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Spin polarization of projectile fragments $^{37}$K and $^{39}$Ca has been observed in 106 *A* MeV $^{40}$Ca + $^{197}$Au collisions near the grazing angle. The fragment polarization was determined to be positive for points on the high momentum side of the distribution and negative for points on the low momentum side. At the highest energy, the spin polarization follows the same systematics observed at much lower energies, where it is believed very different reaction mechanisms dominate. A simple fragmentation model explained the observed momentum dependence of the polarization quite well.

The projectile fragmentation process in heavy-ion collisions at hundreds of MeV/nucleon has been studied mainly through measurements of the production cross sections as a function of the fragment momentum and the scattering angle on various fragments. A measurement of spin polarization of projectile fragments, in addition, should provide an important clue for further elucidation of the mechanism. Fragment polarization in heavy-ion reactions has been observed so far at low incident energies, around 10 $A$ MeV [1-4], and at 40 $A$ MeV [5]. In the present experiment, spin polarization of 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 near the grazing angle in $^{40}$Ca on Au collisions at a higher incident energy of 106 $A$ MeV.

The experimental setup is shown in Fig.1. A $^{40}$Ca primary beam was extracted from the Bevalac at the Lawrence Berkeley Laboratory once every 4 seconds, and used to bombard a 380 μm thick Au target at an energy of 118 $A$ MeV. The energy loss in the target was 25 $A$ MeV, so the average energy was 106 $A$ MeV. The production angle of the fragments was defined by a slit collimator placed 0.6 m downstream of the target. Only desired nuclides were selected and purified in the down stream of the angle defining slit by magnetic-rigidity and energy-loss analyses using a fragment separator [6]. The rigidity was selected by a pair of slit jaws at the intermediate dispersive focus of the separator, and the fragments were separated, based on the mass to charge ratio $A/Z$. Just after the jaws, the fragments passed through a plastic energy degrader, the thickness of which was adjustable by rotation. They were then separated again by the succeeding rigidity analyzer. The combination of the degrader and the analyzing magnet provide separation based on the ratio $A^{2.5}/Z^{1.5}$[7]. A desired nuclide was thus uniquely selected and was implanted in a thin catcher plate.

In order to maintain polarization during the nuclear lifetimes, single ionic crystals of KBr and CaF$_2$ were used as catchers for $^{37}$K and $^{39}$Ca, respectively, and a strong external magnetic field, $H_0$= 5.16 kOe, was applied to the catcher region in the direction normal to the reaction plane, i.e., the direction of the expected polarization. Beta rays emitted from the implanted nuclei were detected, after the beam bombarding time of 100 msec, by two sets of plastic-scintillation counter telescopes placed above and below the catcher relative to the reaction plane. In order to cancel the geometrical asymmetry in the detection system, the spin polarization was inverted using the adiabatic-fastpassage (AFP) method in the nuclear magnetic resonance (NMR) technique [8]. For the AFP, a strong rf magnetic field of 30 Oe was applied perpendicular to the external magnetic field for 10 msec.

The nuclear spin polarization of beta-emitting fragments $^{37}$K and $^{39}$Ca was measured by detecting asymmetric beta-ray distributions. The beta-ray angular distribution is given by $W(\theta) = \{1 + (v/c)\mathcal{A}P\cos\theta\}$, where $\theta$ is the angle between the polarization $P$ and the direction of the outgoing beta ray, $\mathcal{A}$ is the asymmetry parameter, and $(v/c)$ is the beta-ray velocity divided by the light velocity which is to be omitted later because it is very close to one for the present beta-ray energy. The ratio $R$ of beta-ray counts $N(\theta)$ at $\theta = 0°$ and 180° yields polarization from the relation $R=N(0°)/N(180°)=G(1+\mathcal{A}P)/(1-\mathcal{A}P)$, where $G$ is the geometrical asymmetry of the detector system. Special care was paid to measure $\mathcal{A}P$ independent of $G$ by adopting a spin manipulation technique, i.e., the NMR technique. The timing for the NMR sequence was shown in the insert of Fig.1. Each beam-count cycle had two counting sections with the spin polarization oppositely oriented. A pair of such beam-count cycles was repeated in the measurement, where the spin sequence of a beam-count cycle was reversed from that of the preceding cycle. Here, the counting sections were denoted as I,II,III, and IV. To extract the magnitude of polarization $P$ from the measured counting-rate ratios, correction factors for the finite detection angle $\eta$ of the beta-ray counters and for the admixture $(1-\alpha)$ of the other background activities were taken into account, and the polarization term $\mathcal{A}P$ in the ratio $R$ was replaced by $\alpha\eta\mathcal{A}P$. Then, $\alpha\eta\mathcal{A}P$ was extracted from the measured counting-rate ratios $R$(I) through $R$(IV) in the pairs of count sections as,

