RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 51, NUMBER 4 APRIL 1995

Nuclear transparency in quasifree electron scattering

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(Received 30 June 1994)

Recently measured Q^2 and A dependences of nuclear transparency (T) in $e,e'p$ interactions are in agreement with theoretical predictions based on a Glauber theory which incorporates the internucleon spatial correlations.

PACS number(s): 25.30.Fj, 24.85.+p

I. INTRODUCTION

Recently the SLAC NE18 Collaboration [1,2] have described their measurement of nuclear transparency (T) in $e,e'p$ interactions and have presented determinations of T for various nuclei as a function of momentum transfer, Q^2. Its purpose was to search for signs of "color screening" [3] which might show up as enhancements in T as a function of Q^2 and magnitudes of T larger than that expected from normal nuclear theory.

Our theoretical method for the calculation of T has been described in much detail [4]. It is a Glauber Monte Carlo calculation in which the spatial correlations are included for both the struck proton in the $e,e'p$ interaction and the spectator nucleons in the path of the outgoing proton.

The transparency is based on those events that contain a single hard scatter. The pertinent parameter need for the calculation of T is the cross section for rescattering of the struck proton. In the NE18 experiment it is claimed that their missing energy cuts remove all inelastic rescatters producing pions and their restricted geometry removes most of the elastic rescatters [5]. (Their maximum accepted missing momentum would also reject events where the energy imparted to a neutron or proton due to rescattering was above about 60 MeV.) Accordingly we have used the total p-n and p-p cross sections in our calculations.

In the experiment the recoil proton momentum was varied from 1.20 to 4.49 GeV/c, corresponding to a range of different Q^2. Since the p-n and p-p cross sections are not constant in this momentum region it is also possible to examine whether the measured values of T reflect this variation of the cross section for *rescattering* of the proton in nuclei of different A.

II. CALCULATION OF T FOR THE $e,e'p$ REACTION

In Ref. [4] (see Ref. [6] for an earlier version of this work) we have previously given a way to include (Jastrow-type) correlation effects in a Glauber calculation of transparency in both the $e,e'p$ and $p,2p$ interactions. In our method we generate N-particle distributions in the nucleus which reproduce both the single-nucleon densities and accepted measures of the two-body spatial correlations. We then make the assumption that each remaining nucleon contributes incoherently to the rescattering of the fast proton. If we further use a straight-line trajectory for this fast particle, we can use the Glauber approximation. Here the transmission coefficient, and thus the transparency, is defined as the product of standard Glauber factors for each nucleon, weighted with the $N-1$ particle density. The transparency T is the probability that the struck proton escapes without rescattering.

Since we shall assume here that the proton and neutron densities are identical, we use a total cross section equal to

$$\sigma_{\rm tot}(p)=\frac{1}{A}[Z\sigma_{\rm tot}(p\text{-}p)+N\sigma_{\rm tot}(p\text{-}n)], \quad (1)$$

where we use the measured p-p and p-n cross sections [7].

We have also shown [4] that the results are close to those obtained using the standard distorted wave impulse approximation (DWIA) method as applied by Benhar *et al.* [8], who also include correlations. However, our method includes both the correlations between particles in the vicinity of the struck proton and the correlations between the nucleons in the outgoing path of that proton.

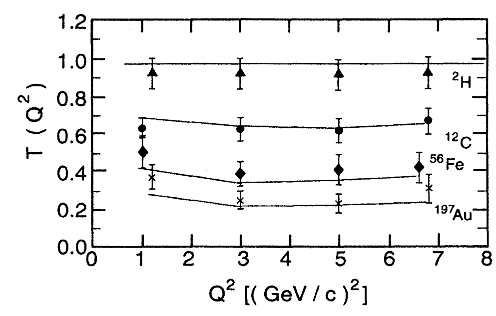

FIG. 1. The calculated transparency compared to the experimental data of Ref. [2]. The calculations were done with a Woods-Saxon density, including correlations [4]. In the deuteron calculation we used a Hulthèn wave function with a hard core of 0.43 fm.

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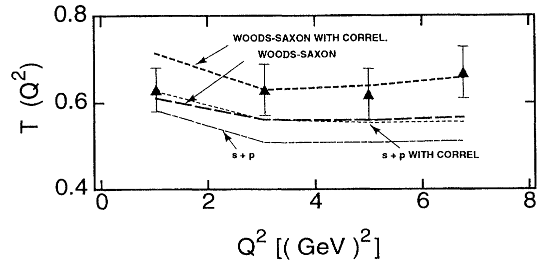

FIG. 2. The calculated transparency for ^{12}C, compared to the experimental data of Ref. [1]. The calculations were done with a Woods-Saxon density, and a Gaussian shell-model density, both with and without correlations.

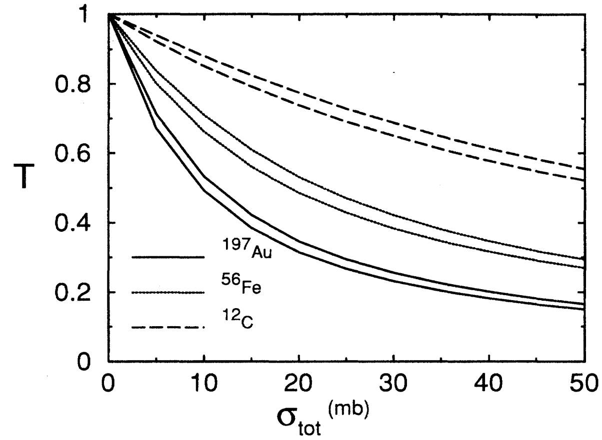

FIG. 3. Transparency vs the effective rescattering cross section. The results use the formalism of Ref. [4]. The upper curves for each A include nucleon correlations. The lower curves do not.

