PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

Interpretation of the Perey-Buck nonlocality in terms of the relativistic optical model formalism

George H. Rawitscher
Physics Department, University of Connecticut, Storrs, Connecticut 06268
(Received 18 October 1984)

Under certain conditions the solution of a nonlocal, nonrelativistic Schrödinger equation is the same as the upper component of a relativistic four-spinor which obeys a local Dirac equation. This result is obtained by combining the observation recently made by Fiedeldey and Sofianos, that a nonlocal Schrödinger equation can be transformed into a local one if a gradient term (or velocity term) is added, together with the well-known fact that the upper component of the solution of a Dirac equation also obeys a second-order equation which has a gradient term. For the case of a nonlocality of the Perey-Buck—type, the gradient term is nearly equal to the Darwin term, and hence the conditions for the validity of the relativistic-nonrelativistic equivalence are nearly valid. A numerical example is presented for the case of 21.7 MeV neutrons scattering elastically from ^{40}Ca, for which a local relativistic optical potential has been recently obtained. The gradient term is given in terms of derivatives of the Wronskian of two independent solutions of the nonlocal equation, and numerical values for the latter are compared with the corresponding relativistic quantity. The differences are not larger than 25%. Results for the nonlocality due to exchange are also shown, and are found to be very similar to the Perey-Buck nonlocality. An implication of these results is that the relativistic optical potential may be less nonlocal than the nonrelativistic one.

I. INTRODUCTION

The relativistic formalism for the description of nucleon-nucleus scattering has lately proved to be very successful, both phenomenologically[1] as well as microscopically,[2] and is beginning to supplant the traditional nonrelativistic method. The potentials in either approach are rather different both in radial shape and in energy dependence, and although they should in principle be both nonlocal, only local versions have been studied up to now. One exception is the nonlocality introduced by Perey and Buck[3] and also by Frahn and Lemmer[4] into the nonrelativistic Schrödinger equation. Their intention was to obtain an energy independent nonlocal potential whose phase equivalent local form would have the same energy dependence as the phenomenological potentials which fit the scattering data.

The relativistic potentials contained in the second-order equation which describe the upper components of the Dirac spinor also acquire a kinematic energy dependence even if the potentials in the first-order equation are constant. Furthermore, the second-order equation contains a gradient term — the Darwin term.[5] But, as Fiedeldey and Sofianos have shown,[6] a gradient term can be interpreted as a nonlocal term in a conventional Schrödinger equation. Hence, the possibility arises that there exists a connection between the Perey-Buck nonlocal nonrelativistic equation and the Dirac equation for nucleon-nucleus scattering. It is the purpose of this paper to discuss the conditions under which such a connection does exist, to establish a relation between the respective wave functions, and, in particular, to offer an interpretation of the Perey damping factor as a renormalization of the relativistic Dirac spinor.

First, the gradient terms will be reviewed in Sec. II, and in Sec. III the Perey-Buck nonlocality case will be discussed. The conclusions are presented in Sec. IV.

II. THE GRADIENT TERMS

The relativistic formulation will be reviewed first. The upper and lower two-spinor components of the Dirac four-spinor are denoted as φ and χ, respectively. They are connected by the time independent Dirac matrix equation

$$\begin{bmatrix} mc^2+U_s & \boldsymbol{\sigma}\cdot\mathbf{p}c \\ \boldsymbol{\sigma}\cdot\mathbf{p}c & -mc^2-U_s \end{bmatrix}\begin{bmatrix}\varphi\\ \chi\end{bmatrix}=\begin{bmatrix} E-U_4 & 0 \\ 0 & E-U_4\end{bmatrix}\begin{bmatrix}\varphi\\ \chi\end{bmatrix} . \tag{2.1}$$

The $\boldsymbol{\sigma}$'s are the conventional Pauli spin matrices, U_s and U_4 are the scalar and 4th component vector potentials, $\mathbf{p}$ is the momentum operator $(\hbar/i)\nabla$, E is the total relativistic energy, and m is the rest mass. The kinetic energy is denoted as T, i.e.,

$$E=T+mc^2 . \tag{2.2}$$

According to Eq. (1) the lower component can be expressed in terms of the upper component as

$$\chi=(E+mc^2+U_s-U_4)^{-1}(\boldsymbol{\sigma}\cdot\mathbf{p}c)\varphi . \tag{2.3}$$