$$\alpha\eta\mathcal{A}P = \frac{\sqrt[4]{x} - 1}{\sqrt[4]{x} + 1}, \quad \text{where} \quad x = \left\{\frac{R(\mathrm{I})}{R(\mathrm{III})}\right\}\left\{\frac{R(\mathrm{IV})}{R(\mathrm{II})}\right\}. \tag{1}$$

Polarization could thus be measured free from the possible fluctuations in the beam position on the target and in the beam intensity as a function of time.

Asymmetry parameters $\mathcal{A}$ were empirically estimated[9] to be - (0.55 ± 0.02) and (0.83 ± 0.02) for $^{37}$K and $^{39}$Ca, respectively, using known *ft* values. The correction factor $\eta$ for the finite solid angle was estimated to be (0.63 ± 0.01) for both $^{37}$K and $^{39}$Ca, taking into account the trajectories of beta rays in the magnetic field between the catcher and the detectors. The fraction (1-$\alpha$) of impurities in the beta-ray counts was estimated by analyzing the beta-ray time spectra. The activity $^{38}$K($T_{1/2}$=0.93 sec) was the main contaminant for both $^{37}$K and $^{39}$Ca measurements. The $^{38}$K fraction was less than 15 % for all the data except for the one measured at the highest fragment momentum, where it reached 50 %. The depolarization effects due to spin-lattice-relaxation phenomena in these catchers were not corrected. This is because the observed relaxation times were longer than 10 sec, which is about 10 times longer than the nuclear lifetimes, as expected for ionic crystals. In addition, when the nucleus of an alkali metal is implanted in the ionic crystals containing only the same kind of positive ions, as in the present cases, 50% to 90% of the original polarization is expected to survive without being caught by the para-magnetic impurities produced in the implantation process[10].

The spin polarization observed for $^{37}$K and $^{39}$Ca are shown in Fig. 2 as a function of the fragment momentum at the production angle $\Theta = 2.0°$, together with the momentum distributions. Here, the sign of the polarization parallel to $\boldsymbol{p}_i$ x $\boldsymbol{p}_f$ is defined as positive [4], where $\boldsymbol{p}_i$ and $\boldsymbol{p}_f$ are the momentum vectors of incoming and outgoing particles. Polarization was also observed at production angles $\Theta = 1.5°$ and 2.5°. The angular dependence of these polarizations is shown in Fig. 3-a. The fragment momentum window was set at the lower momentum region for $^{37}$K and at the higher momentum region for $^{39}$Ca. It was also confirmed, in the case of $^{39}$Ca, that the sign of observed polarization was reversed at the reversed production angle, as shown in Fig. 3-a.

The observed longitudinal momentum distributions of the $^{37}$K and $^{39}$Ca fragments showed a Gaussian-like distribution as seen in Fig. 2, centered at the projectile velocity with a width of 11 $A$ and 8 $A$ MeV/c at FWHM, respectively. These widths can be well accounted for by the Fermi momenta of nucleons in the fragment, as predicted by the Goldhaber model [11] . This is a typical signature of the projectile fragmentation process in high-energy heavy-ion collisions. On the other hand, the observed angular spread of fragments was significantly wider than that expected from the Goldhaber model, and extended up to around the classical grazing angle. It is because of the strong

Coulomb repulsive force exerted by the target nucleus. Such a grazing angle deflection is defined to be positive as shown in Fig. 3-b.

