Anomalous Spin Polarization of Nucleon-Transfer Reaction Products

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We show a possible large spin polarization of the nuclei produced by one-nucleon-transfer heavy-ion reactions and investigate its origin. The asymmetry of the particle-γ angular correlation is also calculated for the ejectile and γ ray emitted from the spin polarized nucleus.

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Studies of nuclear structure and reaction mechanisms by direct measurements of the spin polarization of the reaction products are less common than those using analyzing power data. One reason for this is the technical complication of the polarization measurement; another is the polarization-asymmetry theorem. However, the theorem does not apply to the case of spin polarization of particles from nonelastic and non-ground-state nucleon-transfer interactions. Measurements of spin polarization in such cases are carried out by measuring the asymmetry angular distribution of the correlated ejectile and decay particle such as α, β, γ, and nucleons. The measurements are therefore quite difficult but challenging and are sometimes called exotic.

For these reasons, the magnitude of the polarization and the dynamics of polarization production for the reaction products are less well understood both experimentally and theoretically. Another reason to call the experiment exotic is perhaps to stress the idea of using such polarized unstable nuclei as the injectile (secondary) beams for new reaction experiments, which cannot be studied using stable nuclei as the projectile and target. Therefore it is extremely interesting and important to find cases where the spins of the reaction products are highly polarized and where we also know the dynamics.

In this paper we show a unique case where a large spin polarization of the reaction products may occur. We also explain how this large spin polarization comes about. Before going into details, we briefly review the past studies of the spin polarization of unstable nuclei in both experimental and theoretical works.

Spin polarization of ^{12}B produced through the reaction $^{11}B(d,p)^{12}B$ was first measured in 1967 [1] by coincidence measurements of the proton and decaying β ray; it is about 5% for deuteron energies 0.8–3.2 MeV. In 1977 the same ^{12}B polarization was measured [2] through the heavy-ion reaction $^{100}Mo(^{14}N,^{12}B)^{102}Ru$ at 90-MeV incident energy. The polarization is about 30% in the small-Q-value region and it rapidly decreases with increasing the Q value, changing sign from positive to negative. This result attracted theoretical attention and several models interpreting the result were proposed [3,4]. While the frictional force alone was not able to account for all of this Q-value dependence, the exact finite-range (EFR) distorted-wave Born-approximation (DWBA) calculation that properly includes the continuum final states gives an almost complete interpretation of the result [4]. Three other experiments with calculation of the ^{12}B polarization were done in 1978–1979 on the reactions [5] $^{100}Mo(^{14}N,^{12}B)^{102}Ru$ at 200 MeV, $^{197}Au(^{19}F,^{12}B)^{204}Bi$ at 186 MeV, and $^{232}Th(^{13}C,^{12}B)^{233}Pa$ at 149 MeV.

Recently the $(^{14}N,^{12}B)$ reaction on ^{197}Au at 560-MeV incident energy was carried out, and a polarization changing from +20% to −10% as the Q value increases was observed. Simple semiclassical [6] and quantal microscopic [7] calculations have been made, and both give a successful interpretation of the results.

In deep inelastic collisions, a small (+25%) and a large (+80%) polarization of the excited nuclei were reported for collisions using a different set of nuclei and energies [8,9]; the polarization was deduced by measuring the circular polarization of the deexcitation γ ray. The presence of negative scattering angles (far-side trajectories) on the basis of the frictional picture was found to be consistent with the observed results [9].

In 1979 the spin polarizations of the excited 3^-, 5^-, and 6^+ ^{20}Ne states were determined by ^{12}C-α angular correlation measurement using the $^{16}O(^{16}O,^{12}C)^{20}Ne$ reaction [10]. The magnitude changes from 70% to 90% as the ^{12}C scattering angle changes from 10° to 40°. The polarization in this case corresponds to that of the orbital angular momentum transferred to the residual nucleus. The EFR DWBA calculation reproduces the observed shape, but its magnitude is smaller by a factor of about 1.3 compared with the observed results. The authors pointed out that a simple frictional model is not inconsistent with the observed polarization if an extreme condition for the trajectory is accepted, such that only one (near or far) side trajectory is effective for the transfer reaction. However, the frictional model is, in general, too simple to predict the polarization of residual nuclei excited in discrete levels. This conclusion follows that of Bond [11].

