FIRST OBSERVATION OF PROJECTILE FRAGMENT POLARIZATION IN HIGH ENERGY ION COLLISIONS

M. Ishihara

COLLOQUE DE PHYSIQUE
Colloque C6, supplément au n°22, Tome 51, 15 novembre 1990

FIRST OBSERVATION OF PROJECTILE FRAGMENT POLARIZATION IN HIGH ENERGY ION COLLISIONS

M. ISHIHARA

Faculty of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113, Japan, and Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-01, Japan

Resume -

Nous rapportons l'observation d'un nouveau phénomène de polarisation des fragments du projectile dans les collisions d'ions lourds de haute énergie. Le comportement de cette polarisation (qui vaut jusqu'à 20% au maximum et dépend de l'impulsion du fragment) s'interprète à partir d'un simple argument cinématique. Nous discutons aussi de la perspective de produire des faisceaux radioactifs (RI) pour des applications.

Abstract - A new polarization phenomenon observed for projectile fragments in high-energy heavy ion collisions is reported. Polarization was as large as about 20% at maximum and exhibited a systematic dependence on the momentum of the fragment. The behavior of the polarization is interpreted in terms of a simple kinematical argument. The prospect of producing polarized RI beam for practical applications is also discussed.

1 - INTRODUCTION

The study of unstable nuclei far from stability has been one of the traditional subjects in the field of nuclear spectroscopy. A dramatic development has recently occurred in this field at the advent of high- energy heavy-ion accelerators. The projectile fragmentation reaction has turned out to be so effective in RI production that a wide range of exotic nuclei have newly become accessible for close investigation. In particular this reaction provides unstable nuclei in a form of high- energy beam, which even facilitates the observation of nuclear reactions with unstable nuclei. Such possibilities have brought about a renewed enthusiasm for the study of exotic nuclei. On the other hand polarized nuclei are considered generally to offer unique opportunities to study spin related properties. We were thus tempted to seek for an appropriate polarization method to be applied to those projectile fragments. Such a method should further enrich the capability of the fragmentation method.

The present paper is concerned with a new spin polarization phenomenon observed for reaction products in intermediate-energy heavy-ion collisions. Unstable nuclei produced in projectile fragmentation reactions were found to exhibit sizable polarizations ranging up to about 20%. The magnitude varied in a systematic way depending on the momentum of the ejectile fragment. The phenomenon found may afford a simple and powerful polarization method to be used for exotic nuclei.

In the following we first remark on the background of the present study in Sect. 2, where the characteristics of the projectile fragmentation reaction are described in terms of a means to produce radio-active isotope (RI) beams. Plausible polarization methods relevant to the projectile fragments are also discussed shortly. The experiment of polarization measurements on fragment nuclei are described in Sect. 3, and a theoretical interpretation of the observed phenomenon is presented in Sect. 4. Finally the prospect of production and application of polarized RI beam using this phenomenon is touched in Sect. 5.

2 - PROJECTILE FRAGMENTATION REACTION FOR THE STUDY OF EXOTIC NUCLEI

The projectile fragmentation reaction is a process in which a heavy-ion projectile breaks into fragments at the collision. The fragment nucleus can be any fraction of the projectile nucleus and hence make a variety of nuclear species. The process typically occurs in high-energy heavy- ion collisions at, say, several tens MeV/u and above, where the cross section reaches the order of a barn. Also important is the property that the fragments are ejected in a narrow cone toward the beam direction and with velocities close to the beam velocity. This angular and velocity focusing is due to the Lorentz boost significant in high-energy reaction kinematics. These features combined provide a powerful method to obtain an intense beam of isotopes.