Since the denominator contains twice the rest mass, which is large compared to the momentum of the wave function in the numerator, the lower component is traditionally considered as being negligible. However, in the nuclear interior the potentials U_s and U_4 are large[1] (about -450 and $+350$ MeV, respectively) and of opposite signs, so that U_s-U_4 approximately cancels one of the two rest masses and becomes enhanced. The quantity $A(r)$,

$$A(r)=(E+mc^2+U_s-U_4)/(E+mc^2)\ , \qquad (2.4)$$

can therefore differ from unity by 50% or 60% in the nuclear interior, and approximately 30% of the particle probability amplitude (10% for the probability density) is carried by the lower component in the nuclear interior even at low incident kinetic energies.

Even though the lower component is non-negligible, one can nevertheless eliminate it from Eq. (1) by applying the matrix operator on the right-hand side in Eq. (1) once again to both sides of Eq. (1), as is well known. One obtains a second-order differential equation

$$[(p^2/2m)+V_C+V_{so}\mathbf{l}\cdot\boldsymbol{\sigma}+V_g-T]\varphi=0\ , \qquad (2.5)$$

which is exact and which is similar to the conventional Schrödinger equation in that it is of second order, with the exception of the presence of the gradient term V_g. The latter is the Darwin term,[5] and is of the form

$$V_g(r)=(\hbar^2/2m)[(dA/dr)/A]d/dr\ . \qquad (2.6)$$

Here it has been assumed that U_4 and U_s only depend on the radial distance r and that no other vector potential components are present.

The central potential V_C contains the sum U_s+U_4 plus an energy dependent term of the form

$$(U_s^2-U_4^2+2TU_4)/2m\ ,$$

and the spin orbit potential contains the derivative of the difference U_4-U_s. These expressions for V_C and V_{so} have been given many times before[1] and will not be repeated here.

Next, the nonrelativistic nonlocal equation will be described. The nonlocal wave function $\psi^{\rm N}(r)$ in its partial wave form is given by

$$\psi^{\rm N}(r)=\sum_{l,j}\frac{1}{r}u_{lj}^{\rm N}(r)\,|\,(\tfrac{1}{2}l)jm_j\rangle\ . \qquad (2.7)$$

Each partial radial wave obeys the Schrödinger equation

$$[(p_l^2/2m)+U_{\rm so}\mathbf{l}\cdot\boldsymbol{\sigma}-T]u_{lj}^{\rm N}(r)+\int_0^\infty K_{lj}(r,r')u_{lj}^{\rm N}(r')dr'=0\ . \qquad (2.8)$$

Here K is the nonlocal kernel and the $|j\rangle$'s represent the conventional two-component spinors in which the spin $\frac{1}{2}$ is coupled to the orbital angular momentum l to form the total angular momentum j, and where $p_l^2/2m$ is

$$p_l^2/2m=-(\hbar^2/2m)[\partial^2/\partial r^2-l(l+1)/r^2]\ . \qquad (2.9)$$

As Fiedeldey and Sofianos have shown,[6] the partial radial wave function u also obeys the local equation

$$(p_l^2/2m+U_C+U_{\rm so}+U_g-T)u_{lj}^{\rm N}(r)=0\ , \qquad (2.10)$$

where U_C and U_g are related to Eq. (8) as will now be described.

