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Spin-orbit effect on backward angle anomaly in heavy ion scattering

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It is shown that a spin-orbit potential in heavy ion scattering damps a pronounced oscillation of angular distributions of the backward angle anomaly. The angular distributions with the damped oscillation at back angles in ^{9}Be + ^{12}C scattering are analyzed with a parity dependent optical model by introducing a spin-orbit potential, and fairly good agreement with the data is obtained.

There has been a growing interest in the spin-orbit potential in heavy ion scattering,[1–14] and recent experiments[9–14] show that the spin-orbit potential for the likes of ^{13}C, ^{15}N, and ^{19}F is much stronger than the folding model description. The spin-orbit interaction of heavy ions is, however, scarcely understood compared with that of light ions because a polarized heavy ion beam is not available. Landowne[5] discussed how we can find the effect of the spin-orbit potential in the differential cross section in heavy ion scattering.

On the other hand, one of the characteristic features of heavy ion scattering is the anomalous enhancement of cross sections at back angles, called the backward angle anomaly (BAA), which accompanies the pronounced oscillation in the angular distributions. The BAA phenomena are mostly seen in heavy ion systems with spin zero. In heavy ion scattering of a projectile with spin, the pronounced oscillation does not always appear: In ^{9}Be + ^{12}C scattering,[15] the oscillation is quite damped, although the cross sections are greatly enhanced at back angles.

Numerous attempts[16–23] have been made to understand the BAA phenomena from various viewpoints,[16] such as a quasimolecular shape resonance,[17] the surface transparency optical model,[18] the glory effect,[19] the exchange process,[20] the double-layer model,[21] and the parity dependent optical model.[22,23] However, no prescription has been given for reproducing the damped oscillation. The aim of the present paper is to show that the spin-orbit effect in heavy ion scattering could be seen significantly in the structure of the BAA with damped oscillation. The result of this paper will reinforce the finding of Landowne in Ref. 5.

We investigated the effect of the spin-orbit potential on cross-section angular distributions at back angles. For scattering of a projectile with spin, we introduced the spin-orbit potential into the parity dependent optical model,[22] which has been a powerful model for the BAA phenomena with pronounced oscillation in α-particle scattering[22] and heavy ion scattering,[23] as follows:

$$U(r)=V_{\text{cent}}(r)+V_{ls}(r)\left[\frac{\hbar}{m_\pi c}\right]^2\vec{l}\cdot\vec{s}\ , \tag{1}$$

where

$$V_{\text{cent}}(r)=V_{\text{opt}}(r)+(-1)^L V_{\text{ex}}(r)\ , \tag{2}$$

V_{opt} being the standard optical potential and V_{ex} being a parity-dependent central real potential. We adopted the Woods-Saxon, the derivative type of the Woods-Saxon, and the Thomas-Fermi type, for the form factors of V_{opt}, V_{ex}, and V_{ls}, respectively; the Coulomb potential is included in $V_{\text{opt}}(r)$.

For the sake of simplicity we consider heavy ion scattering of a projectile with spin $\frac{1}{2}$. By regarding the scattering by the potential of Eq. (1) as two potential problems, the two independent scattering amplitudes $f(\theta)$ and $g(\theta)$ are written as:

$$f(\theta)=f_{\text{cent}}(\theta)+f_{ls}(\theta)\ , \tag{3}$$

$$g(\theta)=g_{\text{cent}}(\theta)+g_{ls}(\theta)\ , \tag{4}$$

where $f_{\text{cent}}(\theta)$ and $g_{\text{cent}}(\theta)$ are the amplitudes owing to $V_{\text{opt}}(r)$, and $f_{ls}(\theta)$ and $g_{ls}(\theta)$ are defined in this equation; $g(\theta)$ is defined as the amplitude vanishing in the absence of the spin-orbit potential, and $g_{\text{cent}}(\theta)=0$. The amplitude $f_{\text{cent}}(\theta)$ is strongly enhanced at back angles owing to the parity dependent potential, and the angular distributions show the pronounced oscillation owing to the surface partial waves. The effect of the spin-orbit potential predominantly appears through $g_{ls}(\theta)$, which is also enhanced at back angles, while $f_{ls}(\theta)$ is rather small compared with $f_{\text{cent}}(\theta)$ because the spin-orbit effect is almost cancelled out, as easily understood by a perturbative treatment of the spin-orbit potential.

