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ABSTRACT: The nuclear spin polarization of beta-emitting fragments ^{37}K and ^{39}Ca has been measured at around the grazing angle of the ^{40}Ca + Au collision at 106 MeV/u. Momentum dependence of the observed fragment polarization supports the idea that the origin of the polarization is the orbital angular momentum held by the fragment part of the projectile before the collision takes place. The sizable polarization of about 5% that was observed for the fragments will be a powerful tool for NMR study on the fragments.

1. INTRODUCTION

We are studying the magnetic moments of $f_{7/2}$ shell nuclei. The projectile fragmentation process in high-energy heavy ion collisions efficiently provides such nuclei for the study. A single fragment can be separated out using the Beam 44 fragment separator (Nojiri 1987), and the beta NMR technique (Minamisono 1973) can be applied for a study of the magnetic moment. For this kind of study, a suitable technique for polarizing the fragments is necessary. The so-called tilted foil technique (TFT) is one such technique (Nojiri 1986). The TFT on fragments has been tested (Nojiri 1988) and was successfully applied to the magnetic moment of ^{43}Ti (Matsuta 1989). In an extension of the present study, we have studied another efficient polarization technique, that is, polarization production through the collision itself.

Such polarization phenomena have been studied at low energies (Sugimoto 1977) and intermediate energies (Asahi 1990) using light fragments. In the present experiment, the spin polarization of the projectile fragments, ^{37}K($I^{\pi}=3/2^{+}$, $T_{1/2}$=1.23 sec) and ^{39}Ca($I^{\pi}=3/2^{+}$, $T_{1/2}$=0.86 sec) has been measured as a function of the fragment momentum at around the grazing angle of the ^{40}Ca on Au collision at a high incident energy of (106 ± 12) MeV/u. Polarization reached about 5% when the deflection angle and the fragment momentum were selected. Thus, the polarization phenomenon in the projectile fragmentation process proved its effectiveness for the beta-NMR studies on radioactive fragments.

The light beta emitters ^{12}B and ^{12}N have been very useful nuclear probes for a long time, not only for nuclear physics but also for hyperfine interactions of such nuclear probes in materials. The study of hyperfine fields for ^{12}B or ^{12}N in ferromagnetic Fe and/or Ni is a good example (Hamagaki 1979 and Nojiri 1981). The present technique for production and polarization of the radioactive fragments will provide a good opportunity to study not only nuclear physics but also solid state physics.