The observed fragment polarization was positive for the higher momentum region of the fragment distribution, and was negative for the lower momentum region, for both $^{37}$K and $^{39}$Ca. This trend was also unchanged at the other production angles, as shown in Fig. 3-a. The observed trend in the momentum dependence of the polarization is the same as that observed for the projectile-like fragments in heavy-ion collisions at much lower energies (about 10 $A$ MeV) around the quasi elastic peak, where the transfer reaction is dominant [1-3]. The same trend has also been recently reported in the polarization of a projectile fragment $^{12}$B produced in $^{14}$N + Au collisions at an intermediate energy (40 $A$ MeV) [5]. Thus, the fragment polarization around the quasi-elastic peak persistently showed the same trend over a wide range of projectile energies for various projectile masses and numbers of nucleons removed from the projectile.

In order to explain the observed trend in the fragment polarization, a simple model [5,12] of the projectile fragmentation process was considered. The model assumes that only the part which interacts with the target during the collision is removed from the projectile, and the remaining fragment flies away unaffected (participant-spectator assumption). When the nucleon cluster moving in the forward direction in the projectile frame is removed, the remaining fragment will end up moving in the backward direction in the frame. On the contrary, when the removed cluster is moving in the backward direction, the remaining fragment will move in the forward direction. Thus the fragment momentum is distributed around the momentum corresponding to the projectile velocity, in the laboratory frame. Since the angular momentum and the linear momentum of the removed cluster in the projectile frame (therefore, those of the remaining fragment) correlates to each other, the direction of the orbital angular momentum of the remaining fragment correlates to the fragment momentum. The fragment polarization in such a process stated above was calculated by using the Wigner transform of the one-body density matrix [12,13]. As a result, the observed trend in the momentum dependence of the fragment polarization is qualitatively explained, as shown by the solid line in Fig. 2.

Although the qualitative trend was explained quite well by the model, the absolute magnitude of the experimental polarization was roughly 1/20 of the prediction. There are several reasons for the polarizations to be quenched. Since the nucleus is excited by the collision, several excited states are fed and decay to the ground state emitting gamma rays. The transfer ratios of polarization through these transitions were estimated using Clebsch-Gordan coefficients over the excited states, based on the known spin assignments of the levels. The result was fairly stable regardless of the choice of the distribution of the excited states, and more than 50% of the polarization created in the excited states was found to survive in the ground state after the transitions. There might be reorientation of the spin caused by the strong electromagnetic field near the target nucleus. The depolarization effect due to the reorientation, however, was estimated to be negligibly small. In the case of $^{39}$Ca, the polarization could be reduced by up to 30% due to the mixing of the $^{39}$Ca produced through coulomb breakup of the $^{40}$Ca, in addition to the usual fragmentation process. In the case of $^{37}$K, the loss of $^{37}$K by particle evaporation and the mixture of the $^{37}$K fed by particle evaporation from other fragments have to be considered. The fraction of the $^{37}$K fed directly by the fragmentation process was estimated using the abrasion-ablation model[14], to be 14 to 20%. Assuming no polarization in the $^{37}$K fed by particle evaporation, the total depolarization factor including spin-lattice relaxation could be 1/20 in the case of $^{37}$K. However, the total factor would be close to 1/8 in the case of $^{39}$Ca, which is not sufficient to explain the present 1/20 quenching.

The qualitative trend in the momentum dependence of the fragment polarization was well explained by a model based on the idea that the origin of the polarization is the orbital angular momentum left in the spectator fragment by the sudden disappearance of the participant nucleons from the incident projectile at the instant of the collision. We considered several depolarization effects to resolve the discrepancy between experiment and prediction in the absolute amount of polarization, but there seem to be missing depolarization effects. The model is promising. However, more studies are necessary both experimentally and theoretically for the complete understanding of the polarization mechanism. The most probable explanation for the quenching might be the negative angle deflection (see Fig. 3-b) due to the strong nuclear attractive force. The sizable spin polarization observed here provides a useful tool for studying nuclear structure using radioactive nuclear beams.

