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NUCLEON-NUCLEUS OPTICAL POTENTIAL IN A RELATIVISTIC
THEORY OF NUCLEAR MATTER*

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Abstract:

From a relativistic model of nuclear matter the optical potentials for nucleon scattering from Ca^{40} and Zr^{90} are obtained. These potentials are derived from the properties of the target nucleus and are essentially universal. This means that the integrated strength of the optical potential $J_A = 1/A \int d^3r U_{\text{op}}(r)$ is very weakly dependent on A . The optical potential for anti-particle-nucleus scattering is also computed. Its effective range is greater than that for corresponding particle scattering potential.

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The importance of relativistic effects in nuclear physics has been a question of considerable uncertainty. Naively looking, the comparison of the relevant velocity to that of the velocity of light (v/c) indicates that the relativistic effects should be small. This comparison rests on the assumption that the relevant mass is the free nucleon mass. If in fact the effective nucleon mass inside the nucleus is about half its free mass, then the relativistic kinematic effects could be much larger than the naive calculation would indicate. There are however more subtle aspects of relativity than kinematic effects. The distinction between a Lorentz scalar and vector interaction is purely relativistic and it disappears in the non-relativistic limit. For strong Lorentz scalar and vector interactions this distinction has important dynamical consequences. It has been observed a long time ago by Furry¹⁾ that if V_S is the Lorentz scalar interaction and V_W a vector interaction that a nucleon sees and its motion is given by the Dirac equation, then the binding is determined by the sum of the interactions ($V_S + V_W$) and the spin-orbit interaction by the difference ($V_S - V_W$). This point was exploited by H.-P. Duerr²⁾ to construct a relativistic theory of nuclear matter. He was able to predict the correct magnitude of the nuclear spin-orbit splitting and compute the optical potential for particle and anti-particle scattering from a nucleus. Recently there has been a renewed interest in relativistic theories of nuclear matter. Walecka³⁾ proposed a model field theory in which the nucleons interact with neutral scalar field σ and neutral vector field ω_μ . This approach was extended by Boguta

and Bodmer⁴⁾ to include non-linear self interactions of the scalar field. A more conventional approach was developed by Miller and Green⁵⁾ in which the nucleon-nucleon potential is obtained through one boson exchange with the nucleons satisfying the Dirac equation. In the Hartree approximation the Walecka model is equivalent to the more conventional relativistic method in that the mesonic degrees of freedom can be eliminated in favor of the nucleon source terms. The appeal of the field theoretic approach is that there is a systematic method of studying corrections to the approximations made,⁶⁾ it directly relates the bulk properties of infinite nuclear matter to those of finite nuclei and allows for a search of exotic mesonic configurations in nuclear matter^{4,7)} and can be easily solved numerically in a reliable Thomas-Fermi approximation.⁸⁾

We have reported on the properties of finite nuclei (Ca^{40} , Ca^{48} , Ni^{56} , Zr^{90} and Pb^{208}) in the relativistic quantum field theory of Walecka.⁹⁾ With a judicious choice of interaction parameters and scale lengths (g_s , g_v , M_s) a good overall fit to the densities and rms radii can be obtained. Furthermore, a reasonable description of non-zero temperature nuclei is predicted with a very good value for the level density parameter.¹⁰⁾ The growing body of literature indicates that a relativistic field theory of nuclear matter is phenomenologically quite successful.¹¹⁾

Recently Arnold, Clark and Mercer¹²⁾ and subsequently Jaminon, Mahoux and Rochus¹³⁾ investigated the properties of the optical

potential of $p\text{-}^4\text{He}$ and $p\text{-}^{16}\text{O}$ scattering in a relativistic theory with scalar and vector potentials. The latter work is of note, because they obtain the optical potential from a calculation that describes the ground state properties of ^{16}O .¹⁴ This is important, since the aim of the theory is to correlate various aspects of nuclear properties in a simple and calculable model. In this work we calculate the optical potential for Ca^{40} and Zr^{90} from the ground state properties of those nuclei and explore the resultant regularities that it has as a function of the mass number A . The anti-particle nucleus optical potential is also computed. It has the interesting property of being very attractive and having a longer effective range than the corresponding particle-nucleus potential.¹⁵⁾