Back-angle rising is caused by the surface partial waves, whose angular momentum is generally large in heavy ion scattering, and the Legendre polynomial $P_L(\cos\theta)$ oscillates out of phase with $P_L^1(\cos\theta)$. Therefore, $|f(\theta)|$ also oscillates out of phase with $|g(\theta)|$ at back angles. Hence, the amplitude $g(\theta)$ plays a role in damping the pronounced oscillation caused by $|f(\theta)|$. The greatly enhanced back-angle angular distributions will show the characteristic feature depending on the strength of the spin-orbit potential: When V_{ls} is not very strong, the spin-orbit effect will appear in the reduction of the peak-to-valley ratio of the oscillation of the angular distribution; when V_{ls} is strong enough to give $|g_{ls}(\theta)|\sim|f_{\text{cent}}(\theta)|$, the oscillation will be strongly damped irrespective of the rise of the cross sections. Furthermore, when V_{ls} is very strong to give $|g_{ls}(\theta)|>|f_{\text{cent}}(\theta)|$, the back-angle enhanced cross sections will also show pronounced oscillation, whose angular distribution, however, goes down rapidly toward $\theta=180°$ at extreme back angles.

We investigated elastic scattering of ^{9}Be with spin $\frac{3}{2}$ from ^{12}C measured by Mateja *et al.*[15] at $E_L=20$, 26,

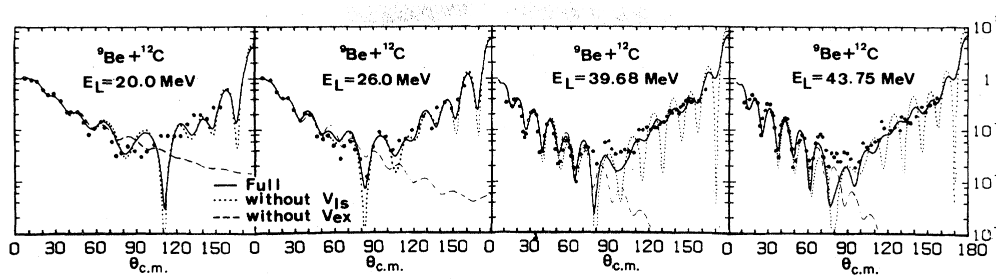

FIG. 1. Angular distributions of $^{9}Be + ^{12}C$ scattering. The curves are discussed in text. The data were taken from Ref. 15.

39.68, and 43.75 MeV, whose oscillation of the angular distributions at back angles is strongly damped, especially at the higher energies, although the cross sections are remarkably enhanced. These characteristic angular distributions have not been successfully explained: Mateja *et al.* showed that the magnitude of the back-angle rise is reproduced by taking account of the ^{3}He exchange amplitude in the distorted-wave Born approximation (DWBA); however, the slope and the shape of the damped oscillation, especially at the higher energies, cannot be reproduced. We analyzed the $^{9}Be + ^{12}C$ scattering from the standpoint of the effect of the spin-orbit potential on the back-angle scattering. We adopted for $V_{\rm opt}$ the potential of Ref. 15, which was determined so as to reproduce the forward angle behavior over the wide energy region. The geometrical parameters $r_{\rm so}$ and $a_{\rm so}$ of the spin-orbit potential were taken to be the same as the real potential. The strength parameter $V_{\rm so}$ was adjusted to fit the slope of the experimental angular distributions by damping the oscillation caused by the parity dependent potential of which the parameters V_π, r_π, and a_π were determined so as to reproduce the magnitude of the back-angle cross sections. The calculated results are shown in Fig. 1 by the solid lines, and the potential parameters are listed in Table I. The agreement of the calculations with the data is satisfactory; both the back-angle rise and the damped oscillations are fairly well reproduced. In Fig. 1, the calculated results switching off the $V_{\rm ex}$ term and the V_{ls} term are also shown by the dashed lines and dotted lines, respectively. It was found that the spin-orbit potential was responsible for damping the pronounced oscillation caused by the $V_{\rm ex}$ term. The spin-orbit effect is rather small at the lower energies of 20 and 26 MeV, and becomes remarkable at the higher energies of 39.68 and 43.75 MeV; this is because the spin-orbit potential is masked by strong absorption at the lower energies.

The scattering amplitudes for particles with spin $\frac{3}{2}$ can be grouped into four parts depending on the angular dependence: (a) $P_L(\cos\theta)$, (b) $P_L^1(\cos\theta)$, (c) $P_L^2(\cos\theta)$, and (d) $P_L^3(\cos\theta)$. The cross sections calculated with the potential in Table I are shown in Fig. 2 dividing into the four parts. It is seen that the total elastic cross section (solid lines) mainly comes from (a) (dashed lines) and (b) (dotted lines), while contributions from (c) (dot-dashed lines) and (d) (two-dot-dashed lines) are small. It is to be noted that the oscillations of the angular distributions of (a) and (b) are out of phase at backward angles. This is in accordance with the previous qualitative discussion for spin $\frac{1}{2}$. Thus, it is found that the pronounced oscillation owing to the surface partial waves is cancelled out by the amplitude owing to the spin flip to give the damped oscillation.

