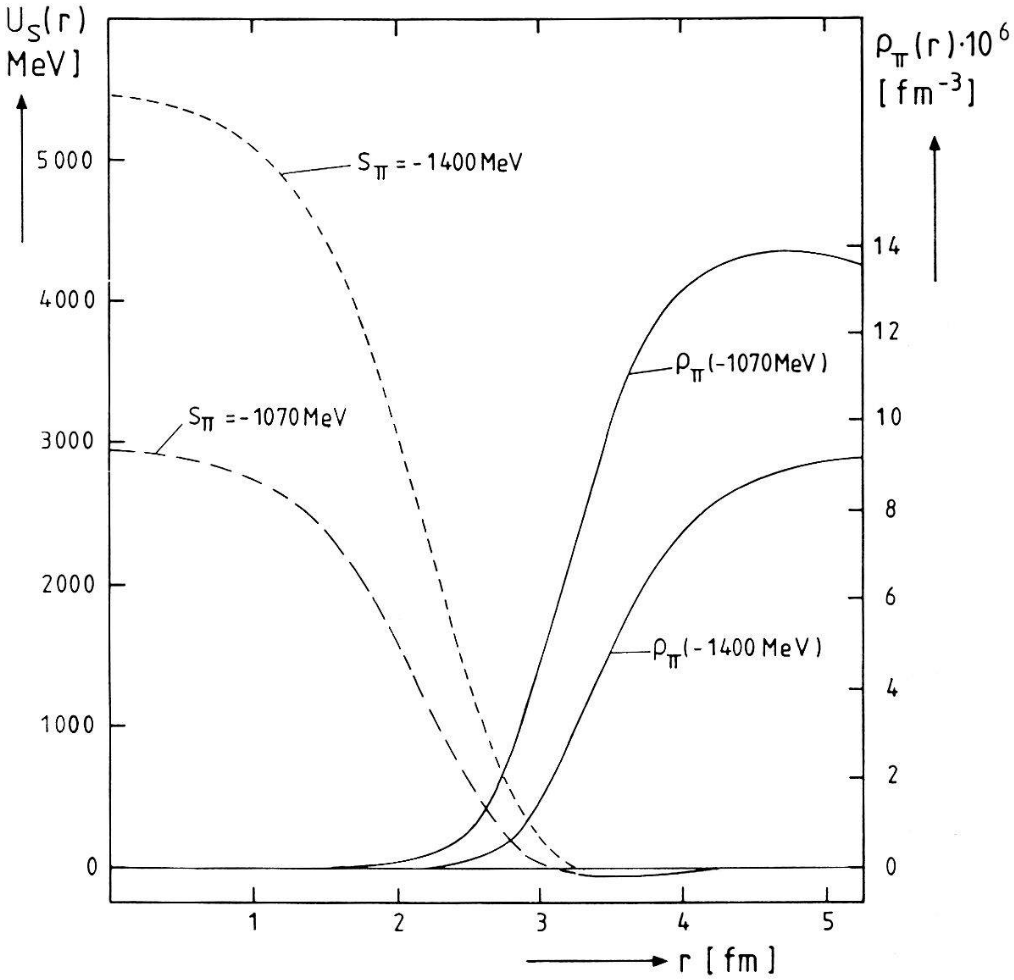

Figure 2
The ^{16}O effective s-wave potential $U_S(r)$ is shown for the two values $S_\pi = -1400$ MeV and −1070 MeV, respectively. These values correspond to the measured 1s level shift and zero level shift, respectively. The pion density distributions $\rho_\pi(r) = \psi^2(r)$ for the two potentials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

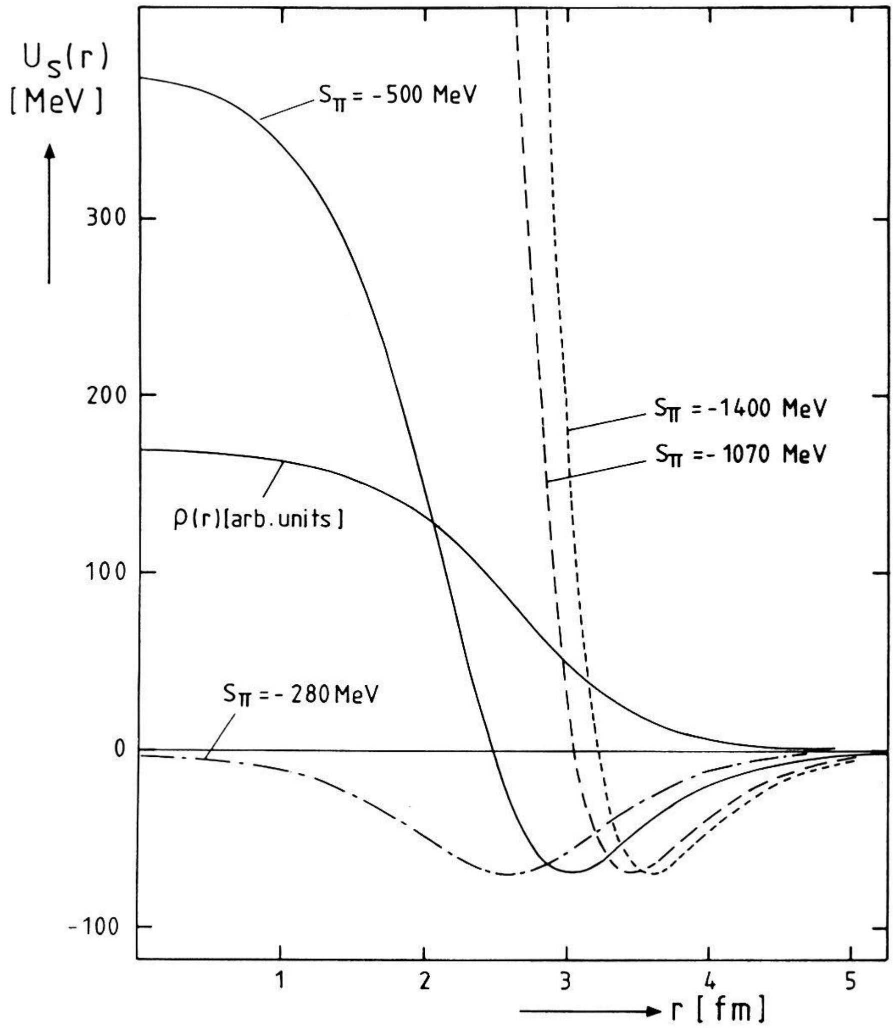

Figure 3
The ^{16}O effective s-wave potential $U_S(r)$ is shown for various values of S_π. Note the constant value of U_S at the minimum (-70 MeV), and the repulsive core for $S_\pi < -280$ MeV. The nuclear density $\rho(r)$ is also displayed.

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

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

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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