As is shown in Ref. 6, one can only obtain expressions for the potentials U_C and U_g if two independent solutions u and v of the nonlocal equation are known. The Wronskian for these two solutions

$$W_{lj}(r)=(du_{lj}^{\rm N}(r)/dr)v_{lj}^{\rm N}(r)-u_{lj}^{\rm N}(r)(dv_{lj}^{\rm N}(r)/dr) \qquad (2.11)$$

is dependent on r for the nonlocal case, Eq. (2.8), and since the solutions u and v also depend on orbital and total angular momenta l and j, so also does the Wronskian, in the general case. The central potential U_C is given by

$$U_C(l,j;r)=\left\{[du_{lj}^{\rm N}(r)/dr]\int_0^\infty K_{lj}(r,r')v_{lj}^{\rm N}(r')dr'-[dv_{lj}^{\rm N}(r)/dr]\int_0^\infty K_{lj}(r,r')u_{lj}^{\rm N}(r')dr'\right\} \qquad (2.12)$$

and the velocity potential is

$$U_g(l,j;r)=(\hbar^2/2m)\{[dW_{lj}(r)/dr]/W_{lj}(r)\}d/dr\ . \qquad (2.13)$$

The formal similarity to the Darwin term, Eq. (6), is obvious. The potentials above have the property that not only are the regular solutions of Eqs. (2.8) and (2.10) identical for all r, but also the irregular solutions are identical to each other.

By defining the local phase equivalent functions u^L,

$$u_{lj}^L(r)=[W_{lj}(r)/W_{lj}(\infty)]^{-1/2}u_{lj}^{\rm N}(r)\ , \qquad (2.14)$$

and similarly for v^L, one can show that both u^L and v^L are the solutions of a local second-order Schrödinger equation in which the gradient term is absent. The corresponding central potential is called the phase equivalent local potential (ELP), and it differs from U_C by terms containing the first and second derivatives of the Wronskian. The relation between the ELP and U_C is given by

$$U^L(l,j;r)=U_c(l,j;r)+(\hbar^2/2m)\times[-\tfrac{1}{2}(W_{lj}''/W_{lj})+\tfrac{3}{4}(W_{lj}'/W_{lj})^2]\ . \qquad (2.15)$$

The above relation corrects a misprint in Eq. (2.18) of Ref. 6, where $U_C\times(2m/\hbar^2)$ is denoted as $\tilde{U}^L$. The ELP is also unique[7] because Eq. (2.14) holds for both the regular and irregular solutions of the equivalent local and the nonlocal Schrödinger equations. The general Perey damping factor[8] which connects the local to the nonlocal wave functions is the square root of the Wronskian, normalized to unity at infinity, as can be seen from Eq. (2.14). The normalized Wronskian also plays the role of a position dependent mass, as is discussed in Ref. 6.

The connection with the relativistic equation is obtained by identifying the gradient terms in each of the two equations (2.13) and (2.6). The identification is possible if $A(r)$, Eq. (2.4), and the normalized Wronskian are the same, or nearly so.

$$A(r)\leftrightarrow W_{lj}(r)/W_{lj}(\infty)\ . \qquad (2.16)$$

The rigorous identity between the functions $A(r)$ and $W(r)$ is not possible in general, but is approximately feasible for the case of the Perey-Buck type of nonlocality, as will be discussed in the next section.

III. THE CASE OF THE PEREY-BUCK NONLOCALITY

In general, the Wronskian for a nonlocal Schrödinger equation is angular momentum dependent, while the relativistic function $A(r)$ is not. Furthermore, the Wronskian goes to unity at the origin,[7] while $A(r)$ does not. Hence the identification of the Darwin term with the gradient term in the velocity dependent local Schrödinger equation is not rigorously possible. The Perey-Buck type of nonlocality offers an exception where the l dependence can be considered as "weak." The nonlocality is of the form

$$K(r,r')=V[\tfrac{1}{2}(r+r')](\pi^{1/2}\beta)^{-3}\exp[(r-r')^2/\beta^2]\ . \quad (3.1)$$

Perey and Buck[3] succeeded in obtaining an approximation for the ELP, as well as for the Perey damping factor, and found both to be independent of the nucleon-nucleus angular momentum l. The validity of Perey and Buck's approximation has been examined by Horiuchi,[9] and more recently by Fiedeldey and Sofianos.[6] They find that the exact ELP as well as the corresponding Perey damping factor are angular momentum dependent at the small radial distances, but near the surface of the nucleus the results of Ref. 3 remain valid. This angular-momentum dependence is, however, not very drastic since it occurs for distances smaller than the turning point for each partial wave examined with the exception of the case for $l=0$. This can be seen from Fig. 1 of Ref. 6 which shows the ELP for n-^{40}Ca scattering at 24 MeV for a standard nonlocality range β of 0.85 fm. The turning points for $l=2$ and 4 are 3.2 and 8.5 fm, respectively, and a significant deviation from the Perey-Buck approximation occurs[6] only at distances less than 2.5 and 4 fm, respectively. For $l=0$ the deviation sets in at distances less than 2 fm, a discrepancy which may be significant. For the purpose of the present discussion this type of discrepancy will be ignored.