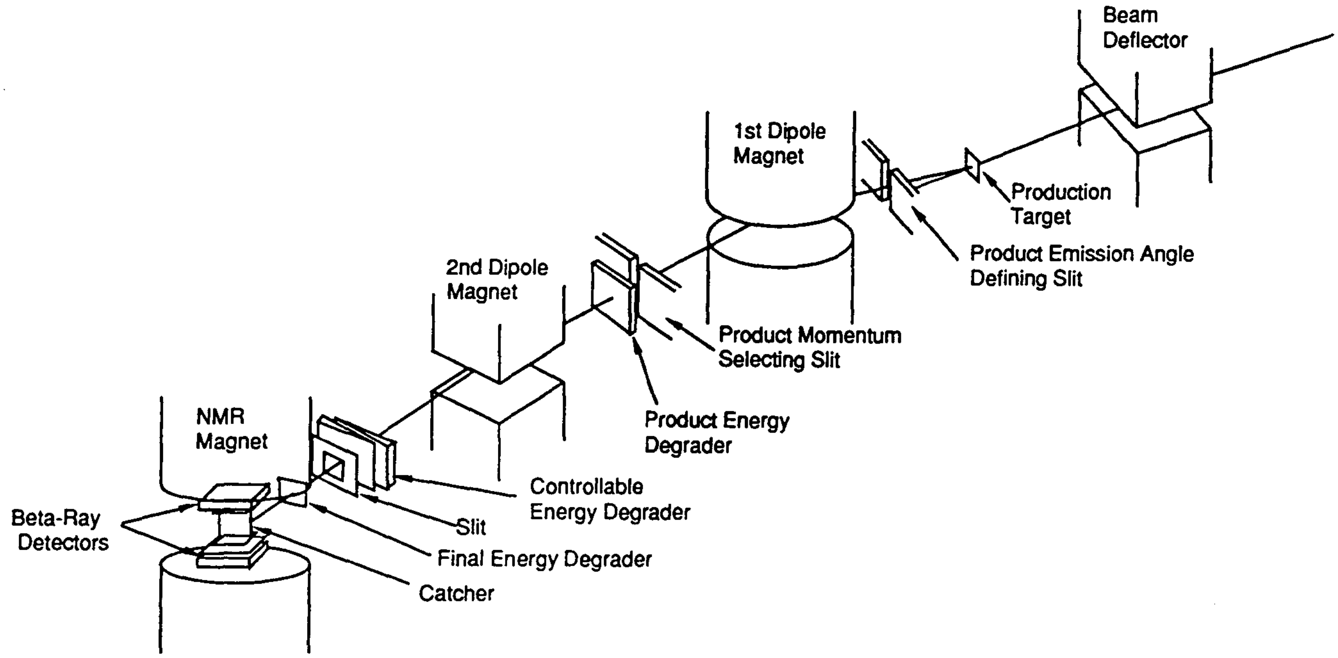

FIG. 1. Schematic view of the experimental setup.

2. EXPERIMENTAL

Nuclear spin polarization of beta-emitting fragments ^{39}Ca and ^{37}K produced in the ^{40}Ca + Au collision has been measured at an effective energy of (106 ± 12) MeV/u. Only the desired nucleus was selected and purified using the Beam 44 fragment separator at the Bevalac of LBL. The fragment polarization was measured as a function of the momentum, by means of asymmetry in the beta-ray distribution.

A schematic view of the experimental setup is shown in Fig. 1. A 380 μm thick Au target was bombarded with a ^{40}Ca primary beam extracted from the Bevalac once every 4 seconds at 118 MeV/u. The incident energy averaged over the energy loss in the target was 106 MeV/u. The fragments emitted to the laboratory angle defined by a collimator placed 0.6 m downstream of the target was brought to the Beam 44 fragment separator to be analyzed. The fragments were identified by means of a time of flight (TOF) measurement and an energy loss measurement. TOF was measured by a pair of plastic scintillation counters placed 8 m apart. The energy loss was measured by a 400 μm thick Si detector. Prior to the polarization measurement, angular distributions of various fragments were measured using the system. Then, only a single fragment was separated using the Beam 44 fragment separator. The separator basically consisted of two dipole magnets and an energy degrader between the dipoles. The rigidity analysis by the first dipole magnet with a pair of slit jaws provided separation based on the mass over charge ratio A/Z of the fragments. At the same time, the fragment momentum was also selected by the slit jaws. Then the fragments were slowed down by an energy degrader. With the succeeding rigidity analysis provided by the second dipole, the fragments were separated in terms of the energy loss. Since the second analysis provides another separation based on the ratio $A^{2.5}/Z^{1.5}$, only a desired fragment was separated out with the combined analysis (Dufour 1986).

The separated fragment was then implanted in a suitable catcher to maintain the polarization using its own kinetic energy. In order to stop the fragment at the desired depth, the range of the fragment was controlled by another energy degrader whose thickness could be controlled continuously. A strong magnetic field was also applied perpendicular to the reaction plane to maintain the polarization. Beta rays emitted from the fragments were detected by two sets of plastic scintillation counters placed above and below the catcher relative to the reaction plane. Spin polarization of the fragment was detected by means of asymmetry in the counters. The direction of the polarization was inverted using the nuclear magnetic resonance (NMR) technique, to cancel out the geometrical asymmetry in the counter system. The strong rf oscillating magnetic field of about 30 Oe applied perpendicular to the external magnetic field was sufficient to invert the polarization.

3. RESULTS

The observed polarization of the fragments is shown in Fig. 2 with the momentum distribution of the fragments. Momentum distributions of the fragments are Gaussian distributions around the momentum corresponding to the beam velocity. The width of the distribution was well accounted for by the Fermi momentum of the nucleons inside the nucleus (Goldhaber 1974). This is typical for the projectile fragmentation process in high-energy heavy-ion collisions. The observed angular distributions of various fragments are shown in Fig. 3. The widths of the distributions, however, are significantly larger than the width predicted by the Goldhaber model. The fragments were distributed up to the classical grazing angle of the present system because of Coulomb bounce off. In the case of ^{39}Ca, the width of the spread is widest when only one nucleon is stripped off from the projectile, and the width becomes narrower as the larger number of nucleons are stripped off.

