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LETTER TO THE EDITOR

Target spin effects in the scattering of composite particles

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Abstract. A recent optical model analysis of ^{3}He elastic scattering data has found evidence of target spin effects. The possible causes of these effects are examined and experiments are suggested which may reveal more information about the target spin effects.

In a recent analysis of ^{3}He elastic scattering from various nuclei, Fulmer and Hafele (1973) found that a larger spin–orbit potential was required to fit the data for nuclei with non-zero spins, apparently indicating some form of target spin effect. There was also the visual evidence of the more damped oscillations in the differential cross sections for non-zero spin nuclei. Similar differences have been observed in large angle alpha scattering from neighbouring nuclei with zero and non-zero spins (C B Fulmer 1973, private communication). It is interesting to compare the possible causes of the observed effects and to consider which experiments may reveal further information. Three of the most likely causes are: (i) an $\boldsymbol{I}.\boldsymbol{\sigma}$ interaction; (ii) an $\boldsymbol{I}.\boldsymbol{l}$ interaction; (iii) collective effects.

There is also the possibility that the increased spin–orbit potential V_S was a result of the optical model fitting procedure, ie compensation for defects in the model which are different for nuclei with different spins. Rao *et al* (1973) have shown how the positions of excited states and reaction channels produce a strong effect on the predicted elastic scattering. Since the density and positions of levels in zero and non-zero spin nuclei are quite different one might expect *a priori* differences in the elastic scattering. It should be noted however, that extensive proton scattering studies (Ridley and Turner 1964, Fricke 1967, Fricke *et al* 1967, Greenlees *et al* 1968) do not reveal such differences, except for lighter, closed shell nuclei, and even when there are extensive polarization data, no differences are found for values of V_S. Since there are no polarization measurements for ^{3}He scattering near 50 MeV which could determine the spin–orbit potential depth or geometry, speculation in this direction must be limited.

The $\boldsymbol{I}.\boldsymbol{\sigma}$ interaction is an interaction between the target spin and the projectile spin, and is zero for alpha particles. A small potential of this type would produce an additional contribution to the differential cross sections proportional to $I(I+1)(V_{I\sigma})^2$, which would tend to 'fill in' the minima. The spin–spin interaction has been investigated by various authors (Batty 1971, Davies and Satchler 1964, Tamura 1965, Stamp 1967, Nagamine *et al* 1970), but for nucleons its magnitude appears to be small ($<0{\cdot}5$ MeV) although Batty (1971) obtained larger values for lighter nuclei. His analysis of 'D' parameter data showed that $V_{I\sigma}$ was required to be a factor of about three larger if the interaction had a surface (derivative) Saxon-Woods form factor. A microscopic description by Stamp (1967) yields form factors that are approximately surface shape for heavier nuclei. Here the different natures of the absorption of ^{3}He and nucleons may be significant. ^{3}He particles are strongly absorbed and so the surface region of the potential has a marked effect upon the scattering, and these ions may be sensitive to features of the interaction which produce only a small effect in the scattering of nucleons. A $V_{I\sigma}$ of 1·5 MeV for 50 MeV protons on ^{59}Co using a surface form (Batty 1971, Davies and Satchler 1964, Tamura 1965) lead us to expect a value of about 0·5 MeV for ^{3}He because the potential must be averaged over the constituent nucleons of the ^{3}He. However, Fulmer and Hafele (1973) observed a difference of about 1 MeV for V_S which seemed independent of nuclear spin I and of mass number A. $V_{I\sigma}$ is expected to show a $1/A$ dependence.

If the effect for alpha scattering is comparable to ^{3}He scattering, this precludes the $\boldsymbol{I} \cdot \boldsymbol{\sigma}$ interaction as the major cause. The $\boldsymbol{I} \cdot \boldsymbol{l}$ interaction, between the target spin and the angular momentum of the projectile, has been considered by Rawitscher (1972) for alpha scattering. He found that the potential had a surface shape but the strength ($< 0 \cdot 1$ MeV) was very much smaller than the values (0·2 to 2 MeV) obtained from phenomenological studies (C B Fulmer 1973, private communication, Taylor *et al* 1965) except when the valence nucleon had $j = l - \frac{1}{2}$, when an increase by a factor ten was calculated. Here again the correction to the cross section is proportional to $I(I+1)(V_{Il})^2$. If the normal spin–orbit potential in the optical model is used to fit alpha scattering data, one is assuming $I = \frac{1}{2}$ and the true value of V_{Il} is given by

$$\frac{V_{\frac{1}{2}l}}{V_{Il}} = \left(\frac{I(I+1)}{\frac{1}{2}(\frac{3}{2})}\right)^{1/2}.$$

If V_{Il} was constant with I, therefore the derived V_S would increase as $[I(I+1)]^{1/2}$. Experimental evidence is limited, but Weller (1972) has recently interpreted spectra of ^{15}N in terms of ^{11}B + alpha particle states, and the level sequence leads him to postulate a dependence of $\boldsymbol{I} \cdot \boldsymbol{l}$ on the j value of the state. Verification of an $\boldsymbol{I} \cdot \boldsymbol{l}$ interaction would involve measuring the polarization of the recoiling target nucleus. This could probably be determined for a light nucleus, eg ^{9}Be, using a proton recoil polarimeter.