In the relativistic quantum field theory of nuclear matter the interaction of the nucleon ψ with a scalar meson field σ , an isoscalar vector field ω_μ , an isovector scalar field R_μ and electromagnetic field A_μ is given by the following interaction Lagrangian

$$\begin{aligned} \mathcal{L} = & -\bar{\psi} \left(\gamma_\mu \frac{\partial}{\partial X_\mu} + m_N \right) \psi - \frac{1}{2} \left[\left(\frac{\partial \sigma}{\partial X_\mu} \right)^2 + m_\sigma^2 \sigma^2 \right] - \frac{1}{4} F_{\mu\nu} F_{\mu\nu} - \frac{1}{4} \hat{G}_{\mu\nu} \cdot \hat{G}_{\mu\nu} \quad (1) \\ & - \frac{1}{4} H_{\mu\nu} H_{\mu\nu} - \frac{1}{2} m_V^2 \omega_\lambda \omega_\lambda - \frac{1}{2} m_V^2 \hat{R}_\mu \cdot \hat{R}_\mu + i g_V \bar{\psi} \gamma_\lambda \omega_\lambda \psi \\ & + i g_r \bar{\psi} \gamma_\lambda \hat{\tau} \psi \hat{R}_\lambda + i e \bar{\psi} \gamma_\mu \frac{(1 + \tau_3)}{2} \psi A_\mu - g_s \bar{\psi} \psi \sigma \end{aligned}$$

The resulting field equations for the finite nuclei was reported elsewhere.⁹⁾ The solutions are the values of $\sigma(r)$, $\omega_0(r)$, $R_0^{(0)}(r)$, $A_0(r)$ for each nucleus. A nucleon scattering from such a nucleus will see these potentials. If the motion of the scattering nucleon is described by Dirac equation, the interaction will be given by the following equation

$$\left\{ -\gamma_\mu \frac{\partial}{\partial x_\mu} + M + g_S \sigma + i g_V \gamma_\mu \omega_\mu + i g_R \gamma_\mu \hat{R}_\mu \cdot \hat{\tau} + i e \gamma_\mu A_\mu \frac{(1 + \tau_3)}{2} \right\} \psi = 0 \quad (2)$$

where

$$\psi = \begin{pmatrix} \psi_p \\ \psi_n \end{pmatrix} \quad (3)$$

and the proton and neutron wave functions have a large and small component

$$\psi_{p,n} = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}_{p,n} \quad (4)$$

By eliminating the small component in favor of the large one and neglecting the derivatives of the potentials the following Schrödinger equivalent equation is obtained

$$[\nabla^2 + k^2 - 2M(U_{op} + U_{so} \vec{S} \cdot \vec{L})] \psi_u = 0 \quad (5)$$

The real part of the optical potential is given by

$$U_{op}^{(p,n)} = g_s \sigma + v^{(p,n)} + \frac{1}{2M} (g_s \sigma + v^{(p,n)})(g_s \sigma - v^{(p,n)}) + \frac{E}{M} v^{(p,n)} \quad (6a)$$

$$k^2 = 2 M E + E^2 \quad (6b)$$

where

$$v^{(p)} = g_s \omega_0 - g_r R_0^{(o)} \quad (6c)$$

$$v^{(n)} = g_s \omega_0 + g_r R_0^{(o)} \quad (6d)$$

For heavy nuclei such as Pb^{208} or Zr^{90} the central density distribution of neutrons and protons is sensitive to isospin one R_μ vector field interaction. Nonetheless, its direct contribution to the optical potential is at most 2 percent and can be neglected.

