Proc. Sixth Int. Symp. Polar. Phenom. in Nucl. Phys., Osaka, 1985
J. Phys. Soc. Jpn. 55 (1986) Suppl. p. 192-197

Elastic Scattering of Polarised ^{3}He and the Near-Side Far-Side Decomposition of the Scattering Amplitudes.

A. Farooq, G. Rai and S. Roman

Department of Physics, University of Birmingham, P.O. Box 363, Birmingham B15 2TT, England.

The interaction of polarised ^{3}He with nuclei has been the subject of many studies in recent years, including both the elastic scattering and the reactions. The reactions generally exhibit j-dependent features notably in the one-nucleon (^{3}He,d) and (^{3}He,^{4}He) transfer channels. Traditionally these features have been useful aids in spectroscopy work. The distorted wave description, assuming a direct mechanism, has been reasonably successful. Certain simple features of the reactions can be well understood in terms of a semiclassical picture, [1] while others indicate clearly that contributions of multistep processes can be important[2] or calling for coupled channels calculation to reproduce the cross section and analysing power data.[3]

The elastic scattering of polarised ^{3}He by complex nuclei has been studied extensively, both to test the models of the interactions of complex projectiles with nuclei and to determine the optical model potentials needed for the reaction analyses. In particular these investigations were predominantly aimed at determining the spin-orbit part of the potential. All previous phenomenological optical model analyses have consistently indicated the need for a spin-orbit potential sharply peaked at the nuclear surface, characterised by a diffuseness parameter in the region of 0.2-0.35 fm. This is contrary to the conventional values found from nucleon-nucleus scattering (0.5-0.7 fm).

In an attempt to understand and confirm these findings it was necessary to extend these measurements to heavier targets upto the Pb mass region and to look for possible nuclear structure effects by investigating groups of neighbouring nuclei (^{207,208}Pb, ^{209}Bi and ^{89}Y, ^{90,91}Zr) expected to show odd-even effects.[4] Systematic optical model analyses were carried out using meaningful multi-dimensional grid searches which enabled quantitative evaluations of the standard deviation errors on the optical model parameters.[5] Other approaches have also been explored including the l-dependent optical potential,[1] the microscopic approach,[6] the separation of spin-orbit distortion in l=0 transfer reactions,[7] the folding model analyses[8] and studies of the radial sensitivity of the optical potential.[9] The results of our recent investigations have confirmed the need for the surface-peaked form of the ^{3}He spin-orbit potential.

In spite of the previous difficulties in interpreting the results using conventional models, some new aspects of the underlying dynamics have recently come to light when a technique originally used for heavy ion scattering was applied to the scattering of polarised ^{3}He.

In the past considerable insight into heavy ion elastic scattering processes was gained when the elastic scattering amplitudes were decomposed into near-side and far-side components. A detailed, up-to-date review of the techniques involved has been published by Hussein and McVoy.[10] However almost all of these studies have concentrated on cross-section data and none until now has seriously addressed the vector analysing powers. We have applied this technique to study the analysing power data for the scattering of polarised 3He from ^{40}Ca, ^{54}Fe, ^{89}Y, ^{90,91}Zr, ^{207,208}Pb and ^{209}Bi. Both the Coulomb and the nuclear amplitudes were decomposed along the lines described by Fuller.[11] In this analysis the elastic scattering amplitude is written as

$$f_T(\theta)=f_N(\theta) + f_F(\theta) \quad (1)$$

where

$$f_i(\theta)=g_i(\theta) + ih_i(\theta) \quad (2)$$

The near-side and the far-side cross-sections are defined by

$$(d\sigma_i/d\Omega) = |g_i(\theta)|^2 + |h_i(\theta)|^2 , \quad (3)$$

and the corresponding analysing powers $Ay_i(\theta)$ are expressed as

$$Ay_i(\theta)=2\mathrm{Im}(g_i(\theta)h_i^*(\theta))/d\sigma_i/d\Omega . \quad (4)$$

The index i=T,N,F denote the total, the near-side and the far-side components, respectively. However, the total cross-section $d\sigma_T/d\Omega$ and the analysing power $Ay_T(\theta)$ are the sum of the individual near-side and far-side components including the interference terms. Explicitly, we have derived the relations

$$(d\sigma_T/d\Omega)=(d\sigma_N/d\Omega) + (d\sigma_F/d\Omega) + 2\mathrm{Re}[g_N g_F^* + h_N h_F^*] \quad (5)$$

and

$$Ay_T(\theta)=Ay_N(\theta)\frac{d\sigma_N/d\Omega}{d\sigma_T/d\Omega} + Ay_F(\theta)\frac{d\sigma_F/d\Omega}{d\sigma_T/d\Omega} + \frac{2\mathrm{Im}[g_N h_F^* + g_F h_N^*]}{d\sigma_T/d\Omega} \quad (6)$$

where the last terms in equations 5 and 6 express the interference between the near and far components of the scattering amplitude. Moreover since the non spin-flip amplitude $g(\theta)$ contains a contribution from the Rutherford scattering, considerable care was taken to properly decompose the Rutherford part[11] without making the customary approximation that the Rutherford scattering is entirely near-sided. A computer program ORION[12] was written to accept the nuclear matrix elements and the Rutherford scattering amplitude from the computer code RAROMP2[13] and to evaluate the near-side, far-side cross-section and analysing powers as well as the interference quantities using the above formalism.