Figure 1 shows our calculations of T compared with the recent data of Ref. [1]. (We use a Woods-Saxon density, with correlations included, in all the calculations.) The general features of the calculated values of T appear in the plot. At the lowest Q^2 (1.04 GeV^2, corresponding with $p=1.20$ GeV/c) the cross sections are low and hence T should be higher than average, while as the momentum of the proton increases the value of T should go through a minimum and then start to rise again slowly, tracking the measured cross sections. The effects should be largest in the heaviest nuclei. As we can see from the data, the ratio $T(Q^2=1.04)/T(Q^2=3.06)$ increases as one goes from carbon to gold. This is expected from the theory since higher A nuclei allow for a larger number of chances of rescattering. In order to fit the data without correlations it would be necessary to decrease the effective cross section by about 12 mb, implying that the cross section is not the normal on-shell cross section. (See Table I in Ref. [2].)

Figure 2 shows a comparison of the carbon data with several theoretical calculations. Here we have used a calculation using both a Woods-Saxon density and a density obtained assuming the ^{12}C is a closed shell nucleus with completely filled harmonic oscillator (HO) shell-model orbitals $0s_{1/2}$ and $0p_{3/2}$ (with the HO length parameter $b=1.64$ fm). For both forms we have calculated the result with and without the nuclear correlations. Without introducing the nuclear correlations the predictions appear to fall substantially below the data.

III. DISCUSSION

The cross section for quasielastic scattering is usually expressed [9,10,4,6,11,8,12,13] in a factorized form useful for any momentum transfer. That factorization is given by

$$d\sigma/dt_{[e-A]}/Z$$

$$=T(\sigma_{\rm tot})\int S(\vec{k},\epsilon,\sigma_{\rm tot})d\sigma/dt_{[e-p]}(k,\epsilon)d\vec{k}d\epsilon. \qquad (2)$$

where $\vec{k}$ is the total momentum of the missing nuclear fragments and ϵ is the missing energy. Both these quantities are reconstructed from the measurement of the final state momenta of the proton and electron. σ is the $e,e'p$ cross section while $\sigma_{\rm tot}$ is the cross section for the *rescattering* of the struck proton by the nucleons in the nucleus. (σ is a strong function of the momentum transfer while the rescatterings determined by $\sigma_{\rm tot}$ are low t processes.) $d\sigma/dt_{[e-p]}(k,\epsilon)$ is the $e,e'p$ cross section calculated at the on-shell values of $s(\vec{k},\epsilon)$ and t. In this equation S is the spectral function that describes data.

In the distorted wave impulse approximation [4,11,8,12], which takes into account rescattering of the struck proton, the same form is obtained. S is just the (normalized to unity) [4] probability of finding a final state with the parameters $\vec{k}$ and ϵ when the proton plane waves are modified by absorption. T then becomes the probability that the proton will escape without scattering if it has a cross section $\sigma_{\rm tot}$. With this factorization, T depends on the property of the nucleus alone, namely, the spatial distribution of its nucleons, but is independent of the function S.

In the special case where $\sigma_{\rm tot}=0$ the spectral function is $P(\vec{k},\epsilon,\sigma_{\rm tot}=0)$, i.e., the spectral function for the plane wave impulse approximation. This is the form which the experimenters use to extract their transparency which we call T'.

For the purposes of this Rapid Communication we need to determine how different the two definitions are. Clearly

$$T'=\frac{T\int S(k,\epsilon,\sigma_{\rm tot})d\sigma/dt_{[e-p]}(\vec{k},\epsilon)d\vec{k}d\epsilon}{\int P(k,\epsilon,)d\sigma/dt_{[e-p]}(k,\epsilon)d\vec{k}d\epsilon}. \qquad (3)$$

Thus we have used the DWIA and PWIA calculations in carbon [4], using closure to sum over all missing energy, to see whether the differences are large. We used the $0s_{1/2}$-$0p_{3/2}$ shell-model wave function mentioned above, and found only a small difference between the shape of the spectral functions in the two cases (actually, for DWIA the longitudinal and transverse spectral functions are different, but even this difference is not very big). This is similar to the results by K. Nakamura *et al.* [14] who used a slightly different form of the DWIA to reach similar conclusions in a study of distortion effects in the low-energy $e,e'p$ reaction on ^{12}C.

For a heavy nucleus we expect larger differences because of the larger absorption and also between the orbits having most weight in the interior of the nucleus and those concentrated on the surface. Until this is established one may have to be cautious about replacing the spectral function with a PWIA prediction in heavy nuclei.

Finally, we show in Fig. 3 a plot of T vs $\sigma_{\rm tot}$ which should be useful to compare with ongoing and future experiments with any total effective rescattering cross section.

IV. CONCLUSIONS

Calculations of the nuclear transparency, taking into account nuclear spatial correlations, agree with the measured data. They appear to verify that in an $e,e'p$ reaction in nuclei the recoiling struck proton has a p-p and p-n cross section indistinguishable from a proton in its asymptotic on-shell final state, i.e., as measured in n-p and p-p scattering experiments.

ACKNOWLEDGMENT

We wish to thank W. Greenberg and W. Lorenzon for useful comments.

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