Characteristic Dirac Signature in Elastic Proton Scattering at Intermediate Energies

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Nonrelativistic nucleon-nucleus first-order multiple-scattering calculations are extended to include virtual (Dirac) negative energy states of just the projectile. This effect may be thought of as virtual $N\bar{N}$ pair production and annihilation in the field of the nucleus. This extension leads to a parameter-free Dirac description of the projectile in elastic proton scattering which produces a characteristic effect in spin observables over a wide range of energies which is in agreement with experiment. This Dirac signature is extremely stable with respect to uncertainties in the microscopic input.

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Recently, studies of the elastic scattering of protons from ^{40}Ca at 500 MeV have shown[1] that nonrelativistic (NR) microscopic impulse-approximation treatments fail to account for the asymmetry (A_y) in the vicinity of the first cross-section minimum, $\theta_{cm} \sim 10°$. Calculations based on a microscopic prescription for incorporating relativistic Dirac (RD) effects have been shown to remove this anomaly.[2,3]

The inclusion of virtual pair (nucleon-antinucleon) production processes in calculations is certainly intuitively appealing and support for their apparent importance is provided by the Dirac phenomenological work which has been carried out over the past few years.[4] However, fundamental theoretical difficulties bar the way to a consistent Dirac multiple-scattering formulation and even a clear understanding of a Dirac description of the nucleus. In the work of Refs. 2 and 3 a Dirac description of the projectile, a Dirac single-particle model of the target, and a complicated relativistic transformation of the two-nucleon scattering amplitude are combined in the calculations which remove the ^{40}Ca anomaly. In view of the absence of a sound theoretical underpinning, it is especially important to untangle the physical significance of these three facets of the calculations of Refs. 2 and 3 to isolate the essential ingredient, and to investigate its observable consequences and stability with respect to the major uncertainties in the calculational input. In this Letter we show, for the first time, that a Dirac description of the projectile alone is the key ingredient and that it has a stable signature, in agreement with experiment, for both ^{40}Ca and ^{16}O in the energy range $\sim$ 100–500 MeV.

Relativistic kinematics as well as relativistic flux-conservation constraints in frame transformations[5] are already a part of most medium-energy work. These simple relativistic aspects are included in work which we refer to as NR. Our next step is to treat the projectile as a Dirac particle without changing our treatment of the nuclear density in any way. With this *Ansatz* we are able to construct a RD multiple scattering "theory" which proceeds very much like its NR analog.[6]

We work with standard spinor basis states[7] for the projectile and in this basis the Dirac equation is equivalent to the coupled operator integral equations[6]

$$T^{++} = U^{++} + U^{++}\Gamma_+ T^{++} + U^{+-}\Gamma_- T^{-+},$$
$$T^{-+} = U^{-+} + U^{-+}\Gamma_+ T^{++} + U^{--}\Gamma_- T^{-+}. \tag{1}$$

The propagators Γ are standard Dirac propagators projected onto this basis.

One then finds that the full Dirac potential U, represented as a 2×2 matrix, is related to the NR optical potential as $U_{11} = U_{\mathrm{NR}} = U^{++} = \Lambda_+ U \Lambda_+$ where $\Lambda_+ (\Lambda_-)$ is the free Dirac positive- (negative-) energy projection operator. Similarly, $U_{12} = U^{+-} = \Lambda_+ U \Lambda_-$, with U^{-+} and U^{--} defined analogously. Because $U^{++} = U_{\mathrm{NR}}$ in this approach, one can determine the equivalent (on the positive-energy space) Dirac scalar (S) and fourth component of a four-vector (V) potentials from the central and spin-orbit parts of U_{NR}. The potentials S and V may then be used to obtain U^{+-}, U^{-+}, and U^{--},[6] subject to the usual ambiguities.[8]

Using the first order "$t\rho$" approximation to U_{NR} we generate the full operator U for the Dirac equation. We have extended the nonrelativistic momentum-space computer code WIZARD1[9] to solve Eq. (1) in momentum space. It is simple to recover the nonrelativistic analog of any relativistic calculation by setting $U^{+-} = U^{-+} = 0$. [We emphasize that in our approach[6,10] Eq. (1) is identical to the NR formulation in the limit $U^{+-} \rightarrow 0$.] Because in our approach the RD optical potential is determined from the NR one, we are able to use the options available in WIZARD1 to investigate sensitivities to uncertainties due to model dependence of the nuclear density, the off-shell and nonlocal behavior of t_{NN}, etc., in precisely the same fashion as in the NR case.[9] The details of these relativistic studies will be presented elsewhere,[10] but they show that the parameter-free calculations and the conclusions presented below are insensitive to uncertainties from the sources mentioned above (except in one special case detailed below).

In the figures we show both the RD calculation and its NR counterpart for comparison, along with the experimental data. The reader is reminded that no adjustments *of any kind* have been made; the figures show our *a priori* predictions. For the calculations shown, we have used the Love-Franey model[11] of t_{NN}. The nuclear proton densities used here are taken from electron-scattering data; the neutron density is set equal to the proton density.