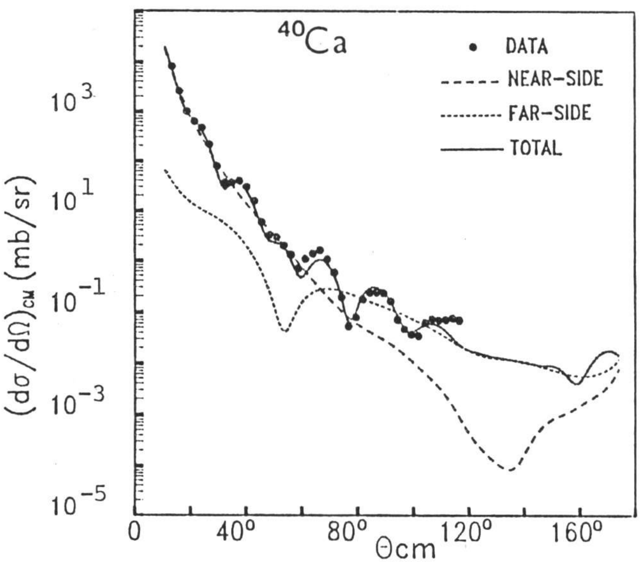

Figure 1. Near-side, far-side decomposition of the optical model calculation.

To illustrate the results we present here the calculations for ^{40}Ca, ^{90}Zr and ^{208}Pb targets at 33 MeV beam energy. A more detailed account of the full analysis is to be published elsewhere.[14] Let us consider first the results for ^{40}Ca where the data, the near-side (N/S), the far-side (F/S) and the full (computed using equation 5) calculations are depicted, see figure 1. At forward angles (<70 degrees), the N/S cross-section dominates, whereas beyond 70 degrees the scattering is F/S dominated. The near-side and the far-side amplitudes interfere to give rise to Fraunhofer oscillations in the full calculation. These become stonger as the two (N/S, F/S) amplitudes become comparable in magnitude but quickly die off as the N/S cross-section falls to a minimum at about 130 degrees. The onset of interference is again observed at extreme backward scattering angles. The broad enhancement or 'hump' in the F/S angular distribution past the minimum at 50 degrees has been interpreted as rainbow scattering,[15] i.e the penetration of the flux into a classically forbidden region. Thus the calculations clearly identify the back angle data as due to the nuclear rainbow phenomenon.

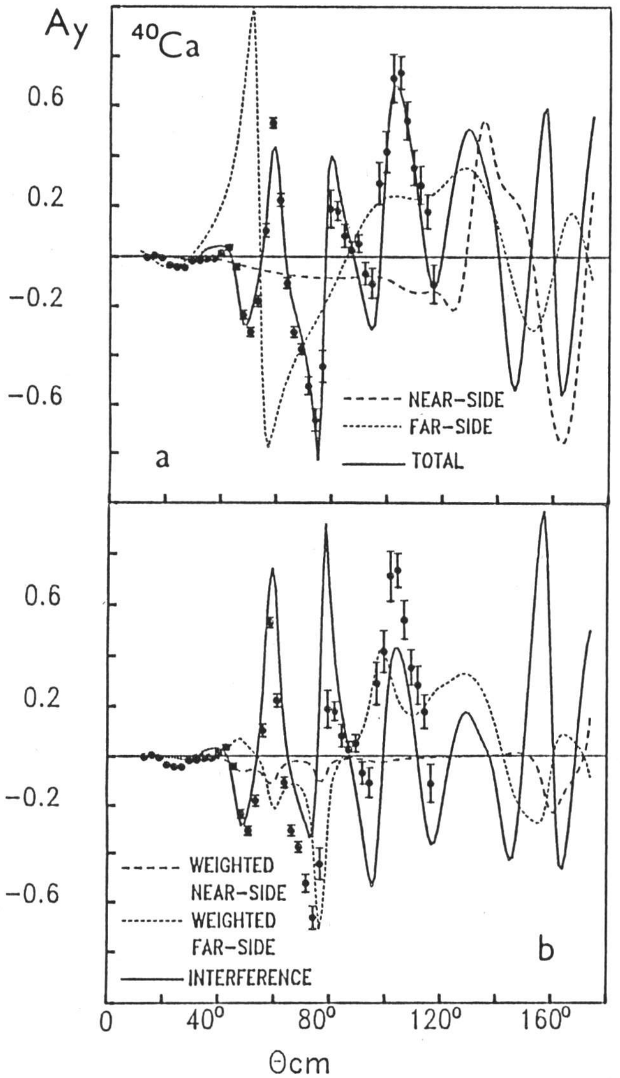

Figure 2. (a) N/S, F/S analysing powers and the full calculations.
(b) Weighted N/S, F/S analysing powers and the interference term.