The collective effects are likely to be the largest of the three causes. Satchler (1963) has discussed in some detail how there is an additional direct contribution to the elastic scattering for odd mass nuclei with spin greater than $\frac{1}{2}$. The quadrupole contribution is the most important and Satchler shows how this is in antiphase to the elastic scattering and tends to fill in the minima in the cross sections. This contribution vanishes for pure vibrational nuclei. The correction to the cross section is proportional to (Satchler 1963)

$$\beta^2 |\langle I 2\, I 0 | I\, I \rangle|^2 = \beta^2 \frac{I(2I-1)}{(I+1)(2I+3)}.$$

When the adiabatic approximation (Satchler 1963) is valid the direct quadrupole contribution is then equal to the cross section for the excitation to the first member of the ground state rotational band multiplied by the ratio of the Clebsch–Gordan factors

$$\left|\frac{\langle I 2\, I 0 | I\, I\rangle}{\langle I 2\, I 0 | I+1\; I\rangle}\right|^2 = \frac{(2I-1)(I+2)}{3(2I+3)}.$$

Blair and Naqib (1970) have shown how the elastic scattering of 42 MeV alpha particles from ^{25}Mg ($I = \frac{5}{2}$) is virtually indistinguishable from the elastic scattering from ^{24}Mg and ^{26}Mg ($I = 0$) when the direct qudrupole contribution is subtracted. The normal angular distribution for ^{25}Mg is much more damped than for ^{24}Mg or

^{26}Mg. An analysis by the author of recent extensive alpha scattering data from ^{25}Mg at 40 MeV (A M Shahabuddin 1973, private communication) using the regular optical model led to an optimum V_S of about 1·1 MeV, in agreement with the magnitude of the effect seen by Fulmer and Hafele. However, they also observed the effect with vibrational nuclei. Satchler (1963) has shown that if the ground states of such nuclei contain an admixture of the one-quadrupole phonon state with amplitude x, then if x is small the quadrupole contribution is reduced by

$$4x^2 \frac{(I+1)(2I+3)}{5I(2I-1)}.$$

Figure 1 shows the spin–orbit potential which would be obtained as a function of I if a normal optical model analysis was carried out on data from different nuclei. Also

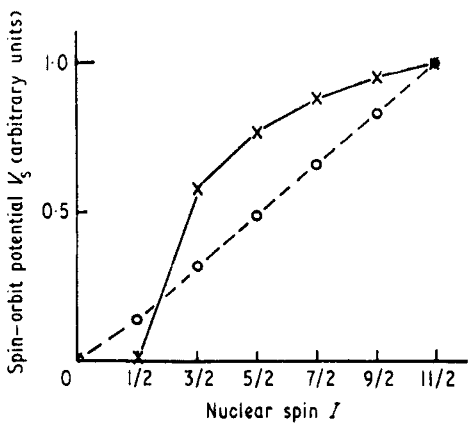

Figure 1. Derived spin–orbit potential as a function of nuclear spin for the quadrupole effect (full curve with crosses) and for an $\boldsymbol{I}.\boldsymbol{l}$ (or $\boldsymbol{I}.\boldsymbol{\sigma}$) interaction (broken curve with open circles).

shown is the $[I(I+1)]^{1/2}$ dependence of an $\boldsymbol{I}.\boldsymbol{l}$ (or $\boldsymbol{I}.\boldsymbol{\sigma}$) interaction; both are arbitrarily normalized at $I = \frac{11}{2}$. Note that for $I = \frac{1}{2}$ the quadrupole effect is zero, so that a suitable means of distinguishing between the collective effects and an $\boldsymbol{I}.\boldsymbol{l}$ (or $\boldsymbol{I}.\boldsymbol{\sigma}$) interaction might be to measure the elastic (and preferably also the inelastic) scattering from nuclei like ^{29}Si and ^{89}Y (both $I = \frac{1}{2}$), together with data from neighbouring spin zero nuclei for comparison.

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