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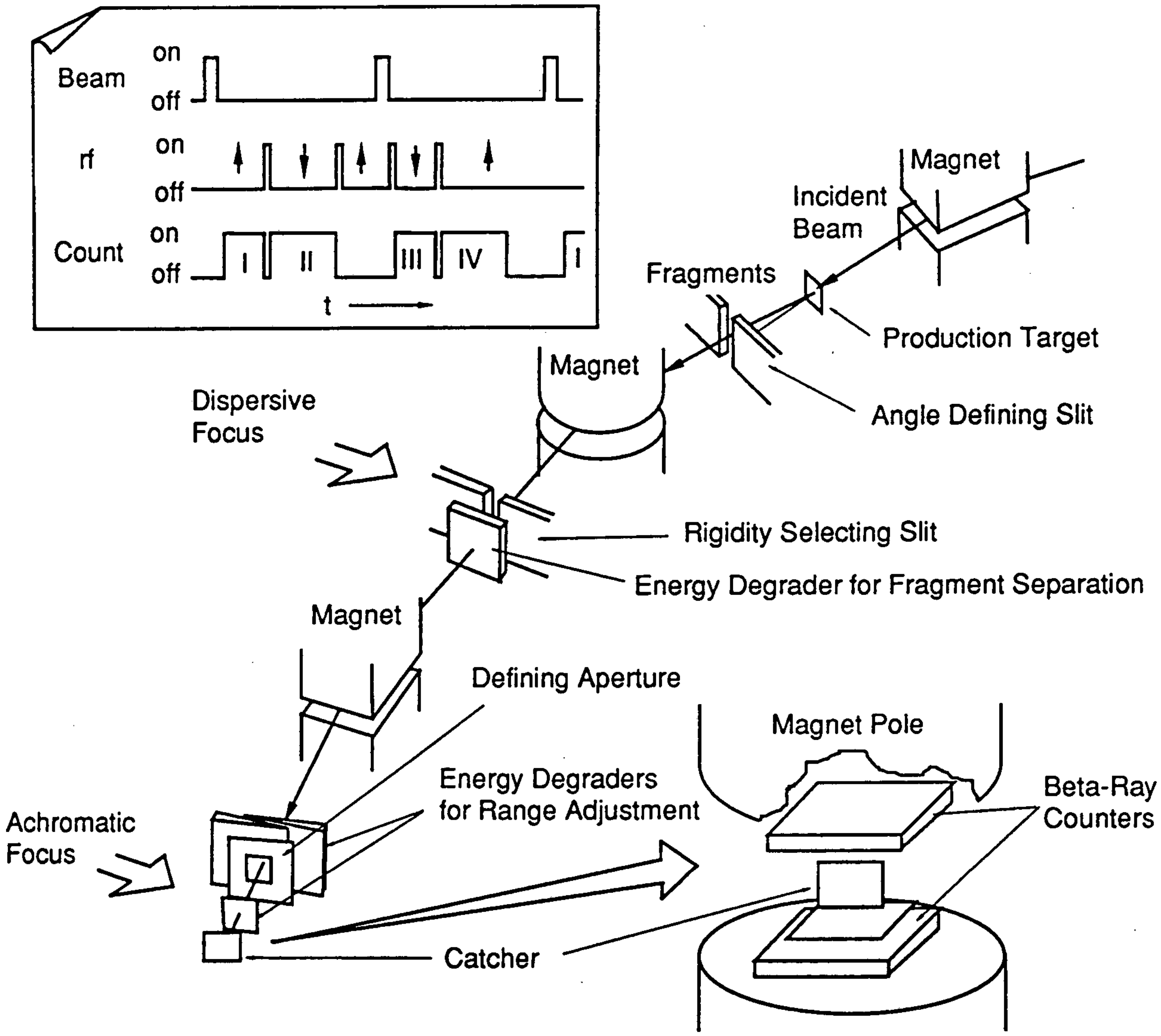

Fig. 1. Schematic view of experimental setup.

The Beam-44 fragment separator is shown without the focussing Q magnets. The insert in the figure shows the timing chart in a pair of beam-count cycles for the AFP in NMR and the data taking sequence for measuring the ratios *R*(I) through *R*(IV). The arrows show symbolically the direction of polarization.