The scalar and vector potentials are shown in Fig. 1. For Zr^{90} the attractive potential is -433 MeV and the repulsive potential is 353 MeV, leading to a zero incident energy optical potential well depth of -46.3 MeV. In Figs. 2a and 2b we show the corresponding optical potentials as a function of incident energy and radius. One immediately sees that the potentials for Ca^{40} and Zr^{90} are in fact identical, save for a larger central extension for Zr^{90} . This is quite understandable. The model predicts and experiment seems to confirm the fact that the proton densities for intermediate and heavy

nuclei are very similar in shape. The surface thickness of these nuclei is about the same. What differs is the value of the central density at the origin. This value differs significantly for Ca^{40} and Pb^{208} . A dynamic calculation of finite nuclei in a relativistic field theory model shows⁹⁾ the interplay of the mesonic potentials σ , ω_μ , R_μ and A_μ that produce these density distributions. A inspection of results for Ca^{40} , Ca^{48} , Ni^{56} , Zr^{90} and Pb^{208} reveals the fact that $\sigma(0)$ and $\omega_0(0)$ are almost identical (to within 1.0 percent) in all of the above mentioned nuclei. The Coulomb field A_0 and the rho field $R_0^{(0)}$ together with the surface tension determine the proton and neutron central densities. Models that neglect the rho field or the Coulomb field A_μ in heavy nuclei will predict distortions in $\sigma(0)$ and $\omega_0(0)$ and hence will hide the above mentioned regularity. Since the scalar field σ and vector field ω_μ essentially determine the optical potential, the model predicts (excluding Coulomb corrections)¹²⁾ that all of the above nuclei will have the same optical potential well depth and the same surface behavior. What will differ is the effective range, which is determined by the size of the nucleus. Since the effective range will approximately be proportional to $A^{1/3}$, this implies that the integrated optical potential strength

$$J_A = \frac{1}{A} \int d^3r V_{\text{op}}(r) \quad (7)$$

should be very weakly dependent on A for intermediate and heavy nuclei. This we find to be true in our model to within 3 percent. In Fig. 3 we show J_A as a function of energy. It agrees with the calculation

of Jaminon et al. Another interesting quantity is the volume integrals of the scalar and vector potentials

$$R = \frac{\int d^3r V_w(r)}{\int d^3r V_s(r)} \quad (8)$$

It should be a very weak function of A . For Ca^{40} , $R = -0.786$ and for Zr^{90} , $R = -0.788$. This is in good agreement with the value of $R = 0.814 \pm 0.006$ found by Arnold et al. This agreement between calculations of the optical potential for heavy nuclei with those made for light nuclei leads one to speculate that perhaps the optical potential is essentially the same for all nuclei, with the effective range determined by the size of the target nucleus.

The optical potential for anti-particle-nucleus scattering can be obtained by reversing the sign of the vector potential in Eq. (6a). The anti-particle will see a very attractive optical potential. This is shown in Fig. 4. Comparing it with the optical potential for particle-nucleus scattering, one sees that the effective range of the anti-particle-nucleus potential is larger. This means that the cross-section for anti-particle-nucleus scattering will always be greater than the geometric cross section. This was demonstrated theoretically 25 years ago by Duerr and Teller.¹⁵⁾

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Figure Captions

Fig. 1. Scalar and vector potentials in MeV for Zr^{90} and Ca^{40} .

The solid line is for Ca^{40} and the broken line for Zr^{90} .

Fig. 2. (a) Optical potential for Ca^{40} as a function of incident energy and radius in fermis.

(b) Optical potential for Zr^{90} as a function of incident energy and radius in fermis.

Fig. 3. Integrated optical potential strength J_A as a function of incident energy.

Fig. 4. Anti-particle nucleus optical potential for Ca^{40} as a function of incident energy and radius in fermis.

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Fig. 1

XBL 809-1986

XBL 809-1987

Fig. 2a

Fig. 2b

XBL809-1988

J_A for ^{40}Ca

Fig. 3

XBL 809-1990

Fig. 4

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