As seen in Fig. 2, the observed fragment polarization was positive (parallel to the $\mathbf{k}_i \times \mathbf{k}_f$, where $\mathbf{k}_i$ and $\mathbf{k}_f$ are the wave vectors of incoming and outgoing particles) for the momentum region higher than that of the projectile, and was negative for the lower region. It is noted that the observed trend in the polarization is the same as that observed at the grazing angle around the quasi-elastic peak in low energy (around 10 MeV/u) transfer reactions (Sugimoto 1977) and that observed for a projectile-like fragment ^{12}B produced in the ^{14}N + Au collision at an intermediate energy (40 MeV/u) (Asahi 1990).

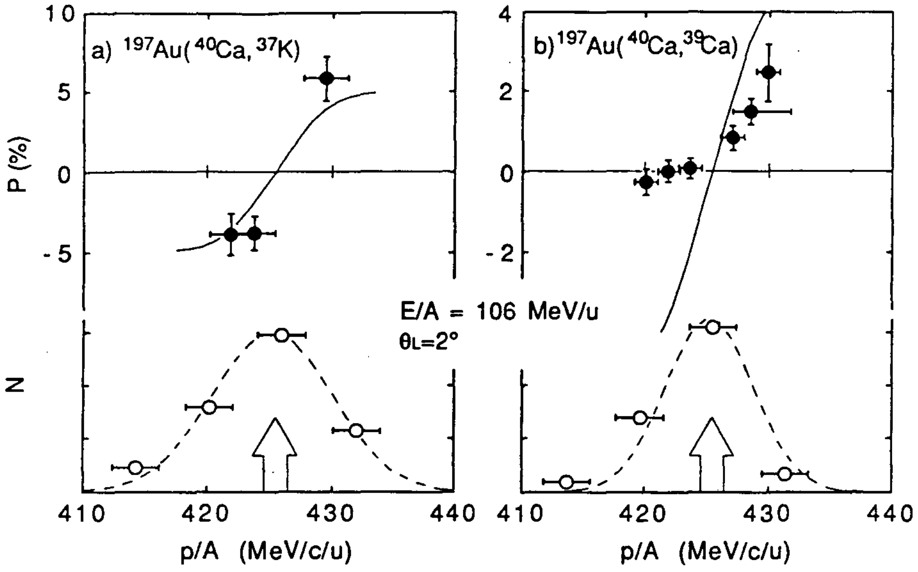

Fig. 2. Momentum dependence of fragment polarization.

Closed circles are observed polarizations in %, and open circles are relative yields. The momentum corresponding to the projectile velocity is also shown in the figure by the arrows. The solid lines are predicted polarizations multiplied by 1/20.

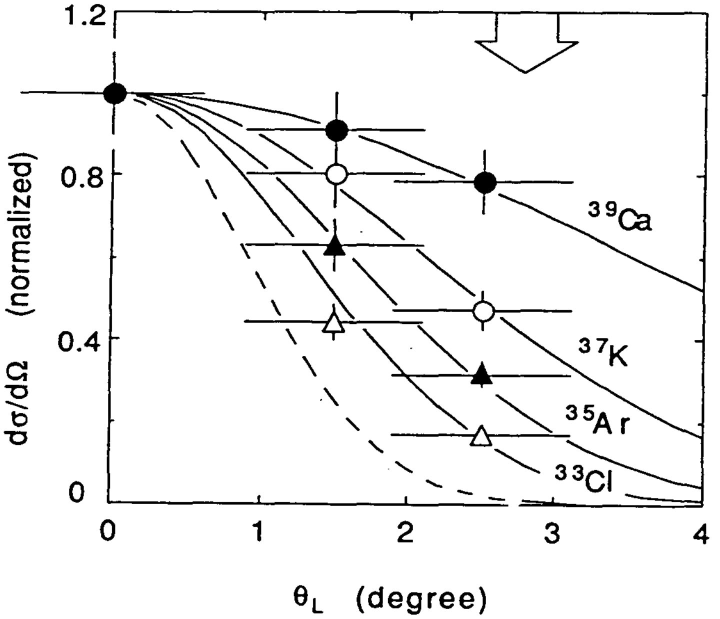

Fig. 3. Angular distribution of the fragments.