In Fig. 1 the 500-MeV differential cross-section data for ^{40}Ca is rather well described by the NR calculation and the RD result is noticeably better. The NR calculation yields a suggestive but, on the whole, unsatisfactory description of the ^{40}Ca 500-MeV analyzing-power data. The inclusion of virtual pair production gives rise to a dramatic improvement in this description, although the dip in the 10° region is not deep enough. Our calculations, however, show extreme sensitivity to the precise admixture of vector and scalar optical potentials here. We find that shifts in the strengths of less than 1% can yield essentially perfect agreement between theory and experiment as was found in Refs. 2 and 3. Thus the precise character of this dip is very sensitive to uncertainties in our calculational input. Such extreme sensitivity is unique, in our calculations, to this particular dip for ^{40}Ca at 500 MeV. Our calculations for the spin rotation function Q show that the relativistic addition for just the projectile reproduces the available data.

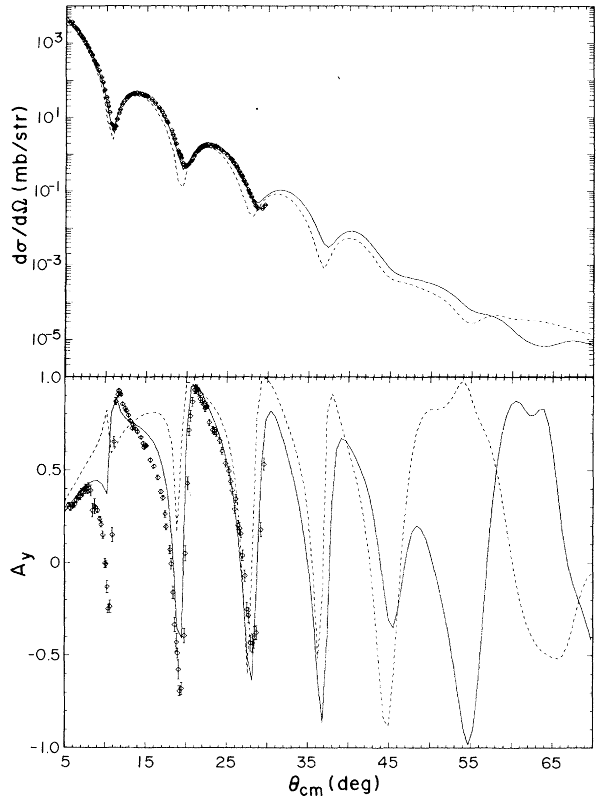

FIG. 1. Differential cross section (top) and analyzing power (bottom) for ^{40}Ca at 500 MeV. The solid (dashed) line is the relativistic (nonrelativistic) calculation. The data are from Ref. 1.

We see from Fig. 2 that for ^{16}O at 500 MeV the NR differential cross-section predictions are very close to the data and the analyzing-power predictions are in qualitative agreement with the data. If

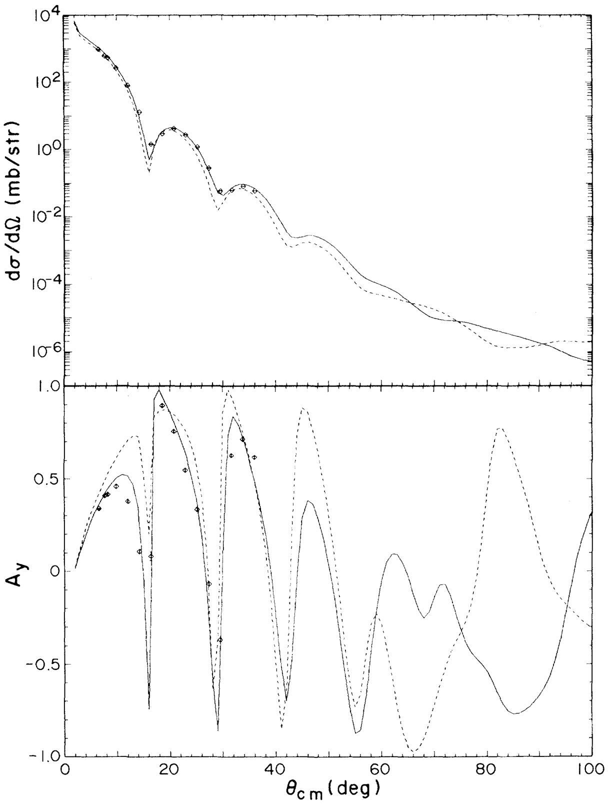

FIG. 2. Same as Fig. 1 except ^{16}O at 500 MeV. The data are preliminary data from Ref. 12.