Turning now to the analysing powers, figure 2a shows the N/S and F/S values calculated as defined by equation 4. The total analysing power is the sum of N/S and F/S components plus the interference between the two. It should be emphasized however that when the analysing powers add to give the total each component is weighted by the ratios of the cross-section, for that side, to the total cross-section, see equation 6. This may at first seem obvious but it could easily lead to a misunderstanding. Note that the F/S analysing power is large and positive at forward angles and rapidly changes to a large negative value near 50 degrees, and its behavior is less erratic untill the onset of oscillations at 140 degrees. On the other hand, the N/S analysing power is very small at forward angles and becomes progressively more negative with increasing scattering angle.

The weighted N/S, F/S analysing powers and the interference term are displayed in figure 2b. The most significant observation is that the analysing power is largely determined by the interference term, albeit, there is some contribution from the weighted F/S analysing power. However, in the case of ^{90}Zr the total analysing power is almost entirely determined by the interference part alone, see figure 3a. Note however that the F/S cross-section has now fallen a few orders of magnitude below the N/S cross-section, even at back angles (figure 3b).

In the case of ^{208}Pb the N/S analysing power dominates, and the F/S component is negligible, however, its effect is seen through the weak interference pattern on top of the N/S component (figure 4a). In this mass/energy region the cross-section is completely dominated by the N/S component, see figure 4b, (which is mostly attributed to Coulomb scattering) hence very little information can be extracted regarding the nuclear potential using the cross section data alone and this highlights the usefulness of the polarisation observables. For instance, the observed lack of oscillations in the analysing power data for ^{207}Pb[4] is now well understood,[5] because the marginally stronger absorption for ^{207}Pb leads to a reduced F/S component such that the interference term almost vanishes; an effect hardly noticeable in the cross-section data.

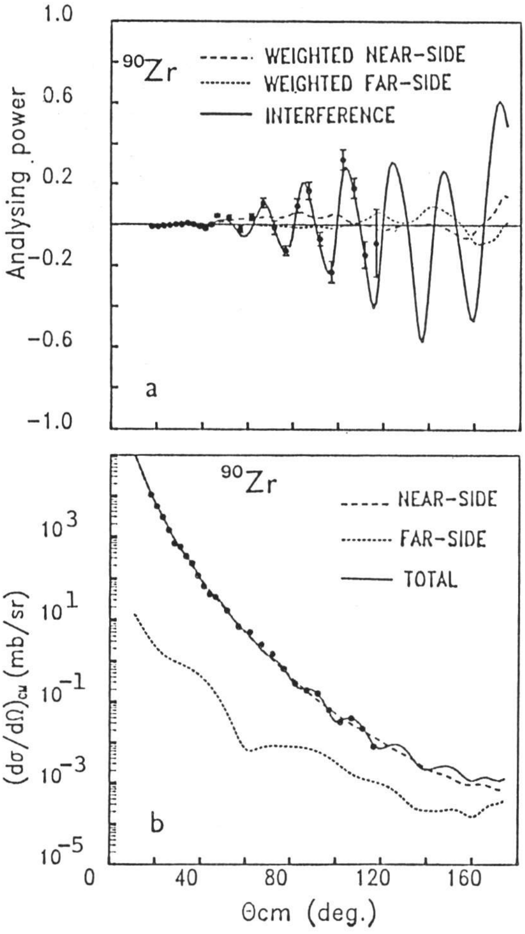

Figure 3.
(a) Analysing power calculations.
(b) Cross-section calculations.