Cross sections are normalized at 0 degree. Lines are guides for eyes. Error bars in abscissa show the window width. The distribution predicted from the Goldhaber model is also shown for ^{39}Ca by the broken line. The classical grazing angle is shown in the figure by the arrow.

4. DISCUSSION

Present results added data for the heaviest fragments at the highest energy with different kinds of reaction channels from that of the previously observed fragment polarization. It was shown that the fragment polarization showed persistently the same trend over a wide range of projectile energies, masses and numbers of nucleons removed from the projectile. Such universality suggests similarity in the polarization mechanism through a whole range of incident energies. Thus, the origin of the polarization is the orbital angular momentum held by the fragment part of the projectile before the collision takes place. Indeed, Asahi's (1990) interpretation based on that assumption explained the trend in the fragment polarization very well. Assuming positive deflection of the fragment, the present trend is accounted for quite well qualitatively by this simple model (Asahi 1986), as indicated in Fig. 2.

Although, the fragment polarization is reproduced well qualitatively, the amount of polarization is strongly quenched from the predicted value. This might suggest the mixing of the far side component. Indeed, sharp focussing around the grazing angle, as expected from orbital deflection by the Coulomb field with angular spread caused by Fermi momentum, was not observed in the actual angular distributions. There might be orbital deflection by a combined Coulomb-nuclear field suggested by Van Bibber et al. (1979). However, the more dispersive deflection has to be included, so that the far side component mixes in the dominant near side component.

It was shown that a large polarization can be expected when the grazing angle is much larger than the angular spread by a random cause such as Fermi momentum, as in the present case. In addition to the grazing angle, actual angular spread is very important, because the fragment is not necessarily distributed up to the grazing angle as shown in Fig. 3. Since ^{39}Ca can be produced with relatively small overlapping with the target nucleus, the fragment is deflected to the positive angle by the strong repulsive Coulomb force. As more nucleons are stripped off, the overlapping region becomes larger, so that the fragment is deflected less, because the relatively strong nuclear attractive force tends to cancel out the Coulomb force. This trend was clearly shown in the figure. To show how far from the projectile the fragments can be effectively polarized, the width of angular spread was compared with that from random cause, i.e., the value from the Goldhaber model, as shown in Fig. 4. So, the greater the width away from the Goldhaber prediction, the more effectively the polarization can be produced. The figure shows that the fragments produced by stripping off up to 5 or 6 nucleons from the projectile can still be effectively polarized.

The amount of polarization reached about 5% for the selected deflection angle and the fragment momentum region. Thus, the polarization phenomenon in the fragmentation process provides a tool for beta-NMR studies on radioactive fragments.

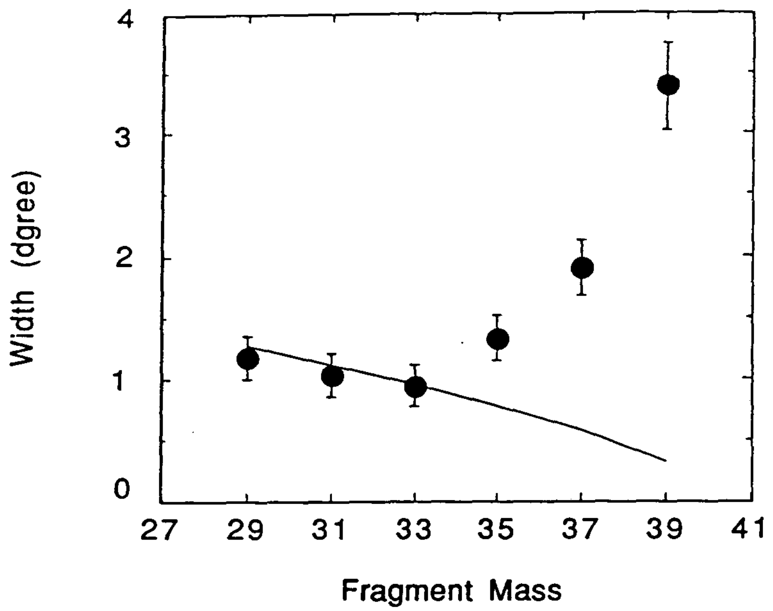

Fig. 4. Width of the angular spread of the fragments.
The solid curve indicates the predicted value from the Goldhaber model.

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