The polarization produced by the spin-orbit distortion has been estimated in the framework of the no-recoil DWBA calculation for $^{14}N(1^+)$ as 30% in the one-nucleon-transfer $^{40}Ca(^{13}C,^{14}N)^{39}K$ and for $^{31}P(\frac{1}{2}^+)$ as 70% in the three-nucleon-transfer $^{28}Si(^{19}F,^{16}O)^{31}P$ reactions [12], but no experimental measurement has yet been reported.

Here we describe a unique case of a large spin polarization of the residual nucleus produced by a simple one-nucleon-transfer reaction. This case happens in a one-nucleon transfer from the $J_a=\frac{1}{2}^-$ state of the projectile to the $J_B=\frac{1}{2}^-$ state of the residual nucleus if the reaction $A(a,b)B$ is a stripping reaction.

We show this by giving, as an example, the result of a calculation of the $^{12}C(^{13}C,^{12}C)^{13}C(\text{g.s.},\frac{1}{2}^-)$ reaction at 100-MeV incident energy. The calculation is made by the EFR DWBA and the distorting potential parameters are the same as those used in Ref. [13]. The neutron bound-state wave functions are calculated by the separation energy method using the Woods-Saxon potential. The potential obtained is used for the transition amplitude calculation in the post form. The elastic transfer mechanism is not included in the calculation because we are interested in the spin polarization arising from the nucleon-transfer mechanism, and anyway the elastic transfer effect is small for forward scattering angles [14].

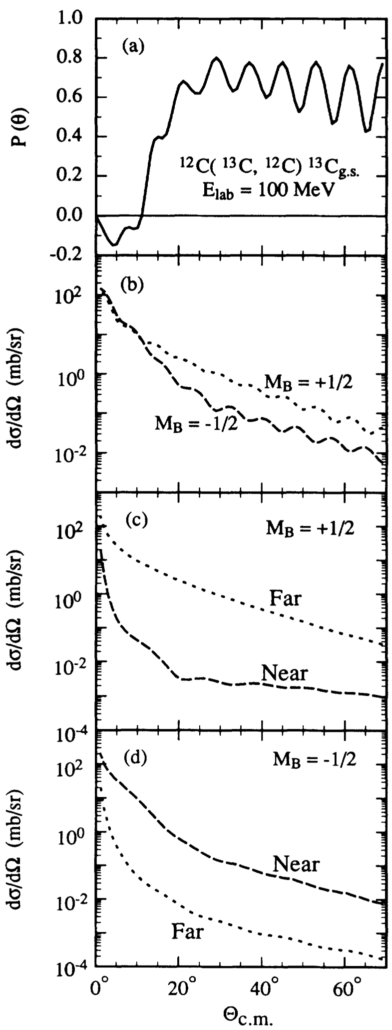

FIG. 1. (a) The calculated polarization of the residual ^{13}C ground-state nucleus. The various cross sections of the one-nucleon-transfer $^{12}C(^{13}C,^{12}C)^{13}C$ reaction at 100 MeV; (b) the partial cross sections for each M_B substate population; (c),(d) the near and far cross sections for each M_B substrate population.

The result of the calculation is shown in Fig. 1(a). This gives the spin polarization of the residual nucleus, along the direction defined by $\mathbf{k}_a\times\mathbf{k}_b$, where $\mathbf{k}_a$ ($\mathbf{k}_b$) is the projectile (ejectile) linear momentum. The predicted magnitude of polarization is about 70% with positive sign, almost independent of the scattering angle.

The transition amplitude for the reaction concerned can be expressed as the sum of two terms corresponding to the two orbital angular momentum transfers, $l=0$ and 1,

$$T=\sum_{L_a}(-1)^{L_a}(2L_a+1)^{1/2}\times\left[P^0_{L_a}(\theta)I^{l=0}_{L_aL_a}+2M_B\left\{\frac{1}{L_a(L_a+1)}\right\}^{1/2}P^1_{L_a}(\theta)I^{l=1}_{L_aL_a}\right], \tag{1}$$

where $I^l_{L_aL_a}$ are the overlap integrals and M_B is the magnetic substrate quantum number of J_B. We use the same notation as Satchler [15], but the z axis is defined as normal to the scattering plane and the x axis is along the incident momentum.

