Production of spin-controlled rare isotope beams

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The degree of freedom of spin in quantum systems serves as an unparalleled laboratory where intriguing quantum physical properties can be observed, and the ability to control spin is a powerful tool in physics research. We propose a method for controlling spin in a system of rare isotopes which takes advantage of the mechanism of the projectile fragmentation reaction combined with the momentum-dispersion matching technique. The present method was verified in an experiment at the RIKEN RI Beam Factory, in which a degree of alignment of 8% was achieved for the spin of a rare isotope 13-14Al. The figure of merit for the present method was found to be greater than that of the conventional method by a factor of more than 50.

The immense efforts expended to fully comprehend and control quantum systems since their discovery are now entering an intriguing stage, namely the controlling of the degree of freedom of spin1-3. The case of nuclear systems is not an exception. In recent years, nuclear physicists have been focusing their efforts on expanding the domain of known species in the nuclear chart, which is a two-dimensional map spanned by the axes of N (number of neutrons) in the east direction and Z (number of protons) in the north direction. The key technique used to explore the south eastern (neutron-rich, or negative in isospin T) and north western (proton-rich, or positive in T) fronts of the map has been the projectile fragmentation (PF) reaction, in which an accelerated stable nucleus is transmuted into an unstable one through abrasion on collision with a target. Several new facilities for providing rare-isotope beams by this technique, such as RI Beam Factory (RIBF; ref. 6) in Japan, FRIB (refs 7-9) in the United States, and FAIR (refs 10-12) in Europe, have been completed or designed for exploration of the frontiers of the nuclear chart. Beyond such efforts towards exploring the N and Z axes, nuclear spin may be a ‘third axis’ to be pursued. The study reported in the present article concerns the control of the spin orientation of an unstable nucleus produced in a rare-isotope beam at such fragmentation-based rare-isotope beam facilities. The ability to control spin, when applied to state-of-the-art rare-isotope beams, is expected to provide unprecedented opportunities for research on the nuclear structure of species situated outside the traditional region of the nuclear chart, as well as for application in materials sciences, where spin-controlled radioactive nuclei implanted in a sample could serve as probes for investigating the structure and dynamics of condensed matter3-5.

The fragmentation of a projectile nucleus in high-energy nucleus–nucleus collisions is described remarkably well by a simple model that assumes the projectile fragment produced in the PF reaction to be a mere ‘spectator’ of the projectile nucleus; as a spectator, this fragment survives frequent nucleon–nucleon interactions, and the other nucleons (‘participants’) are abraded off through the reaction3, as illustrated in Fig. 1. In the model, the projectile fragment acquires an angular momentum (in other words, a nuclear spin), whose orientation is determined simply as a function of the momentum of the outgoing fragment. Although the spin orientation may practically be reduced owing to cascade y decays following the fragmentation, we assume that a significant amount of spin orientation survives in the fragment. Here the degrees of spin orientation of rank one and two, in particular, are referred to as spin polarization and spin alignment, respectively. This implies a unique relation between the spin orientation and the direction of the removed momentum p, as illustrated in Fig. 1, which can be used as an obvious means for producing spin-oriented rare-isotope beams. One advantage of this method of orienting the fragment spin is that the resulting spin orientation does not depend on the chemical or atomic properties of the rare-isotope. However, the method also shows a drawback in the sense that the spin orientation thus produced in the PF reaction tends to be partially or completely attenuated because the fragmentation generally involves the removal of a large number of nucleons from the projectile. This is quite a non-negligible flaw with respect to the yields attainable for spin-oriented beams as high-intensity primary beams are only available for a limited set of nuclear species, and consequently in most cases rare-isotopes of interest must be produced through the removal of a large number of nucleons from the projectile. Accordingly, there has been high demand for a new technique for preventing the attenuation in spin orientation caused by large differences in mass between the projectile and the fragment. In this paper, we present a method for producing highly spin-aligned rare-isotope beams by employing a two-step PF process in combination with the momentum–dispersion matching technique.

Figure 2 illustrates three different schemes for producing spin-aligned rare-isotope beams, where each scheme uses a different configuration of elements, namely primary and secondary targets.