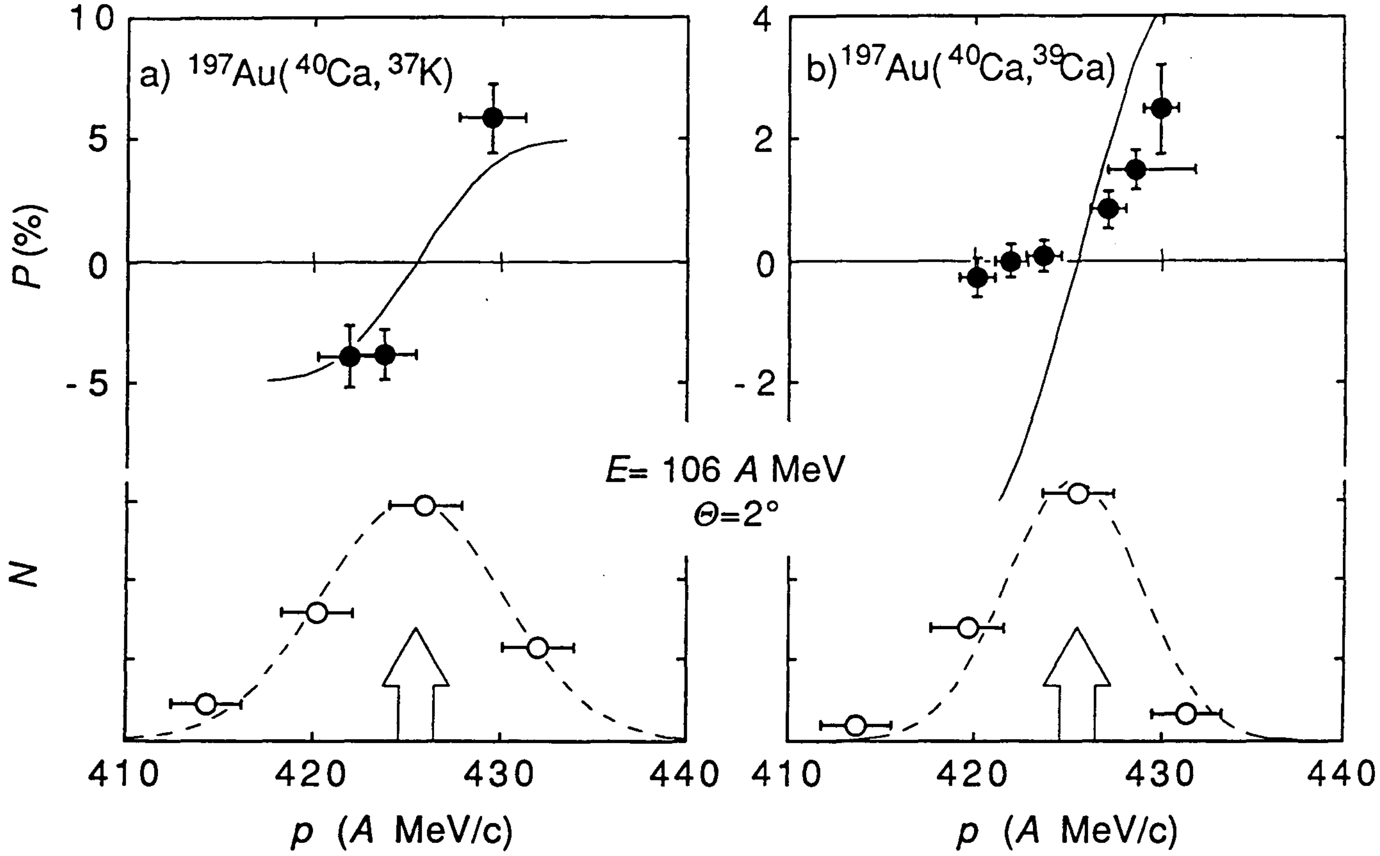

Fig. 2. Momentum dependence of fragment polarization.

The closed circles are polarizations observed at production angle $\Theta = 2°$ for $^{37}$K and $^{39}$Ca fragments produced through the $^{40}$Ca on $^{197}$Au collision at 106 *A* MeV. The open circles are the relative yields of the fragments. Horizontal bars show the momentum windows. The momentum corresponding to the beam velocity is shown by the arrows. The solid lines represent the calculated polarization by a simple model multiplied by 1/20, and the broken lines are the Gaussian fits to the momentum distribution.

