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OFF-SHELL EFFECTS OF NUCLEON-NUCLEON POTENTIAL MODELS ON PROTON-NUCLEUS ELASTIC SCATTERING OBSERVABLES

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Résumé
Les observables de spin et la section efficace de diffusion élastique p+40Ca sont calculées dans un modèle de convolution complète utilisant les matrices t de l'interaction NN libre basées sur les potentiels de Paris et de Bonn. Les deux familles de calculs sont comparées entre elles et aux données à 200 MeV ainsi qu'au modèle t.rho plus conventionnel. Les calculs en convolution complète reproduisent beaucoup mieux les données et montrent qu'à cette énergie un bon traitement des effets hors couche est plus important que le choix entre les deux potentiels NN considérés.

Abstract - Spin observables and cross sections are calculated for p+40Ca elastic scattering in a full-folding model using nucleon-nucleon (NN) free t-matrices based on the Paris and Bonn (OBE) potentials. The two sets of calculated observables are compared with each other, with conventional tρ results and with data at 200 MeV. The differences between full-folding and tρ results are striking, with the full-folding results being in much better agreement with the data. At this energy the choice between the two NN potentials considered is found to be less critical than a proper treatment of off-shell effects as prescribed by the full-folding model.

In recent years, proton elastic scattering from nuclei at intermediate energies has been a subject of intensive research. In particular, the availability of high precision data on elastic scattering spin observables at energies between ~100 MeV and ~1 GeV combined with deficiencies of the non-relativistic impulse approximation (in an on-shell "tρ" form) for describing them has stimulated the development of alternative approaches for calculating the optical potential for projectile nucleus elastic scattering. One of these new approaches is the Dirac impulse approximation. In this approach /1/ the optical potential is based on a generalization of the factorized non-relativistic on-shell tρ approximation. Over most of the above energy range, the agreement between the data and the calculated scattering observables is notably superior to that obtained using the traditional non-relativistic tρ approximation. More recently, an approach known as the non-relativistic full-folding model has also been implemented /2-3/. As in the relativistic approach, one finds substantial corrections to the non-relativistic tρ model. In the full-folding approach an accurate treatment of the collision of the projectile with each target nucleon is emphasized. As a result, the calculation of the nucleon-nucleus optical potential requires the evaluation of the NN effective interaction off-the-energy-shell. The accurate incorporation of these off-shell effects in the full-folding model provides a significant improvement /2/ relative to the standard tρ approximation in the description of spin observable data below ~400 MeV incident energy. The present contribution is based on this latter approach.

In the absence of medium corrections to the NN effective interaction and when the single particle energies of the bound nucleons may be approximated by an average value \( \varepsilon (\varepsilon \approx -25 \text{ MeV in the case of } ^{40}\text{Ca}) \), the full-folding optical potential for proton-nucleus scattering can be expressed in terms of the free t-matrix \( t \) and the ground state mixed density \( \rho \) by /2/

\[
U(k',k;E) = \int dq \rho(P+q,P-iq) \langle k'|t(z)|k \rangle ,
\]

where \( q=k-k' \) and \( \rho \) is given in terms of occupied single-particle states \( \varphi_{\alpha} \) by

\[
\rho(P+q,P-iq) = \sum_{\alpha} \varphi_{\alpha}^* (P+q) \varphi_{\alpha} (P-iq) .
\]

The momenta and energy variables in the t-matrix are defined by

\[
k' = \frac{i}{2} (K-P-q) ; \quad k = \frac{i}{2} (K-P+q) ; \quad z = E + \varepsilon - \frac{(P+K)^2}{2M} ; \quad K = \frac{i}{2} (k+k') .
\]
The integration is over the mean momentum of the struck nucleon before and after collision. The momentum \( k (k') \) represents the incoming (outgoing) relative momentum in the NN center of mass and \( z \) the propagating energy in the same system. These three variables are not constrained to be on-shell. The free t-matrix is calculated off-shell from realistic NN potentials by solving the Lippmann–Schwinger integral equation.

A unique feature of the optical potential in the full–folding approach is the inclusion of off–shell effects consistently as allowed by the momentum distribution of the mixed density \( \rho \). In Fig. (1) we show a plot of the quantity \( P_2^2(P+q/2,P-q/2) \) for \(^{40}\text{Ca} \) as a function of \( P \) and \( q \) for any choice \( \theta /2 \) of the angle between \( P \) and \( q \). From this figure it becomes evident that the dominant contributions to the optical potential take place for \( P \lesssim 1.5 \text{ fm}^{-1} \). The variation of the momentum \( P \) yields an off–shell sampling of the NN effective interaction as given by Eq. (3).