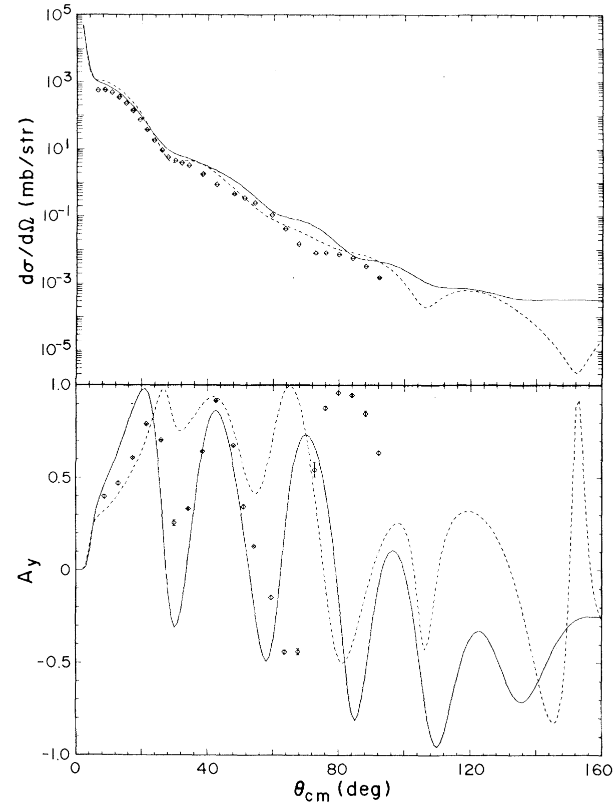

FIG. 3. Same as Fig. 1 except ^{16}O at 135 MeV. The data are from Ref. 13.

the RD calculation were to have as marked an effect on the analyzing power for this case as it has for the previous case, the relativistic curve would not describe the data very well. The RD calculation, however, further improves the agreement with the data.

The situation with respect to ^{16}O at 135 MeV (Fig. 3) is especially interesting because the most compelling initial argument in favor of a density-dependent t_{NN} in NR first-order scattering calculations came from the study of p-^{16}O scattering at this energy.[13] In Fig. 3 the RD and NR angular distributions have some of the qualitative features of the experimental data, but neither provides a good description, nor do the data favor the relativistic curve. However, the analyzing-power results present quite a different picture. The NR result bears little, if any, discernible relation to the data. On the other hand in the angular region $\theta \lesssim 60°$, the relativistic result takes on the qualitative features of the data. Again, we see a definite relativistic signature. Furthermore, we have repeated this calculation with a less well-founded density which takes the differential cross section curve through the data points and have observed that the qualitative improvement in the analyzing power is retained. Thus, because our calculations employ the free nucleon-nucleon t matrix, the need to go beyond the free t matrix remains unsettled.

The situation at 300 MeV for ^{40}Ca is not so dramatic (Fig. 4). The incorporation of virtual pair effects does not significantly improve the results for the cross section. The analyzing-power data are in somewhat better agreement with the relativistic calculation than with the nonrelativistic, although both do reasonably well. However, the calculations shown in Fig. 4 do serve to reinforce the assertion that the relativistic effects do not reduce the quality of the agreement between the nonrelativistic calculations and experiment, particularly for analyzing powers, when that agreement is good.

We conclude that, over a wide energy range, a Dirac treatment of just the projectile provides a consistent and stable improvement in agreement between theoretical calculations and experiment. Where the NR calculation is already close to the data, the relativistic addition provides a small but definite improvement. Where the NR calculation is

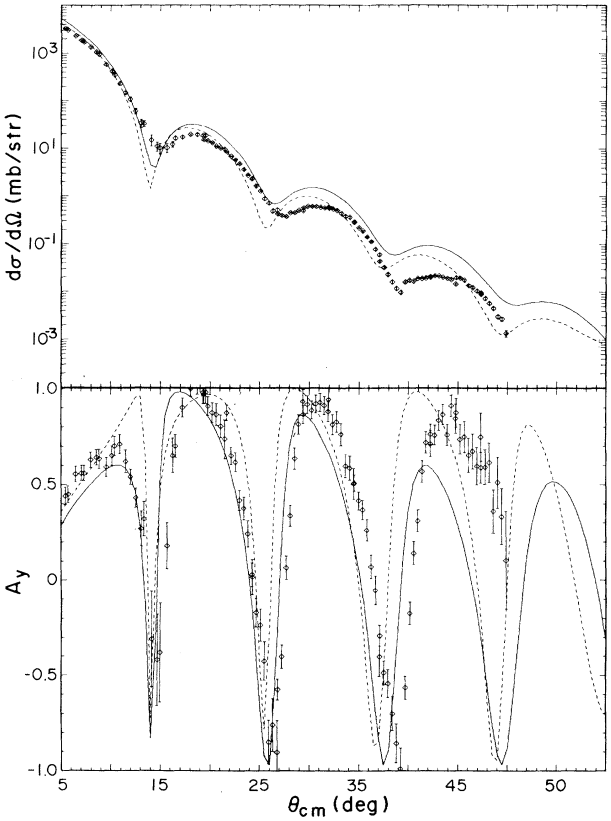

FIG. 4. Same as Fig. 1 except ^{40}Ca at 300 MeV. The data are from Ref. 14.

in poor agreement with the analyzing power data, one finds a *definite* Dirac signature from the RD calculation which significantly improves agreement with data. These conclusions are supported by similar results for these nuclei at other energies.

These calculations give strong substantiation to the claim that the physical effect (virtual pair production) implicit in a Dirac treatment of the projectile has a characteristic signature that must be addressed for a microscopic understanding of nucleon-nucleus scattering.

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