It seems necessary to investigate a quadrupole deformation effect on the back-angle cross sections, since ^{9}Be has a large static quadrupole moment. We calculated the differential cross sections by taking account of the reorientation effect of ^{9}Be with use of the deformation length of 2.5 fm (Ref. 24) and the potential of Table I (without the spin-orbit potential). It was found that the reorientation only slightly damps the pronounced oscillation at backward angles and the calculated angular distribution is still far from the experimental data. Coupled channel calculations including the $\frac{5}{2}^-$ (2.43 MeV) state assuming a rotational model of $K=\frac{3}{2}^-$ were also done. However, the coupled channel effect of the excited state for damping the pronounced oscillation is also slight. Thus, the large quadrupole deformation is not responsible for the damped oscillation of the angular distribution.

The spin-orbit potential has also been introduced in order to explain the phase problem of the angular distribution of the one-nucleon transfer reaction such as (^{13}C,^{14}N)

TABLE I. Optical potential parameters of the spin-orbit and the parity dependent terms. Other potential parameters are $V_0=33.686$ MeV, $r_0=0.964$ fm, $a_0=0.921$ fm, $W_0=6.524$ MeV, $r_I=1.509$ fm, and $a_I=0.478$ fm. $R=r(A_1^{1/3}+A_2^{1/3})$, $r_c=1.45$ fm.

E_L (MeV)	$V_{\rm so}$ (MeV)	$r_{\rm so}$ (fm)	$a_{\rm so}$ (fm)	V_π (MeV)	r_π (fm)	a_π (fm)
20	3.0	0.964	0.921	11.55	1.154	0.482
26	3.0	0.964	0.921	10.20	1.233	0.377
39.68	3.0	0.964	0.921	3.66	1.284	0.250
43.75	3.0	0.964	0.921	3.20	1.284	0.230

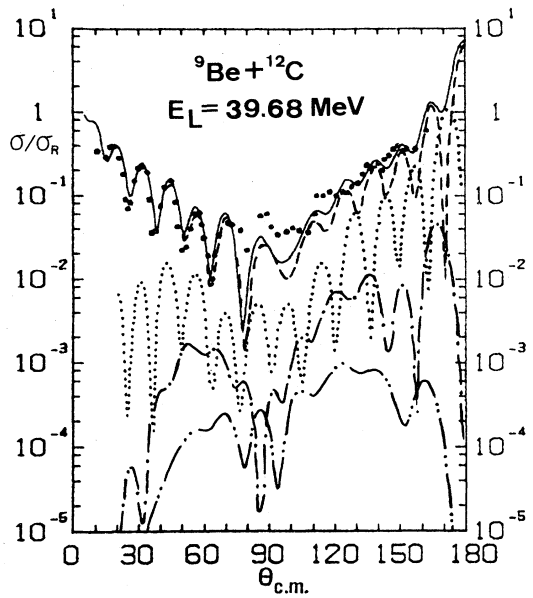

FIG. 2. The cross section of $^9Be + {}^{12}C$ scattering at 39.68 MeV calculated with the potential in Table I is shown divided into four constituents, which are represented by (a) dashed lines, (b) dotted lines, (c) dot-dashed lines, and (d) two-dot-dashed lines, respectively. The solid lines are the sum of the four constituents.

(Ref. 12): The angular distribution is well reproduced by this phenomenological spin-orbit potential. However, the physical meaning or origin of the phenomenological spin-orbit potential is not understood yet. On the other hand,[25] it has recently been pointed out that the spin-orbit potential of composite particles such as ^{7}Li and ^{6}Li is mostly induced by a dynamical process, and the spin-dependent interaction folded from the two-body nucleon-nucleon spin-orbit interaction is not very strong. If the spin-orbit potential is mostly structural dependent, being induced dynamically, it may change from nucleus to nucleus depending on its structure. The strong spin-orbit interaction required in the potential model approach in $^9Be + {}^{12}C$ scattering may be understood by taking account of the fact that ^{9}Be has a well-developed cluster structure, particularly of which excited states are the particle-decaying states.

To summarize, we have shown that the spin-orbit potential in heavy ion scattering significantly influences cross sections of the BAA and damps the oscillation of the angular distributions. The angular distributions of $^9Be + {}^{12}C$ scattering with the damped oscillation were fairly well reproduced with the parity dependent optical model by introducing the spin-orbit potential phenomenologically. The present result reinforces the finding of Landowne in the phenomena of the BAA. It seems necessary to study the origin of the phenomenological spin-orbit potential in connection with the cluster structure of the projectile. Furthermore, it is interesting to extensively see the spin-orbit effect on the backward angle anomaly in heavy ion scattering.

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