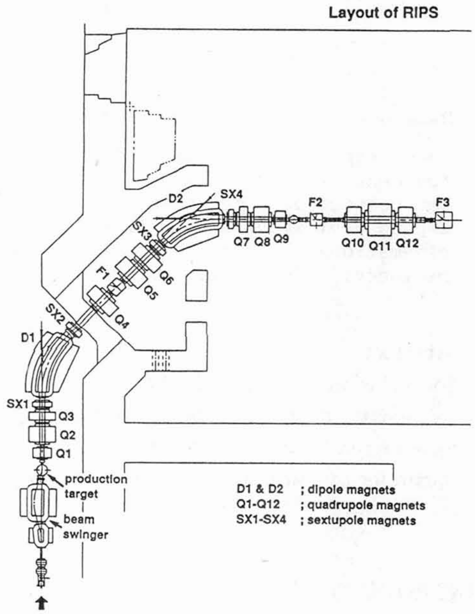

Fig. 1 - Schematic view of RIKEN projectile fragment separator. A beam swinger is placed upstream of the production target to let the ejectiles emitted at finite angles to be accepted for the analysis and transportation. An energy degrader is placed at the dispersive focal plane F1 to obtain separation of nuclear species at the achromatic focus F2. An image of F2 after being selected for a particular nuclear species is formed at F3 in an open and quiet environment.

Practical apparatus using this method have been developed at LBL-Bevalac and GANIL /1,2/. They have been used extensively and served to promote numerous new types of experiments on exotic nuclei. At RIKEN we have recently completed a similar setup of projectile fragment separator (RIPS) /3/ to be coupled with RIKEN Ring Cyclotron, which accelerates heavy ions up to 135 MeV/u. Ejectile fragments are accepted into the apparatus to be efficiently collected and be separated according to the nuclear species. As shown in Fig. 1 major components of the setup are two dipole magnets, the first to provide a momentum dispersive focal plane at F1 and the second to bring the rays back into achromatic focusing at F2. By inserting a wedge-shaped energy degrader at F1, a mass resolution of $A/\Delta A \simeq 100$ can be easily obtained at F2. Because of improved figures of acceptance and maximum magnetic rigidity this setup can produce RI beams about 100 times more intense than the earlier apparatus, yielding, e.g., several times 10^4 particles per second for a drip-line nucleus ^{11}Li and 10^6 to 10^7 particles for nuclei closer to the stability line.

Attempts to obtain polarized unstable nuclei have had a long history and a variety of ingenious methods have been so far established. However in the light of the above development, it should be worth while making a new effort to investigate a polarization method effective to the projectile fragments. Since the fragments emerge in the form of a high- energy beam, one should better consider those methods which apply to nuclei in flight.

A celebrated technique of this category has been the optical pumping method using laser beam in collinear geometry. Unfortunately the method does not work properly in this case for two reasons. There is a finite spread in the fragment velocity, causing considerable Doppler broadening at photon absorption. Moreover the fragments are often produced in charge states with atomic electrons totally stripped, yielding no resonance states useful for the optical reactions.

Another plausible method is the tilted-foil method in which fragments are let go through a tilted foil to achieve atomic polarization. Subsequent exertion of hyper-fine interaction yields nuclear polarization. As a matter of fact this possibility has been tested at LBL /4/ and a polarization close to one % has been obtained. The method requires for the fragments to be in proper charge states at the exit of the foil. Hence a finely tuned low-energy beam is to be prepared. This requirement does not fit easily with the fragments ejected in high-energy reactions.

In view of these difficulties it would be interesting to ask whether the fragments are produced with any polarization through the nuclear reaction process itself. If that is the case, it would naturally offer a most direct and simple method to obtain spin-polarized unstable nuclei. This possibility has motivated the present study.

3 - MEASUREMENT OF SPIN POLARIZATION OF PROJECTILE FRAGMENTS

The measurement of spin polarization has been made for several different species of residual nuclei in intermediate-energy projectile fragmentation reactions. Table 1 summarizes reaction systems studied. Varied projectiles and incident energies were taken. The polarization was measured as a function of the momentum of the outcoming fragment and also of the emission angle in some cases. The first experiment was made on ^{12}B fragment in ^{14}N fragmentation reaction on ^{197}Au at 40.6 MeV/u using the setup shown in Fig. 2, while the other experiments were made using RIPS. In all cases appreciable polarization of the fragment has been observed. In the following we shall focus on the first experiment since it involves typical features.