The relativistic potentials required to fit elastic n-^{40}Ca scattering data[10] at 21.7 MeV have been recently obtained by the group at Ohio State University.[11] The real and imaginary parts of the two relativistic potentials have Woods-Saxon forms with individually adjusted parameters. The function $A(r)$, defined in Eq. (2.4), was calculated from these parameters, and is compared in Fig. 1 with the normalized Wronskian, obtained in Ref. 6 for 24 MeV n-^{40}Ca scattering. One sees that the two results are quite similar, the relativistic one differing more from unity than the nonrelativistic result at the small distances by about 25%, and being of shorter range.

The central part of the phase equivalent local potentials for the two cases are compared in Fig. 2. The relativistic potential is somewhat deeper (by about 25%) and of shorter range. In order to determine whether this type of disagreement is significant, it would be desirable to reanalyze the 21.7 MeV data with the Perey-Buck formal-

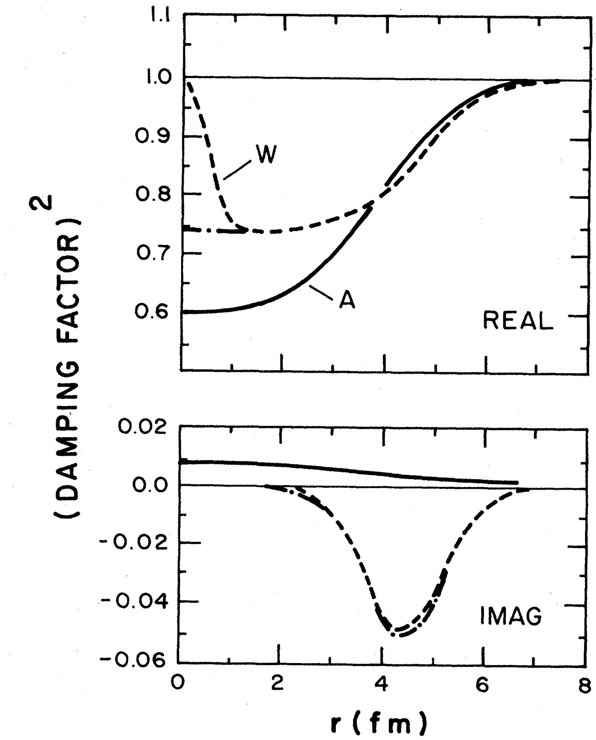

FIG. 1. Comparison of $A(r)$ and $W(r)$ as a function of radial distance r. The relativistic function A is calculated from Eq. (2.4) using the geometrical parameters given in Ref. 11 for n-^{40}Ca at 21.7 MeV (lab), and is represented by the solid line. The dashed line represents the Wronskian obtained in Ref. 6 for the Perey-Buck potential which fits 24 MeV n-^{40}Ca scattering, for the nucleon-nucleus angular momentum $l=0$. The dash-dot line represents the original approximation to the Wronskian given by Perey and Buck.