It is interesting to note that the above expression contains only M_B but not the other six magnetic quantum numbers: M_A of target spin J_A, M_a of projectile J_a, M_b of ejectile J_b, m_a of incident partial waves L_a, m_b of exit partial waves L_b, and m of l. This is due to the existence of the special selection rule among the angular momenta appearing in the present $J_a=\frac{1}{2}^-$ to $J_B=\frac{1}{2}^-$ transition and also to our choice of the coordinate axes; namely, from parity conservation, we have the relations $L_a=L_b$ and $M_a=M_B$ (Bohr theorem) for the present $J_A=J_b=0$ reaction, that is, $m=0$ even for $l=1$ transfer. It is also worthwhile to note that the transition amplitude for $l=0$ transfer is independent of M_B and that M_B appears as an overall factor only for the $l=1$ amplitude.

Equation (1) shows that this large polarization is produced by the interference of the natural (no-recoil) and the unnatural (recoil) parity l-transfer amplitudes. A similar situation has been found in the case of polarization of ^{12}B in the small-Q-value region [4].

We show each cross section for $M_B=\frac{1}{2}$ and $-\frac{1}{2}$ in Fig. 1(b). In Figs. 1(c) and 1(d), we show the decomposition of each M_B cross section into the near-side and the far-side contributions [16]. We find a marked difference of the relative magnitudes of the near and far cross sections between the $M_B=\frac{1}{2}$ and $-\frac{1}{2}$ cases; namely, in the $M_B=\frac{1}{2}$ cross section [Fig. 1(c)], the far-side cross section shows a large constructive interference between the

$l=0$ and 1 amplitudes, whereas the near-side cross section shows a large destructive one. These interference features are opposite in the $M_B = -\frac{1}{2}$ cross section [Fig. 1(d)] and now the far-side cross section almost cancels out. This is because (1) the transition amplitude takes a very simple interference form for the present $J_a = \frac{1}{2}^-$ to $J_B = \frac{1}{2}^-$ transition, and (2) the sign of the interference depends on M_B itself as we noted for Eq. (1). The far-side cross section with the $M_B = \frac{1}{2}$ orientation predominates among the four cross sections and therefore a large polarization of positive sign is obtained.

We made the same calculation for the target nuclei ^{16}O, ^{20}Ne, ^{24}Mg, ^{32}S, ^{40}Ca, and ^{48}Ca, assuming every ground-state spin to be $p_{1/2}$. We found that, while the near-side cross section becomes larger, the far-side cross section becomes smaller as the mass number increases, and now the near-side cross section with the $M_B = -\frac{1}{2}$ orientation turns out to be predominant. Finally a large negative-sign spin polarization is obtained for the ^{48}Ca target. This change of dominance from the far-side to the near-side trajectory is mainly due to the Coulomb repulsion.

To show this, the result of a calculation for one of the realistic cases is given in Fig. 2(a). The reaction is ^{48}Ca(^{13}C,^{12}C)^{49}Ca*(2.022 MeV, $\frac{1}{2}^-$) at 47-MeV incident energy, which corresponds to about a half of the incident energy used in the above trial calculations. This choice emphasizes the Coulomb effect and therefore the near-side contribution, and also uses the same distorting potential parameters as those used in Ref. [17].

As we can see in Fig. 2(a), the spin polarization is also quite large, and now negative, and is almost constant at -90% between 20° and 60° where the cross section shows a broad peak. The near-far decomposition of each $M_B = \frac{1}{2}$ and $-\frac{1}{2}$ cross section is shown in Figs. 2(c) and 2(d). As mentioned above, the near-side component of the $M_B = -\frac{1}{2}$ cross section [Fig. 2(d)] is now predominant.

The polarization for the other final states such as $s_{1/2}$ ($l=1$), $p_{3/2}$ ($l=1,2$), and others were also evaluated, but no predominance of a particular M_B direction was found since such a simple interference form as in the case of the $p_{1/2}$ state does not occur.

