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FURTHER EVIDENCE FOR THE EEL EFFECT†

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Abstract

By looking at the inelastic scattering to the first excited 0^+ state in ^{12}C , it is shown that multiple scattering in the pion-nucleus system is strongly suppressed.

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It is the purpose of this letter to point out that a recent experiment [1] on the scattering of pions by ^{12}C at 67.5 MeV provides essentially unambiguous evidence for the strong suppression of multiple scattering in the propagation of the pion through a nuclear medium. Basically the argument rests on the shape of the differential cross section to the 0^+_2 (7.65 MeV) state which is very similar to the 2^+_1 cross section, but completely different from the elastic cross section.

Qualitatively, this result is completely natural in the context of the (undistorted) impulse approximation:

$$\frac{d\sigma}{d\Omega} \propto |b_0 + b_1 \cos\theta| \int_0^\infty F_q(r) j_q(qr) r^2 dr |^2$$

where b_0 and b_1 are the strengths of the s- and p-wave pion-nucleon amplitudes, F_q is the radial part of the form-factor and q is the momentum transfer. The s-p interference minimum is a common feature of all the cross section, and is superposed on an overall shape determined by the factor inside the integral. At low energies, the power series expansion of $j_q(qr)$ dictates that the elastic cross section will be forward peaked, and the 2^+_1 cross section will be backward peaked, with both displaying the interference dip around 65° . However, for the 0^+_2 state, the form-factor plays a large role in determining the shape. Due to the orthogonality between the ground state and the excited state, $F_0(r)$ has a node and the radial integral

$$\int_0^\infty F_0(r) r^2 dr$$

vanishes. (For $q \neq 0$ the angular dependence takes care of orthogonality.) It thus follows that the leading term in the integral goes like q^2 and that the cross section is backward peaked much like the 2^+ cross section.

The interesting point is that the shape of the ground state and the 2^+_{11} cross sections are determined primarily by the angular momentum transfer, whereas the shape of the 0^+_{22} cross section depends critically on the extent to which the incident pion can freely penetrate the nuclear interior. A strongly absorbed or multiple scattered pion does not feel the node in the form factor and the resulting cross section is forward peaked. This is the usual result obtained with a Kisslinger potential fitted to the elastic scattering data.

The results of a more detailed impulse approximation analysis are shown in figs. 1 through 3. We use a first order optical potential

$$2WV = -b_0 k^2 \rho + b_1 \nabla \cdot \rho \nabla - \frac{1}{2} \frac{E + m}{m} b_1 (\nabla^2 \rho) - B_0 \rho^2$$

with b_0 and b_1 determined from pion-nucleon scattering [2] and B_0 taken from the work of McManus et al. [3], but with kinematic factors deleted. The p-wave Pauli reduction factor is taken to be 0.5 [3]. Conventional gaussian form-factors are used, with the nuclear size and shape parameters taken from elastic electron scattering [4] (and not adjusted for finite proton size).

$$\begin{aligned} \rho_{gs} &= \text{norm.} (1 + \alpha x^2) e^{-x^2} \\ \rho_{tr} &= (2k+1)^{-1/2} \beta_0 Y_{\ell m} F_{\ell}(r) \\ F_2 &= -r \frac{d}{dr} \rho_{gs} \\ F_0 &= c^{-3} (1 + \alpha x^2) e^{-x^2} \end{aligned}$$

The deformation parameters β_0 and β_2 are fitted to the experimental $M(0)$ and $B(E2)$ values [5]. All the parameters are listed in table 1. Coulomb distortion of the pion waves was included exactly, not because it affects the inelastic cross sections, but because the Coulomb

contribution to the elastic cross section is important at forward angles. Otherwise the calculation is done in first Born approximation. These Coulomb distorted Born approximation (CWBA) results fit the inelastic cross sections well. The overall shapes, the location of the interference dip, and the absolute magnitudes of the cross sections are close to the data, and consistent with the uncertainties in the input parameters. The CWBA result for the elastic cross section is also reasonable. Indeed a better fit would be worrisome: it is one thing to argue that multiple scattering is suppressed, but quite another to claim that there is none at all. This is particularly true of the s-wave rescattering which, although small, is not suppressed by the EELL effect and whose inclusion would improve the agreement with the data.

For comparison, the results obtained using the phenomenological Kisslinger type optical potential of Amann et al. [1] in a full DWBA calculation are shown. The 0^+_{22} cross section has qualitatively the wrong shape.

There are of course good theoretical reasons for expecting a strong suppression of the multiple scattering processes, partly because of nucleon-nucleon correlations, and partly because of ρ -exchanges. Normally, this Lorentz-Lorenz Ericson-Ericson (LEE) effect is included in the optical potential by the substitution

$$\rho \rightarrow \rho (1 + \frac{1}{3} \xi b_1 \rho)^{-1}$$

In the p-wave term of the optical potential and the corresponding change in the p-wave transition operator. We have therefore also carried out a full DWBA calculation with the same first order potential as in the Coulomb wave case but now with the LEE parameter $\xi = 2.0$

instead of zero. This value is chosen to fit the elastic scattering data. The results are also shown in the figures. While the argument with the elastic cross section is much better, the fit to the 0^+ in-elastic cross sections is not as good, though much better than what would happen without suppression of the multiple scattering. The major qualitative difficulty is that the shape is not steep enough, and the forward peak is not suppressed enough. This deterioration of the fit is not really surprising, because the arguments for introducing the LEE effect through a modified density are based on nuclear matter calculations, and may not hold well enough for small nuclei. The physical effect is there nevertheless: the data require a strong suppression of the multiple scattering, and we would argue that the effect is strong enough to make calculations based on the Born series more useful than solving the optical model Klein-Gordon equation.

Most of these calculations were carried out using a modified version of the programme NDWPI [7].

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Table 1
Parameters for the form factor and the potential.

	C	Z	B
gs	1.672	1.150	
$2^+(4.44)$	1.672	1.150	0.46
$0^+(7.65)$	1.672	-0.667	0.17
$b_0 = -1.0 + 0.59i$			
$b_1 = 8.41 + 1.72i$			
$B_0 = -2.14 + 2.14i$			

Figure captions

1. The differential cross section for π^+ elastic scattering on ^{12}C at 67.5 MeV. The solid curve is the Coulomb wave Born approximation. The dashed curve is from an optical model calculation with the same potential and $\xi = 2.0$ while the dash-dot curve is from a calculation using a phenomenological Kisslinger-type optical potential [1].
2. The differential cross section for inelastic scattering of π^+ on ^{12}C at 67.5 MeV to the 2^+ state at 4.44 MeV. The solid curve is the Coulomb wave Born approximation. The dashed curve is a DWBA calculation using the same potential and $\xi = 2.0$ while the dash-dot curve is a DWBA calculation using a phenomenological Kisslinger-type optical potential [1].
3. The same as fig. 2 except for the 0^+ state at 7.65 MeV.

Fig. 1

Fig. 3