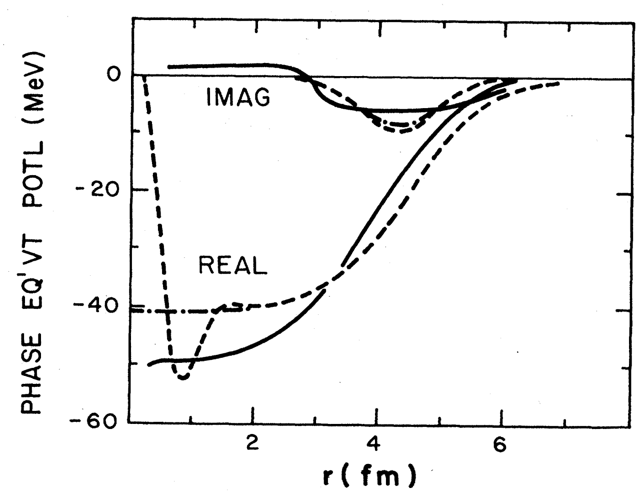

FIG. 2. The central part of the phase equivalent optical potential for n-^{40}Ca scattering. The dashed curve represents the nonrelativistic result and is taken from Fig. 1 of Ref. 6 for $l=0$ at 24 MeV. The dash-dot line is the corresponding result given by the approximation of Perey and Buck. The solid line represents the result obtained from the relativistic optical potentials given in Ref. 11 for 21.7 MeV.

ism, and also extend the comparison to other cases, such as, for example, 26 MeV n-^{58}Fe data[12] for which the nonrelativistic optical potentials were found to be in good agreement with nonrelativistic microscopic results.[12]

IV. DISCUSSION AND CONCLUSIONS

The main point of this paper is to suggest that the presence of a Perey-Buck type of nonlocality in the nonrelativistic Schrödinger equation serves the purpose of approximately simulating a relativistic local Dirac description. What makes this suggestion feasible is the fact that the gradient term which occurs in the local velocity dependent version of the nonlocal equation is only weakly dependent on the angular momentum of the projectile, and hence it can be approximately identified with the Darwin term which arises in the second-order form of the Dirac equation.

A comparison of the functions A and W for nucleon-calcium scattering near 24 MeV, illustrated in Fig. 1, shows that they are similar, which is encouraging. The former is obtained from the relativistic approach, the latter from the standard nonrelativistic Perey-Buck approach. The numerical agreement between these two functions is not very good, however, and the corresponding phase-equivalent central potentials, shown in Fig. 2, are also not the same. This difference can be attributed to a number of reasons, which need to be investigated in more detail. For example, it is possible that the standard Perey-Buck nonlocality simulates several effects at once: (a) the nonlocalities inherently present in the relativistic scalar and four-vector Dirac potentials, which manifest themselves as an energy dependence in the phenomenological relativistic local potentials, and (b) the energy dependence which arises when one translates these relativistic potentials into the second-order Schrödinger-like form.

The nonlocality which is due to exchange effects in the nucleon-nucleus interaction has been recently examined by Bauhoff *et al.*[13] in a microscopic study of the optical potential in terms of density dependent t matrices. These authors obtain the Wronskian which corresponds to the exchange nonlocality for p-^{40}Ca scattering at various energies. Their result is compared with the Darwin function A in Fig. 3 at two energies. At 30 MeV the Wronskian due to the exchange is very close to the function A obtained from the fits[11] of n-^{40}Ca scattering at 21.7 MeV, and is even more similar to the Wronskian due to the Perey-Buck nonlocality, shown in Fig. 1 by the dashed line. At an incident nucleon energy of 100 MeV the exchange nonlocality is already smaller than at 30 MeV (Fig. 3), while the relativistic function A has hardly changed.

From the above comparison it appears that a large portion of the Perey-Buck nonlocality is due to exchange effects. The effect which such exchange terms have on the relativistic optical potentials is not known as yet. By contrast, the nonlocality due to channel coupling appears to be of a rather different nature. The nonlocality due to channel coupling has been examined[14] for the case of elastic deuteron-nickel scattering at 21.6 MeV. The inelastic channels in this case are the deuteron breakup channels, which are strongly coupled to each other as well as to the elastic channel.[15] The Wronskian for this case[14] is shown in Fig. 4. The imaginary part of the Wronskian is about an order of magnitude larger than that for either the Perey-Buck or the exchange nonlocality, and the l dependence of both the real and imaginary parts is present over the whole range of the radial interval.