Table 1 - List of reaction systems studied for polarization measurements

FRAGMENT	PROJECTILE	ENERGY (MeV/u)	TARGET	ANGLE (DEGREE)	P_{MAX} (%)
^{12}B	^{14}N	40.6	^{197}Au	5	17
^{12}B	^{15}N	111.6	^{197}Au	2	4
^{12}B	^{15}N	111.6	^{197}Au	4	6
^{12}B	^{15}N	111.6	^{197}Au	6	7
^{13}B	^{15}N	111.6	^{197}Au	2	5
^{13}B	^{15}N	111.6	^{197}Au	4	7
^{12}N	^{16}O	131.5	^{197}Au	2	2
^{39}Ca[a)]	^{40}Ca	106	^{197}Au	2	3
^{37}K [a)]	^{40}Ca	106	^{197}Au	2	6

[a)]Studied at LBL /9/

Fig. 2 illustrates a schematic view of the experimental setup. A 97-mg/cm^2 thick ^{197}Au target was bombarded with ^{14}N ions from RIKEN Ring Cyclotron. The effective incident energy at one-half of the target thickness was 39.4 MeV/u. The relatively thin target was used so that the original momentum distribution of the emerging fragment was not distorted too significantly by the energy loss. Fragments of ^{12}B emitted at an angle of $\theta_L = 5°$ were transmitted through a dipole magnet to be analyzed with respect to momentum, and were focused with a quadrupole magnet downstream. The fragments were stopped in a 200-mm thick Pt foil after passing through an energy degrader. A collimator with a 7 mm diameter hole placed 7 cm upstream of the stopper served to define the fragment momentum with $\Delta p_f/p_f = \pm 0.5\%$ and also to separate ^{12}B from the other isotopes. Thus only ^{8}Li and ^{13}B fragments remained as noticeable but weak contamination.

A static magnetic field of $B = 58.3$ mT normal to the reaction plane was applied to the stopper to preserve the polarization of implanted ^{12}B fragments. The spin polarization P of the ^{12}B fragment was measured using a standard method based on beta-ray asymmetry. The beta ray in the decay of ^{12}B to ^{12}C was recorded at scintillation counter telescopes located above and below the stopper. The angular distribution of beta rays from polarized ^{12}B is given as $W(\theta) = 1 - (v/c)P\cos\theta$, where θ and v/c are the emission angle and velocity of the beta particle, respectively. The angle is relative to the polarization axis which is defined according

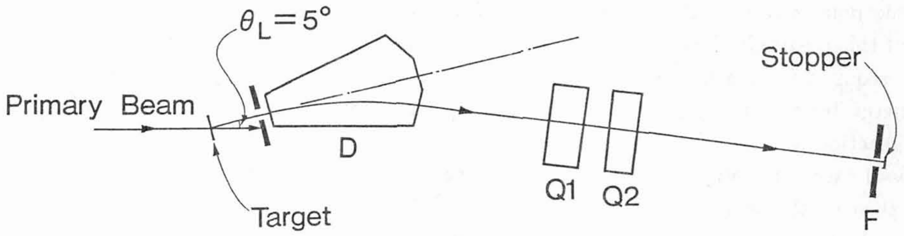

Fig. 2 - The setup for the polarization measurement for projectile fragment is schematically shown. Beta counters and NMR apparatus are installed around the stopper.

to the Basel convention. Thus the up vs. down ratio of beta-ray counting rates may be approximated as $U/D = (1-P)/(1+P)$ and was used to determine P. The experiment involved other techniques to elaborate the data such as use of a pulsed beam and incorporation of the adiabatic fast passage method to invert the polarization direction.

Fig. 3 shows the experimental results after correction for the beta-ray impurities and the other minor effects. The lower portion illustrates the momentum spectrum of the ^{12}B fragment. The shape is nearly Gaussian with a maximum around the momentum corresponding to the beam velocity. It has a slight asymmetry tailing more toward lower momenta. The width σ of the distribution deduced from higher momentum side corresponds to $\sigma_0 = 74$ MeV/c when it is fitted with the Goldhaber formula /5/ ($\sigma = \sigma_0[A_F(A_p - A_F)/(A_p - 1)]^{1/2}$ where A_F and A_p are fragment and projectile masses). This is somewhat smaller than those obtained at relativistic energies. Whole these features conform to the characteristic trends of projectile fragmentation process at intermediate energies.