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and slits for selection. The most basic scheme employs the configuration in Figure 2a, in which a nucleus of interest is directly produced from a primary beam through a single occurrence of the PF (a single-step PF reaction). As stated earlier, this scheme suffers from the drawback that the degree of spin alignment tends to be small. To overcome this problem, the configuration in Figure 2b adopts a two-step PF reaction, where a beam of nuclei produced in the first PF reaction (secondary beam) is used to obtain a beam of the nuclide of interest through a second PF reaction. In particular, using a slit installed at a momentum-dispersive focal plane, the particles forming the secondary beam are chosen to be of a nuclide containing one proton or neutron more than the nuclide of interest. Thus, the target rare-isotope beam is produced via a PF reaction in which only one proton or neutron is removed. For the rare-isotope beam obtained from the drawback that the degree of spin alignment tends to be small, this scheme suffers from the angular momentum \( j \) of the projectile nucleus, owing to the removal of nucleons that, before collision, were in internal motion in the projectile nucleus (Fermi motion). Here, \( p_0 \) is the sum of momenta of the removed nucleons (participants), and \( R_0 \) is the position vector of the participants in the projectile rest frame. Furthermore, the linear momentum \( p_{PF} \) of the fragment is given as \( p_{PF} = p_0 - p_n \). Thus the orientation of the spin is \( I_{PF} = R_0 \times (p_0 - p_{PF}) \) is determined clearly as a function of the momentum \( p_{PF} \) of the outgoing fragment. In the figure, the axis of polarization is perpendicular to the reaction plane, while the axis of alignment is parallel to the beam axis.

Insets a–c illustrate cases which produce spin orientation for the fragments in the left wing, centre and right wing of the momentum distribution, respectively.

Figure 1 | Principle of producing spin orientation in PF reaction. A projectile with an initial momentum \( p_0 \) is incident on the target. In a ‘participant-spectator’ model, the nuclear spin \( I_{PF} \) of the fragment arises from the angular momentum \( R_0 \times (−p_n) \) with respect to the centre of mass of the projectile nucleus, owing to the removal of nucleons that, before collision, were in internal motion in the projectile nucleus (Fermi motion). Here, \( p_0 \) is the sum of momenta of the removed nucleons (participants), and \( R_0 \) is the position vector of the participants in the projectile rest frame. Furthermore, the linear momentum \( p_{PF} \) of the fragment is given as \( p_{PF} = p_0 - p_n \). Thus the orientation of the spin is \( I_{PF} = R_0 \times (p_0 - p_{PF}) \) is determined clearly as a function of the momentum \( p_{PF} \) of the outgoing fragment. In the figure, the axis of polarization is perpendicular to the reaction plane, while the axis of alignment is parallel to the beam axis.

Insets a–c illustrate cases which produce spin orientation for the fragments in the left wing, centre and right wing of the momentum distribution, respectively.
Comparison of three schemes for producing a spin-aligned rare-isotope beam of $^{32}$Al from a primary beam of $^{48}$Ca. The graphs below each scheme represent the typical momentum distribution and the corresponding alignment, with abscissas representing the momentum $p$ of $^{32}$Al.

**a.** Single-step PF method. The $^{32}$Al beam is directly produced from $^{48}$Ca. As PF involves a large number of nucleons, the expected spin alignment is small.

**b.** Two-step PF method. $^{32}$Al is produced via an intermediate nucleus $^{33}$Al. The expected spin alignment is high, whereas the production yield is low because of the two-fold selection with momentum slits.

**c.** Two-step PF method with dispersion matching. Direct selection of the change in momentum $\Delta p$ in the second PF can be achieved by placing a secondary target in the momentum-dispersive focal plane and a slit in the double-achromatic focal plane, because the momentum spread $\Delta p$ of the incident beam is compensated for by fulfilling the condition of momentum-dispersion matching. The effect of momentum-dispersion matching is represented by graphs connected by a broad arrow. This method yields an intense spin-aligned rare-isotope beam while avoiding cancellation between the opposite signs of spin alignment caused by the momentum spread $\Delta p$.