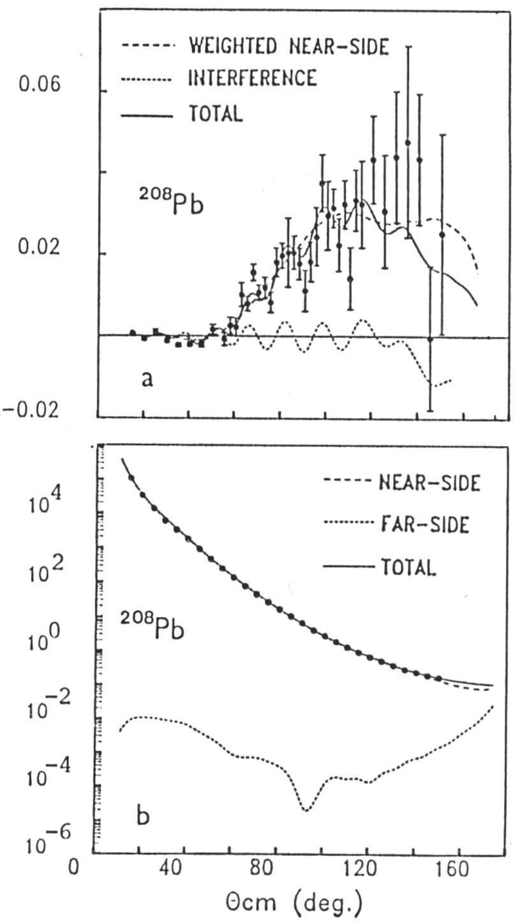

Figure 4.
(a) Analysing power calculations.
(b) Cross-section calculations.

The results of our investigations have shown that the interference in the analysing power is not very sensitive to the geometry of the spin-orbit potential. In contrast the spin-orbit geometry has a marked influence on the individual N/S, F/S components. Therefore, in cases where the analysing power is governed by the interference term e.g. ^{90}Zr, the spin-orbit diffuseness parameter is not well determined. This is a very interesting result and would explain why reasonable optical model fits to the data can sometimes be obtained using a large spin-orbit diffuseness parameter.

In order to settle the geometry of the spin-orbit potential one needs to perform experiments in a mass/energy region where one component i.e. N/S or F/S is predominant. To this end both ^{40}Ca and ^{208}Pb cases discussed above provide a useful illustration; the former being F/S dominated (at large angles) and the latter N/S dominated throughout the angular range.

When using the diffuse M3Y folded spin-orbit potential the fit to the ^{208}Pb data is particularly poor at forward angles, when compared with the phenomenological potential[8) therefore it would be reasonable to infer that it is the outer tail of the folded spin-orbit potential which is the cause of the relatively poor fit to the data at forward angles. Therefore, the evidence suggests that the spin-orbit interaction falls off more rapidly, with increasing seperation between the target and the projectile, than in the case for nucleon scattering. This situation prevails even in the case where the back angle scattering is totally governed by the F/S component and hence from nuclear rather than Coulomb scattering. Thus this analysis justifies the need for a sharply peaked spin-orbit potential. However, since the data are not very sensitive to the interior of the potential, any form which falls off rapidly with increasing radius would give good fits to the data.

References

1) Y.-W. Lui et al.: Nucl. Phys. A333 (1980) 205.
2) J. M. Barnwell et al.: Nucl. Phys. A364 (1981) 62.
3) F. Entezami et al.: Nucl. Phys. A366 (1981) 1.
4) A. Farooq et al.: University of Birmingham, Nuclear Structure Group Report 1984, p44, p46 (unpublished).
5) A. Farooq: Ph.D Thesis, Univ. of Birmingham, 1985 (unpublished).
6) J. S. Hanspal et al.: Phys. Rev. C31 (1985) 1138.
7) J. D. Brown et al.: Nucl. Phys. A436 (1985) 125.
8) A. Farooq et al.: Contributed papers to this conference.
9) J. D. Brown et al.: J. Phys. G 10 (1984) 1391.
10) M. S. Hussein and K. W. McVoy: Progress in Particle and Nuclear Physics, Vol. 12, (1985).
11) R. C. Fuller: Phys. Rev. C12 (1975) 1561.
12) Program ORION (A. Farooq and G. Rai) University of Birmingham, (unpublished).
13) Program RAROMP2 (G.J. Pyle, Univ. of Minnesota Report COO-1265-64, unpublished, extended version A. Farooq , unpublished).
14) A. Farooq, G. Rai and S. Roman: to be submitted to Nucl. Phys. A.
15) K. W. McVoy and G. R. Satchler: Nucl. Phys. A417 (1984) 157.

DISCUSSION

FICK: Is ^{3}He-Pb scattering pure Coulomb scattering and if so is this system not the one from which the dynamical origin of your small diffuseness of spin-orbit potential can be learned?

ROMAN: Yes, it is very nearly all Coulomb and, clearly, for lead and bismuth the spin-orbit diffuseness is better determined than say for ^{90}Zr, where the analysing power is interference dominated and less sensitive to the choice of parameters.

FICK: Is there now any dynamical interpretation of the small diffuseness of ^{3}He spin-orbit potential?

ROMAN: We have no dynamical interpretation. What we need is sharper fall-off than possible with the Woods-Saxon form. By selecting a narrow width of the spin-orbit potential we got a steeper gradient on the outside - where it matters. That is why we get only very few potential waves contributing - but it need not to be so, since what happens on the inside is unimportant.