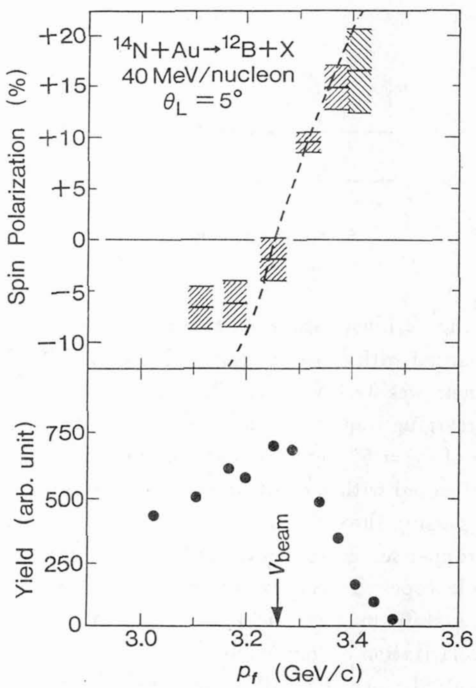

Fig. 3 - Experimental results on the ^{12}B fragments in the ^{14}N + ^{197}Au reaction at 40.6 MeV/u. The yield and polarization spectra as a function of the momentum of the ^{12}B ejectile are shown in the lower and upper portions, respectively. The horizontal and vertical lengths of the hatched area for each data point of P respectively correspond to the sizes of error of P and uncertainty of p_f involved. The dotted line represents a calculated curve as described in text.

The upper part of Fig. 3 shows the polarization of ^{12}B as a function of the fragment momentum. Polarization as large as 17% was observed. A remarkable feature is the dependence on the momentum p_f. The polarization varies almost linearly with p_f, changing sign from positive at higher momenta to negative at lower momenta. The zero crossing occurs around the momentum corresponding to the peak of the momentum spectrum. There is a small difference in the magnitude of P between the high and low momentum sides. This may be related to a mechanism which causes the slight asymmetry in the shape of momentum spectrum.

4 - INTERPRETATION AND DISCUSSION ON THE OBSERVED POLARIZATION PHENOMENON

The projectile fragmentation reaction is supposed to be a collision process in which nucleons of the projectile in the volume overlapping with the target nucleus are removed and the rest of the projectile emerges as a projectile fragment. There have been several theoretical models proposed to describe the process /6,7,8/ on the basis of experimental data on momentum and angular distributions. A common ingredient of these theories is the assumption that the fragment part remains as a spectator through the reaction. This implies that the linear momentum of the fragment portion remains the same in the Lab. frame before and after the reaction to be eventually recorded as p_f. Similarly the internal angular momentum J of the fragment portion should be conserved through the reaction.

The observed correlation between p_f and $P = J_z/J$ can be consistently described in terms of the above assumptions of general nature, as schematically illustrated in Fig. 4. We note that $\vec{p}_f$ and $\vec{J}$ be given by the expressions, $\vec{p}_f = m\vec{v}_0 - \vec{k}_r$ and $\vec{J} = -\vec{R} \times \vec{k}_r$, where m and $\vec{v}_0$ are the fragment mass and the projectile velocity, respectively, and $\vec{R}$ is the position vector pointing from the center of the fragment to that of the removed portion at the instant of the reaction. The important variable $\vec{k}_r$ stands for the linear momentum in the rest frame of projectile which is carried by the removed portion before the collision. These relations are obtained by artificially dividing the projectile before the collision into two parts and considering the partitions of the linear and angular momenta between the two. The latter relation arises since the vector sum of the internal angular momenta of the two parts and the relative angular momentum between them, $(\vec{R} \times \vec{k}_r)$, should make up the projectile spin. For simplicity we assume zero spin of the projectile and ignore the intrinsic spins of removed nucleons.