![Mixed density plot](image)

**Fig. 1** Mixed density \( \rho(P+q,P-q) \) times \( P^2 \) for protons in \(^{40}\text{Ca} \).

Only very recently have calculations of this type \( /2–3/ \) been performed. Traditionally, the most widely used approximation to the full–folding integral has been the on–shell \( t_p \) approximation \( /4/ \) where one assumes, for example, a small variation of the \( t \)–matrix in the vicinity of \( P=0 \) and an approximately local behavior in the small \( q \) region. In this case the optical potential takes the form \( U=(q)e(q) \) with the \( t \)–matrix always evaluated on–shell. In this contribution we present calculations of the optical potential using both the full–folding model and the on–shell \( t_p \) approximation to it. The theoretical considerations and calculational procedures follow Ref. (2).

Using both Paris and Bonn NN potentials, we demonstrate the importance of a proper treatment of the off–shell NN \( t \)–matrix for calculating proton–nucleus (pA) optical potentials for an incident proton energy of 200 MeV. For the Paris potential we use the parameterized version given in Ref. (5). For the Bonn potential we use the momentum–space one–boson–exchange version (OBEPQ) given in Ref. (6). Each of these potentials is based, in part, on the exchange of known mesons and is assumed to give a reasonable description of the available NN data below \( \sim 350–400 \) MeV.

In the first column of Fig. 2 we illustrate the level of agreement between the two potentials in describing the isoscalar (\( \Delta T=0 \)) part of those scattering "observables" in the NN system most closely related to those we will consider in the pA system. For the present purpose, only the central and spin–orbit NN amplitudes were included. These observables were calculated at a nucleon lab energy of 210 MeV where considerable NN data exist. In each part of Fig. 2 the solid (dotted) curves correspond to the Paris (Bonn) potential. The same NN scattering observables, i.e. cross section \( (d\sigma/d\Omega) \), analyzing power \( (A_y) \), and spin rotation parameter \( (Q) \), were also calculated from NN amplitudes based on a phase–shift analysis by Arndt and coworkers \( /7/ \); these are denoted by \( 's \). From Fig. 2 we see that the isoscalar on–shell NN "observables" are not strictly equivalent. In the N–N part of Fig. 2 we should note that no Coulomb effects have been included and these are most important at small momentum transfer \( (q) \). The on–shell differences in the NN system preclude an unambiguous assessment of the sensitivity of pA scattering to the off–shell behavior of the NN potential models considered here.
For each NN potential, we have calculated the corresponding off–shell free $t$–matrix and used it in the calculation of the full–folding optical potential for $p + ^{40}\text{Ca}$ scattering at 200 MeV. These calculations are compared with each other and with the measured \cite{8} observables in the full–folding (FF) part of Fig. 2. The $t_\rho$ part of Fig. 2 shows analogous results for these two potentials using the traditional on–shell $t_\rho$ approximation. For each potential the full–folding results differ considerably from those using the on–shell $t_\rho$ approximation. Moreover, the full–folding results agree much better with the measured observables than do the $t_\rho$ results, especially $d\sigma/d\Omega$ and $A_\gamma$. These results demonstrate the importance of a proper treatment of the off–shell free NN $t$–matrix. We note that the $t_\rho$ results provide a further measure of the inequivalence of the free NN $t$–matrices corresponding to the two potentials considered, in that only on–shell NN $t$–matrices are used. Use of the Breit frame prescription \cite{2,4} for the energy at which the NN $t$–matrix is evaluated in the $t_\rho$ calculations implies that $t$–matrices at energies other than 200 MeV are required for the corresponding optical potentials.

In comparing results from the two NN potential models, we see that, at 200 MeV, the Bonn potential provides a superior description of $A_\gamma$ while the Paris potential provides a somewhat better description of the differential cross section. It should be stressed, however, that no explicit medium effects have been considered; work on their inclusion within the full–folding framework is in progress.
In summary, the explicit inclusion of off-shell effects in the free NN t-matrix is found to be important at 200 MeV for both the Paris and Bonn potentials. The inequivalence of their on-shell properties prohibits a preferred choice based on their off-shell extensions alone. Work on this general topic over a wider energy range and using other potentials is underway.

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