To the extent that the Perey-Buck nonlocality does provide an approximate simulation of the Dirac formulation, the solution of the nonlocal nonrelativistic Schrödinger equation should be the same—or very similar to—the

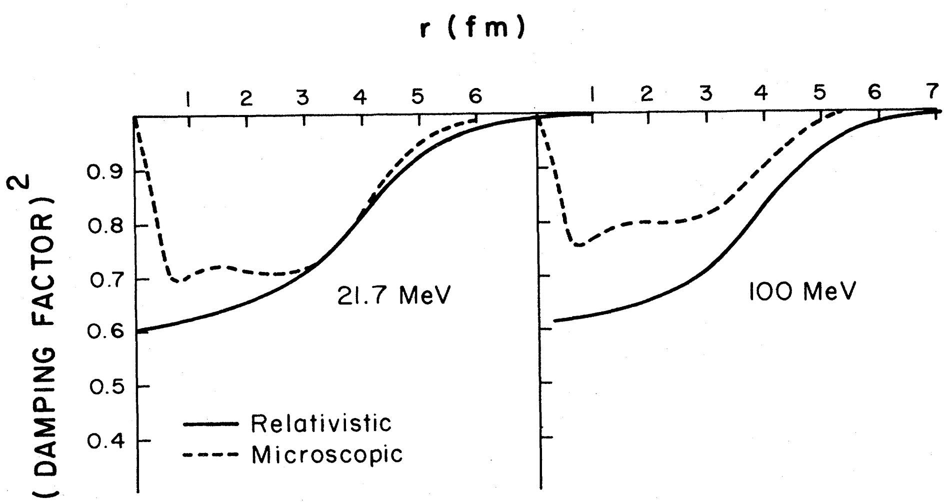

FIG. 3. The solid line represents the function $A(r)$, calculated according to Eq. (2.4), from the relativistic optical potentials given in Ref. 11 for 21.7 MeV n-^{40}Ca scattering, evaluated at 21.7 MeV (left panel) and 100 MeV (right panel) neutron incident energies. The dashed line represents the Wronskian which arises from the exchange nonlocality in the description of the p-^{40}Ca interaction, as calculated in Ref. 13 for incident proton energies of 30 MeV (left panel) and 100 MeV (right panel).

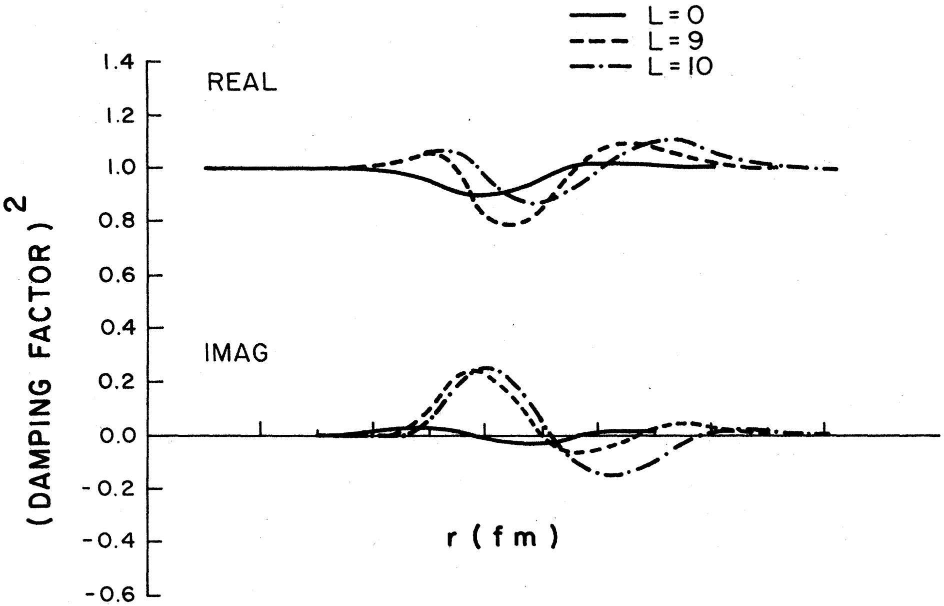

FIG. 4. Wronskians for a nonlocality due to channel coupling. This case corresponds to 21.6 MeV $d-{}^{58}Ni$ scattering. The "inelastic" channels represent deuteron breakup, as described in Ref. 15. Only the relative n-p angular momentum of zero is included in the description of breakup space, and enough momentum bins are included so as to give stable results for the elastic scattering matrix elements. As is described in Ref. 14, the interior (small distance) part of the elastic to inelastic coupling potentials has been smoothly cutoff to zero so as to allow the calculation of the irregular solution to the coupled equations, and multiplied by a factor of 2 so as to simulate the additional n-p relative angular momenta larger than zero. Each of the large division marks on the abscissa corresponds to a distance of 2 fm. The last mark is at 12 fm.