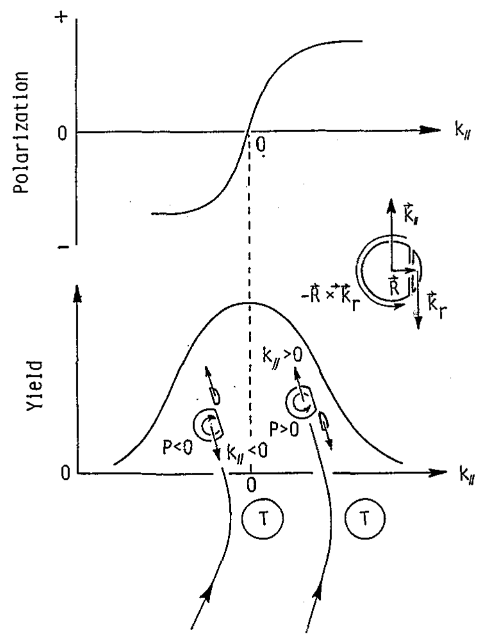

Fig. 4 - Schematic illustration of the projectile fragmentation process. Inherent correlation between P and p_f is kinematically involved via the conservation of linear and angular momenta.

An interesting aspect is that both $\vec{p}_f$ and $\vec{J}$ are given as a function of a same parameter, $\vec{k}_r$. Thus a close correlation is established between the two variables. If the reaction occurs for a projectile with $\vec{k}_r$ parallel (anti-parallel) to the beam direction, the resultant fragment should carry lower (higher) momenta and negative (positive) polarization. The zero polarization is expected to occur for events with $\vec{k}_r$ normal to the beam, which in average corresponds to p_f for the beam velocity. The observed behavior of the sign of P with p_f nicely agrees with this simple argument. According to the above relations, the magnitude of P as well as the momentum spectrum is expected to be symmetric between the low and high momentum sides. The slight reduction in size of P and skewed spectral shape of the yield distribution both observed at lower momentum side indicate some contribution from more complicated reaction processes for that momentum region.

A more quantitative estimate of the polarization may be obtained by considering a realistic $\vec{k}_r$ distribution. Such a distribution may be given in terms of the Wigner transform of the one-body density matrix. In the present case we assume that the two protons removed from ^{14}N are originated from specific valence orbitals of $1p_{1/2}$ and $1p_{3/2}$. Indeed the ground state of ^{12}B has such a configuration. Using harmonic-oscillator wave functions for these orbitals, the $\vec{k}_r$ distribution of removed nucleons at the surface of the projectile was obtained. By incorporating this distribution with the basic expressions for $\vec{p}_f$ and $\vec{J}$, spectra of the yield and P of ^{12}B vs. $\vec{p}_f$ were calculated. The dotted curve shown in the upper part of Fig. 3 corresponds to the calculation. Attenuation effects due to the non-zero spin of ^{14}N, the nucleon intrinsic spins and γ-decay population feeding from excited-states of ^{12}B are also taken into account among other effects. The agreement with experiment is fairly good.

According to this treatment the magnitude of polarization is dependent on the coupling scheme of angular momenta of individual removed nucleons. A largest polarizaion is expected to occur when the net spin of the removed portion is constructed with a spin coupling of a stretched configuration. In contrast attenuation should occur for anti-parallel spin coupling. This indicates a tendency of larger P for projectile fragments with smaller number of removed nucleons.

In the above argument we have implicitly assumed that the reaction proceeds along a near-side trajectory. If a far-side trajectory is relevant, the relation of the sign of P with p_f is to be reversed. There has so far been little experimental evidence to decide relative importance between the two types of trajectories. On the other hand the present result provides a clear indication in favor of near-side trajectories.