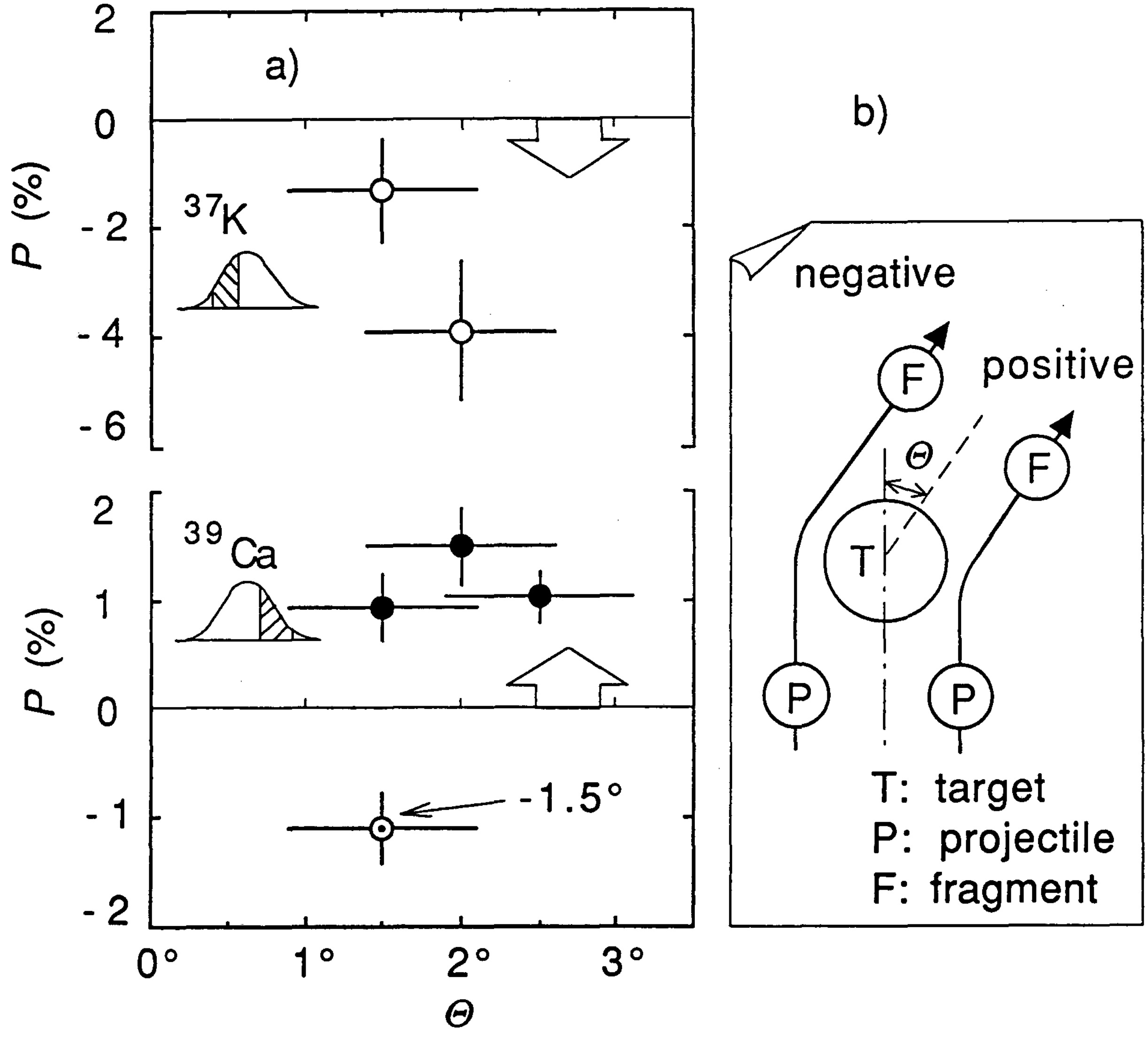

Fig. 3 Angular dependence of fragment polarization.

a) The angular acceptance is ±0.6°(rms) for both $^{37}$K and $^{39}$Ca. The momentum windows are (421.9±1.8) *A* MeV/c (low momentum side) and (429.5±2.3) *A* MeV/c (high momentum side) for $^{37}$K and $^{39}$Ca, respectively, as shown schematically in the inserts of the figure. The arrows show the classical grazing angle for the $^{40}$Ca on $^{197}$Au collision.

b) The definitions of positive and negative deflection of the fragments are shown.

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