upper component of the solution of the corresponding Dirac equation. The phase equivalent local wave function, which obeys a local phase equivalent Schrödinger equation, after it has been multiplied by the appropriate Perey damping factor, should then be also nearly equal to the upper component of the Dirac spinor. Indeed, the suppression in the nuclear interior of the local optical potential Schrödinger wave function, provided by the standard Perey damping factor, appears to improve the calculation of rearrangement reactions,[16] at energies which are not too high.[17] However, the use of the Perey damping factor is not rigorously valid since the operators which appear in the nonrelativistic transition matrix element should be transformed into the relativistic ones so as to also take into account the lower components of the Dirac spinor. Work to establish a relativistic framework for a rearrangement calculation is still in progress[18] and is complicated by the difficulty of obtaining a relativistic wave function for a composite particle such as the deuteron. The present arguments reinforce the desirability of carrying out such a relativistic program.

Historically the need for a nonlocality in the Schrödinger formulation arose from the study of saturation of nuclear matter. In the 1950's it was already known that the Hartree description of nuclear matter, using local potentials, does not provide saturation.[19] This recognition led Frahn,[4] Perey[8] and Buck,[3] and others,[7] to include a nonlocality into the optical model potential as well. It later became known that the relativistic Hartree description of nuclear matter does lead to saturation with local potentials, which suggested, already at that time, that the relativistic nucleon-nucleus potential is inherently more local than the nonrelativistic one. The present paper comes to the same conclusion by starting from the premise that if the Dirac equation is used to analyze nucleon-nucleus scattering, then the equivalent nonrelativistic formulation should be nonlocal.

A basic question raised by the present study concerns the nonlocalities which should inherently be present in both the relativistic and the nonrelativistic descriptions. Is the deviation of the energy dependence of the relativistic potentials from the theoretical prediction a manifestation of the fact that nonlocalities exist (for example, due to exchange) which have not explicitly been taken into account, just as was suggested by Perey and Buck for the nonrelativistic case? Furthermore, do the exchange nonlocalities reduce or enhance the channel coupling nonlocalities? Also, given a particular nonlocality for the relativistic description, how does it manifest itself in the nonrelativistic case, given the fact that the energy dependences of the potentials in the two descriptions are not inherently the same? These questions have to await further investigation.

In summary, an approximate correspondence between the solution of a nonlocal Schrödinger equation and the solution of a local Dirac equation has been suggested in the present paper. This connection provides some support for the use of the Perey-Buck damping factor in calculations of reaction processes which use local optical distorted waves. This study also points to the need for investigating the presence of other nonlocalities in both the relativistic and the nonrelativistic nucleon-nucleus scattering formalisms.

ACKNOWLEDGMENTS

Conversations with Dr. D. H. Feng concerning the nonrelativistic interpretation of the Dirac equation, as well as conversations with Dr. B. Mulligan and Dr. L. Arnold concerning nonlocalities, were of great value for the development of the present ideas. The author thanks Professor B. C. Clark for making available the relativistic optical parameters for the fit to the 21.7 MeV data prior to publication. Support from The National Science Foundation, Grant PHY 8214571, also is gratefully acknowledged.

---

[1]B. C. Clark, S. Hama, and R. L. Mercer, in *The Interaction Between Medium Energy Nucleons in Nuclei—1982,* Proceedings of the Workshop on the Interaction Between Medium Energy Nucleons in Nuclei (Indiana University Cyclotron Facility) AIP Conf. Proc. No. 97, edited by H. O. Meyer (AIP, New York, 1983), p. 260.