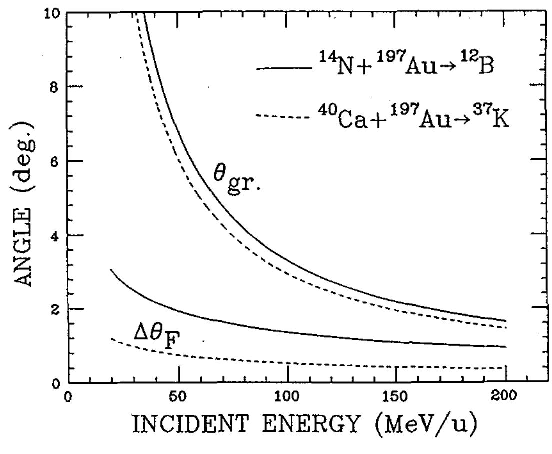

Fig. 5 - The grazing angle $\theta_{gr.}$ and the angular dispersion $\Delta\theta_F$ of fragmentation are compared for the ^{197}Au(^{14}N,^{12}B) and ^{197}Au(^{40}Ca,^{37}K) reactions at different incident energies. The former is calculated assuming the Coulomb trajectory and latter is based on the Goldhaber formula /5/.

A criterion for the dominance of near-side trajectories may be given by a condition that the repulsive Coulomb deflection should be larger than the effect of angular dispersion caused by the Fermi motion of nucleons inside the projectile nucleus. Because of the peripheral nature of the reaction the deflection angle of the projectile fragment may be distributed around the grazing angle $\theta_{gr.}$. The fragment emission angle may be further affected by a recoil effect at the fragmentation which may be expressed by $\Delta\theta_F = \sigma/p_f$. Thus near-side trajectories may be dominant when $\theta_{gr.}$ is sufficiently large as compared to $\Delta\theta_F$. In Fig. 5 these two variables are compared for different reaction systems and incident energies. Near-side collisions are favored at relatively low energies and/or with heavier ions.

So far we have only discussed the result of the ^{14}N+^{197}Au reaction at 40.6 MeV/u leading to ^{12}B. The kinematical argument presented above is in good accord with the experiment. In view of the fairly general nature of the argument, similar behavior of P vs. p_f may be anticipated for other reactions. Indeed the result on a considerably different reaction $^{197}Au(^{40}Ca,^{37}K)$ at 106 MeV/u has exhibited the characteristic momentum dependence of P expected from the kinematical argument /9/.

On the other hand the preliminary results for reactions at higher energies and with lighter projectiles appear to show somewhat different features, though the details will be described elsewhere. While significant magnitudes of P are maintained as indicated in Table 1, the momentum dependence does not necessarily reproduce the particular behavior that P varies almost linearly with p_f crossing zero in midway. As the incident energy goes up, a larger contribution from far-side collisions is anticipated (see Fig. 5). Such an effect might be relevant to the variation of the phenomenon.

5 - PROSPECT OF PRODUCING A POLARIZED RI BEAM

The initial motivation of the present experiment was to search for a proper polarization method for projectile fragments. The observed phenomenon appears to suffice for such a quest by affording several useful features. The reaction process itself generates polarization. No additional procedures are required except for selectively accepting those fragments which are emitted at a finite angle and with momentum in a particular range. Thus a standard setup of projectile-fragment separator may be used to obtain polarized fragments. For example RIPS can accept and transport fragments emitted at a finite angle (up to 15°) and yield an achromatically and spatially focused beam of unstable nuclei at the exit. In the procedure the nuclear species and momentum of the fragments are properly selected. The beam would involve a certain energy spread of a few % to profit in the yield. Average polarization of few to several % may be achieved for a variety of isotopes.

The validity for practical application may be decided by the beam intensity. This should depend on the nuclear species of interest as well as the primary beam intensity available. As compared to the case of unpolarized beam, a certain reduction of intensity is inevitable, since the ranges of emission angle and momentum should be limited to avoid cancellation in P. As an example we can estimate the intensity of a possible polarized beam of ^{12}B based on the data for the $^{197}Au(^{15}N,^{12}B)$ reaction at 112 MeV/u. An intensity of $I \simeq 10^4$ particles/sec may be obtained by accommodating fragments emitted at 2 to 4 degrees and with momentum within a 4% range in the neighborhood of the yield peak (In this case of a higher-energy reaction the position of zero-crossing of P is somewhat shifted from the peak of the momentum spectrum providing a more favorable situation for gaining intensity). A polarization of more than 3% may be maintained. These figures correspond to less than 1 hour of measurement time required to determine an unknown g-factor of a nucleus within an accuracy of 1%. Still more powerful beams may be obtained for isotopes closer to the stability line.