The $^{32}$Al nucleus is known to exhibit an isomeric state $^{32m}$Al (ref. 24) at 957 keV with a half-life of 200(20) ns. The spin and parity of $^{32m}$Al have not been fixed among the 4$^+$ and 2$^+$ candidates. It is known that $^{32m}$Al undergoes de-excitation by $E2$ transition$^{25}$ with emission of $\gamma$ rays with an energy of 222 keV and subsequently decays in cascade to the ground state by emitting 735-keV $\gamma$ rays. Figure 4a shows a $\gamma$-ray energy spectrum measured with the Ge detectors, where 222-keV de-excitation $\gamma$ rays are clearly observed as a peak. The time variations $N_{32}(t)$ and $N_{33}(t)$ of the intensities for this peak obtained with detectors pairs Ge 1–3 and Ge 2–4, respectively, are presented in Fig. 4b, in which the corresponding abscissas represent the time difference of the signals at either of the Ge detector pairs relative to the beam particle signal at a plastic scintillator placed in front of the stopper crystal. The $R(t)$ ratio evaluated according to equation (1) is shown in Fig. 4c.

From the least $\chi^2$ fitting of the theoretical function of equation (2) to the experimental $R(t)$ ratio of equation (1), we obtained the degree of spin alignment as $A = 8(1)\%$, and the $g$-factor of $^{32m}$Al was determined for the first time to be $g = 1.32(1)$. Also, the spin and parity were assigned to be $I^g = 4^+$ through comparison of the $g$-factor with theoretical calculations. Detailed analysis and extended discussion regarding the $^{32}$Al nuclear structure based on the obtained $g$-factor and spin-parity will be presented elsewhere.

A remeasurement of the degree of spin alignment was also performed during the experiment, in which the momentum acceptance in the F5 focal plane was narrowed to be $\pm 0.5\%$, while maintaining other conditions unchanged. This measurement corresponded to the two-step PF reaction without dispersion matching (the case shown in Fig. 2b). The degree of spin alignment derived from this measurement, 9(2)%, is consistent with the above value obtained with the proposed method, 8(1)%, thus confirming...
that the present method of producing spin-aligned rare-isotope beams is valid and performs well.

An additional experiment was carried out to compare the performance of the present method with that of the single-step method. $^{32}$Al was directly produced in a PF reaction of a $^{48}$Ca beam on a 4-mm thick Be target. The thickness of the production target was chosen such that the energy loss in the target was comparable with the Goldhaber width (expected to be 4% in this case). To compare with the case of the two-step method under the equivalent condition, this measurement was carried out by selecting a momentum region of $\pm 0.5\%$ around the centre of fragment momentum distribution. For this momentum region a maximum prolate alignment is expected. As a result, the spin alignment was measured to be less than $0.8\%$ ($2\sigma$ confidence level). A comparison of the two methods is summarized in Table 1. The figure of merit (FOM) for the production of such spin-aligned rare-isotope beams should be defined to be proportional to the yield and the square of the degree of alignment. In the measurement with the single-step PF reaction, a primary beam whose intensity was deliberately attenuated by a factor of 1/100 was used to avoid saturation in the counting rate at the data acquisition system. Here, the FOM was compared on the basis of actual effectiveness without correction for the attenuation, in which the resulting FOM for the new method was found to be improved by a factor of more than 50. Note that the degree of spin alignment in the single-step PF reaction could not be determined within a measurement time comparable to that of the two-step PF reaction. The superiority in FOM of the new method over the single-step PF reaction method should be even more pronounced for nuclei located farther from the primary beam.

Theoretically, the maximum of the spin alignment for the case of single-nucleon removal from $^{33}$Al with a momentum acceptance of $\pm 0.15\%$ is estimated to be $30\%$ in a way similar to that described in refs 26,27. The estimation is based on a model, where the cross-section for the abrasion of one nucleon leading to a fragment of substrate $m$ with momentum $p$ is proportional to the probability of finding a particle of substance $m$ with momentum $p$ at the surface of the target nucleus. The maximum evaluated in this way is in fact four times greater than that obtained experimentally, which may result from de-excitation from higher states populated through the FF reaction, such as the $4^-$ (ref. 28) and $1^-$ (ref. 25) states. This suggests that the ability to select the reaction path in populating the state of interest is key to achieving augmented spin alignment. Thus, spin alignment via PF reactions depends strongly on both the reaction mechanism and the nuclear structure. Under these circumstances, the achieved degree of alignment, $1/4$ of the theoretical maximum which was obtained despite the situation that the reaction path to the isomeric state was not unique, is rather satisfactory. If we choose a nucleus produced by a unique reaction path, a degree of spin alignment closer to the theoretical maximum might be possible to achieve.