The large spin polarizations predicted here for the ^{49}Ca excited state may be experimentally detectable by the particle-γ angular correlation techniques. The angular distribution of the emitted γ ray (2.022 MeV) shows an-

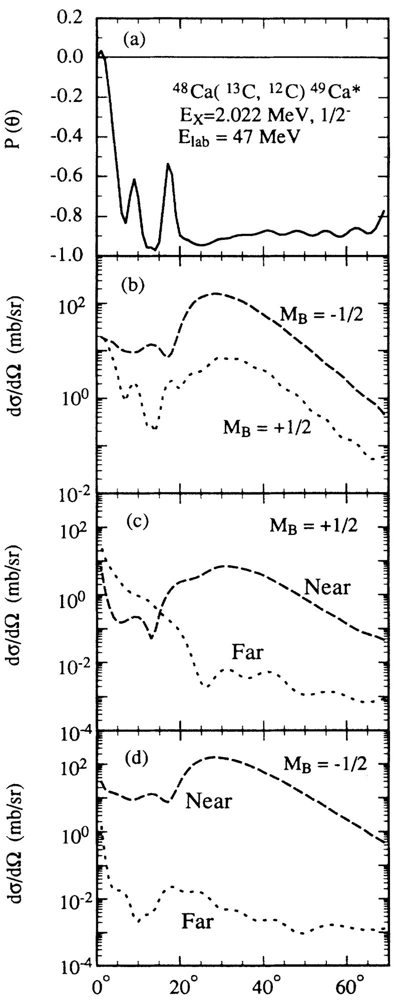

FIG. 2. (a) The calculated polarization of the residual ^{49}Ca* $\frac{1}{2}^-$ nucleus. The various cross sections of the ^{48}Ca(^{13}C, ^{12}C)^{49}Ca* reaction at 47 MeV; see the caption of Fig. 1 for (b)-(d).

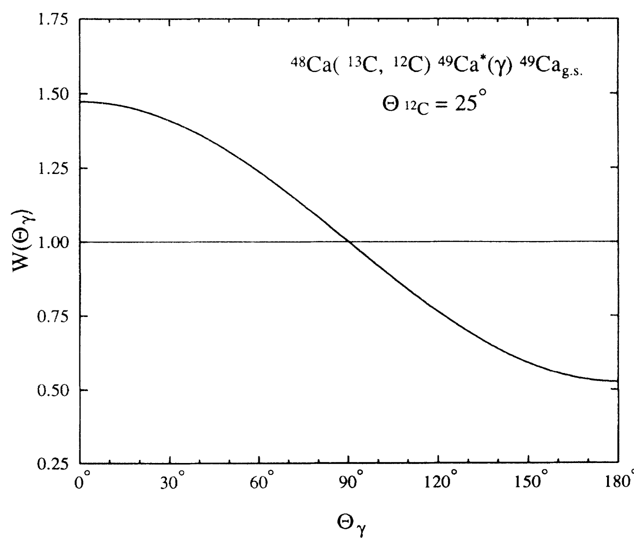

FIG. 3. The ^{12}C-γ angular correlation distribution for $\theta_{^{12}C} = 25°$. The calculation is made for the γ ray of right-hand circular polarization and emitted in the $M1$ transition from the 2.022-MeV $\frac{1}{2}^-$ state to the ground state of ^{49}Ca produced by the (^{13}C,^{12}C) reaction at 47 MeV.

isotropy if the spin of the intermediate state (^{49}Ca*) is polarized. However, it is known that the γ ray decaying from the $\frac{1}{2}$ spin state shows an isotropic angular distribution unless the polarization of the emitted γ ray itself is observed [18]. For example, if the right-hand circular polarization of the γ ray is observed, the angular correlation function is given by

$$W(\theta_\gamma)=1-\tfrac{1}{2}P(\theta)\cos\theta_\gamma, \qquad (2)$$

where θ_γ is the polar angle for the case of the z axis parallel to $\mathbf{k}_a\times\mathbf{k}_b$. This function is independent of the azimuthal angle. In Fig. 3 we show the calculated angular distribution for the ^{12}C emission angle of $\theta=25°$ ($P=-95\%$) for the ^{48}Ca(^{13}C,^{12}C)^{49}Ca* reaction at 47 MeV. It is extremely interesting and important to make this angular correlation measurement to confirm the present prediction and to further extend spin physics using unstable polarized nuclei produced by the nuclear reactions.

In conclusion, we have found a unique case where a large spin polarization of the produced nucleus occurs in a one-nucleon-transfer heavy-ion reaction. Also we have predicted the asymmetry angular correlation between the ejectile and the γ ray decaying from the polarized nucleus, which shows maximum deviation of about 50% from the isotropic distribution.

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