The polarized beams thus obtained may be used either directly, e.g., to study secondary nuclear reactions or by being implanted into a material for off-beam experiments. Obviously no wet chemistry is involved in RI treatment. A straightforward application of those beams may be to determine unknown g-factors of exotic nuclei. There are about 160 of such nuclei within the limited mass region of $A \leq 50$. The fairly large figures of merit (P^2I) anticipated may also provide improved opportunities for more sophisticated experiments such as on symmetry problems. Another possibility accessible is to use the polarized nuclei as a probe of microscopic structures of condensed matter. NMR techniques are to be incorporated. In this respect an effort is being made presently to prepare polarized beam of ^{13}O, which is a rare oxygen RI useful for NMR.

6 - SUMMARY

We have shown a polarization phenomenon which has been found for different projectile fragments in high-energy heavy ion collisions. Those fragments exhibited polarization ranging up to $\sim$ 20%, which varied with fragment momentum. A typical behavior was that P varies almost linearly with p_f and changes the sign around the middle of the momentum spectrum. A simple kinematical argument based on models of fragmentation reactions nicely explains this feature. On the other hand somewhat modified behaviors were seen for the results of higher energies suggesting a more complicated nature of the reaction.

Using this phenomenon an intense beam of polarized nuclei can be easily obtained. The celebrated capability of the projectile fragmentation reaction is to be exploited to gain the intensity. In the case of ^{12}B for example, a beam of P more than 3% and $I \simeq 10^4$ pps may be obtained. The method offering such figures of merit should well compete with other useful techniques for polarization. In extending the method to a variety of isotopes, further studies are desirable to understand a whole scope of the reaction mechanism relevant to the polarization phenomenon.

The present work has been made in collaboration with the following people; K. Asahi, N. Inabe, T. Ichihara, T. Kubo, H. Okuno, M. Adachi, H. Takahashi, M. Kouguchi, M. Fukuda, D. Mikolas, D. J. Morrissey, D. Beaumel, T. Shimoda, H. Miyatake and N. Takahashi. I specially acknowledge K. Asahi, T. Kubo and H. Okuno for their cooperation in preparing this manuscript.

REFERENCES

/1/ T.J.M. Symons, Y.P. Viyogi, G.D. Westfall, P. Doll, D. E. Greiner, H. Faraggi, P.J. Lindstrom, D.K. Scott, H.J. Crawford, C. Mcparland, Phys. Rev. Lett. 42 (1979) 40

/2/ R. Anne, D. Bazin, A.C. Mueller, J.C. Jacmart, and M. Langevin, Nucl. Instru. Methods A257 (1987) 215

/3/ T. Kubo and M. Ishihara, Proc. Second IN2P3-RIKEN Symp. on Heavy Ion Collisions, Obernai, France, April 9-12, 1990, edited by B. Heusch and M. Ishihara, World Scientific (1990) p. 40

/4/ Y. Nojiri, K. Matsuta, T. Minamisono, K. Sugimoto, K. Takeyama, K. Omata, Y. Shida, I. Tanihata. T. Kobayashi, S. Nagamiya, K. Ekuni, S. Shimoura, J.R. Alonso, G.F. Krebs, T.J.M. Symons, Nucl. Instr. Methods B33 (1988) 193

/5/ A.S. Goldhaber, Phys. Lett. B53 (1974) 306

/6/ W.A. Friedman, Phys. Rev. C27 (1983) 569

/7/ J. Hufner and M.C. Nemes, Phys. Rev. C23 (1981) 2538

/8/ C.Y. Wong and K. Van Bibber, Phys. Rev. C25 (1982) 2990

/9/ K. Matsuta *et al.*, Contribution to this conference (48F)