[2]L. G. Arnold and B. C. Clark, Phys. Lett. **B84**, 46 (1979); J. A. McNeil, J. Shepard, and S. J. Wallace, Phys. Rev. Lett. **50**, 1443 (1983); M. L. Bartlett, W. R. Coker, G. W. Hoffmann, and L. Ray, Phys. Rev. C **29**, 1407 (1984); J. Boguta, Nucl. Phys. **A372**, 386 (1981); L. S. Celenza and C. M. Shakin, Phys. Rev. C **29**, 1784 (1984).

[3]F. G. Perey and B. Buck, Nucl. Phys. **A32**, 353 (1962).

[4]W. E. Frahn, Nuovo Cimento **4**, 313 (1956); W. E. Frahn and R. H. Lemmer, *ibid.* **5**, 523 (1975); **5**, 1564 (1975).

[5]C. G. Darwin, Proc. R. Soc. (London) **A118**, 654 (1928).

[6]H. Fiedeldey and S. A. Sofianos, Z. Phys. **A311**, 339 (1983). This paper contains references to various nonlocalities in current use.

[7]H. Fiedeldey, Nucl. Phys. **77**, 149 (1966); **A96**, 463 (1967); N. Austern, Phys. Rev. **137**, B752 (1965); M. Coz, A. D. MacKellar, and L. G. Arnold, Ann. Phys. (N.Y.) **58**, 505 (1970); **59**, 219 (1970); L. G. Arnold, Phys. Rev. Lett. **26**, 1263 (1971).

[8]F. G. Perey, *Direct Interactions and Nuclear Reaction Mechanisms,* edited by E. Clementel and C. Villi (Gordon and Breach, New York, 1963), p. 125.

[9]H. Horiuchi, Prog. Theor. Phys. **64**, 184 (1980); K. Aoki and H. Horiuchi, *ibid.* **69**, 1154 (1983).

[10]R. Alarcon, D. Wang, J. R. Annand, and J. Rapaport, Bull. Am. Phys. Soc. **29**, 636 (1984).

[11]B. C. Clark, S. Hama, E. D. Cooper, and R. L. Mercer, in *Neutron-Nucleus Collisions, A Probe of Nuclear Structure—1984,* Proceedings of the Conference on Neutron Nucleus Collisions—A Probe of Nuclear Structure, Burr Oak State Park, Ohio, 1984, AIP Conf. Proc. No. 124, edited by J. Rapaport, R. W. Finlay, S. M. Grimes, and F. S. Dietrich (AIP, New York, 1985), p. 123. The author is indebted to B. C. Clark for communicating to him the parameters of the relativistic potential prior to publication.

[12]S. Mellema, R. W. Finley, F. S. Dietrich, and F. Petrovich, Phys. Rev. C **28**, 2267 (1983).

[13]W. Bauhoff, H. V. von Geramb, and G. Palla, Phys. Rev. C **27**, 2466 (1983).

[14]G. H. Rawitscher, Bull. Am. Phys. Soc. **29**, 700 (1984), and (unpublished).

[15]R. Rasoanaivo, Ph.D. thesis, University of Connecticut, 1982; G. H. Rawitscher and G. Delic, Phys. Rev. C **29**, 1153 (1984).

[16]K. Hatanaka, M. Fujiwara, K. Hosono, N. Matsuoka, T. Saito, and H. Sakai, Phys. Rev. C **29**, 13 (1984).

[17]P. W. F. Alons, J. J. Kraushaar, D. W. Miller, J. D. Brown, D. L. Friesel, W. W. Jacobs, W. P. Jones, and H. Nann, Phys. Lett. **B144**, 34 (1984).

[18]E. D. Cooper, A. O. Gattone, and M. H. MacFarlane, Phys. Lett. **130B**, 359 (1983); J. Phys. G **8**, L131 (1983).

[19]V. F. Weisskopf, Nucl. Phys. **3**, 423 (1957); Rev. Mod. Phys. **29**, 174 (1975); see also Ref. 3 in Arnold and Clark, Ref. 2.