Figure 5 shows the result of simulating the accessibility of unstable nuclei via the two-step PF method (red region) and the conventional method (blue region). In the simulation, the primary beam is assumed to be restricted to within a class of beam species which are available with high intensities at RIBF (ref. 6). Clearly, the adoption of the two-step method greatly expands the set of accessible nuclei in the nuclear chart. As well as the simplest case that the nucleus of interest was produced through the one-nucleon removal reaction as presented in this article, the two-step scheme also allows one to use few-nucleon removal reactions as well as few-nucleon pickup reactions, which are known to produce significant spin orientation.

The FOM of our proposed method was found to be more than 50 times greater than that of the conventional single-step
The de-excitation of Fig. 3. The Cu stopper is 3.0 mm in thickness and 30 mm in length. The Cu stopper serves to absorb the 30 mm of the target and to prevent the 30 mm of the target from being lost. The Cu stopper is placed at a distance of 7.0 cm from the stopper and at angles of 45° and 135° with respect to the beam axis. The relative detection efficiency was 35% for one and 15–20% for the other three. A plastic scintillator of 0.1 mm in thickness was placed upstream of the stopper, the signal from which provided the time-zero trigger for the TDPAD measurement. The TDPAD apparatus enabled us to determine the spin of the secondary PF reaction is 50%; and an external magnetic field be 1/1,000, as usual; the isomeric to ground state population ratio for the de-excitation in the Cu crystal, and de-excitation 1520% for the other three. A plastic scintillator of 0.1 mm in thickness was placed located at a distance of 7.0 cm from the stopper and at angles of 45° and 135° with respect to the beam axis. The relative detection efficiency was 35% for one and 15–20% for the other three. A plastic scintillator of 0.1 mm in thickness was placed upstream of the stopper, the signal from which provided the time-zero trigger for the TDPAD measurement. The TDPAD apparatus enabled us to determine the spin alignment as well as the g-factor of 32m Al by observing the changes in anisotropy of the de-excitation γ rays emitted from spin-aligned 32m Al in synchronization with the spin precession in the presence of an external magnetic field.

PF reaction in this particular case and numerical simulations indicate that the present method greatly expands the domain of accessible nuclei in the nuclear chart. Such an ability to control spin, when applied to state-of-the-art rare-isotope beams, is expected to provide unprecedented opportunities for research on the nuclear structure of species situated outside the traditional region of the nuclear chart, as well as for applications in material research where spin-controlled radioactive nuclei implanted in a sample serve as probes into the structure and dynamics of condensed matter.

Methods

Time-differential perturbed angular distribution (TDPAD) methods: The 32Al beam was stopped in a Cu crystal stopper mounted on the experimental apparatus for TDPAD measurements, which was placed in a focal plane after the achromatic focal plane F7. The TDPAD apparatus consists of a Cu crystal stopper, a dipole magnet, Ge detectors, a plastic scintillator and a collimator, as shown in the inset of Fig. 3. The Cu stopper is 3.0 mm in thickness and 30 × 30 mm² in area, and the dipole magnet provides a static magnetic field B₀ = 0.259 T. 32m Al are implanted into the Cu crystal, and de-excitation γ rays are detected using four Ge detectors located at a distance of 7.0 cm from the stopper and at angles of ±45° and ±135° with respect to the beam axis. The relative detection efficiency was 35% for one and 15–20% for the other three. A plastic scintillator of 0.1 mm in thickness was placed upstream of the stopper, the signal from which provided the time-zero trigger for the TDPAD measurement. The TDPAD apparatus enabled us to determine the spin alignment as well as the g-factor of 32m Al by observing the changes in anisotropy of the de-excitation γ rays emitted from spin-aligned 32m Al in synchronization with the spin precession in the presence of an external magnetic field.

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References

1. Wolf, S. A. et al. Spintronics: A spin-based electronics vision for the future. Science 294, 1488–1495 (2001).

2. Benioff, P. Quantum mechanical models of Turing machines that dissipate no energy. Phys. Rev. Lett. 48, 1581–1585 (1982).

3. Neumann, P. et al. Multiparticle entanglement among single spins in diamond. Science 320, 1326–1329 (2008).

4. Kato, Y. K., Myers, R. C., Gossard, A. C. & Awschalom, D. D. Current-induced spin polarization in strained semiconductors. Phys. Rev. Lett. 93, 176601 (2004).

5. Kumada, N., Kamada, T., Miyaishi, S., Hirayama, Y. & Fujisawa, T. Electric field induced nuclear spin resonance mediated by oscillating electron spin domains in GaAs-based semiconductor. Phys. Rev. Lett. 101, 157602 (2008).

6. Yano, Y. The RIKEN RI beam factory project: A status report. Nucl. Instrum. Methods B 261, 1009–1013 (2007).

7. Morrissey, D. J. for the NSCL Staff The coupled cyclotron project at the NSCL. Nucl. Phys. A 616, 45–55 (1997).

8. http://science.energy.gov/fsp/participates/frib.

9. http://www.frib.msu.edu...

10. Henning, W. The GSI project: An international facility for ions and antiprotons. Nucl. Phys. A 734, 654–660 (2004).

11. Geissel, H. et al. The super-FRS project at GSI. Nucl. Instrum. Methods B 204, 71–85 (2003).

12. http://www.gsi.de/portrait/fair_e.html.

13. Frank, M. On systematics in the 31F electric hyperfine interactions. Fortschr. Phys. 47, 335–388 (1995).

14. Bharuth-Ram, K. Hyperfine interaction studies in diamond. Physica B 389, 29–36 (2007).

15. Hüfner, J. & Nemes, M. C. Relativistic heavy ions measure the momentum distribution on the nuclear surface. Phys. Rev. C 33, 2358–2357 (1981).

16. Asahi, K. et al. New aspect of intermediate energy heavy ion reactions. Large spin polarization of fragments. Phys. Lett. B 251, 488–492 (1990).

17. Ishihara, M. et al. Spin-polarization measurement in the 197Au (35F, 23B) reaction. Proc. Res. C2 23–25 (1979).

18. Yoneya, K. et al. Deformation of 34Mg studied via in-beam γ-ray spectroscopy using radioactive-ion projectile fragmentation. Phys. Lett. B 499, 233–237 (2001).

19. Cohen, B. L. Resolution of accelerator magnetic analyzing systems. Rev. Sci.Instrum. 30, 415–418 (1959).

20. Blosser, H. G. et al. Ultra-high resolution spectrometer system for charged particle studies of nuclei. Nucl. Instrum. Methods 91, 61–65 (1971).

21. Kubo, T. In-flight RI beam separator BigRIPS at RIKEN and elsewhere in Japan. Nucl. Instrum. Methods B 204, 97–113 (2003).

22. Goldhaber, A. S. Statistical models of fragmentation processes. Phys. Lett. B 53, 306–308 (1974).

23. Morinaga, H. & Yamazaki, T. In-beam Gamma-Ray Spectroscopy (North-Holland, 1976).

24. Robinson, M. et al. New isomer 32Al*. Phys. Rev. C 53, R1645 (1996).

25. Grévy, S. et al. Spectroscopy at the N = 20 shell closure: The β-decay of 32Mg. Nucl. Phys. A 734, 369–373 (2004).

26. Asahi, K. et al. Observation of spin-aligned secondary fragment beams of 18B. Phys. Rev. C 43, 456–496 (1991).

27. Schmidt-Ott, W-D. et al. Spin alignment of 45Sc produced in the fragmentation of 500 MeV/u 44Ti. Z. Phys. A 350, 215–219 (1994).

28. Fornal, B. et al. γ-ray studies of neutron-rich N = 18, 19 nuclei produced in deep-inelastic collisions. Phys. Rev. C 55, 762–765 (1997).

29. Stenhammer, K. & Blank, B. Modified empirical parametrization of fragmentation cross sections. Phys. Rev. C 61, 034607 (2000).

30. Groh, D. E. et al. Spin polarization of 17K produced in a single-proton pickup reaction at intermediate energies. Phys. Rev. Lett. 90, 202502 (2003).

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Author contributions

Y. Ichikawa, H.U. and K.A. designed the experiments. H.U. is a spokesperson for the proposal of the present experiment at the RIBF, and the collaboration of all the other authors with him led to the accomplishment of the experiment. Y. Ichikawa and Y. Ishii analysed data. Y. Ichikawa, H.U. and K.A. chiefly wrote the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.