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Production of spin-aligned RI beam via two-step fragmentation with dispersion matching

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Abstract. To produce a radioactive-isotope (RI) beam with high spin alignment, we have developed a novel method, the two-step projectile-fragmentation (PF) method, that employs momentum-dispersion matching. An on-line experiment to produce ^{32}Al from ^{48}Ca via ^{33}Al was performed at RIKEN RI Beam Factory. In the experiment, we succeeded in producing approximately 8% spin alignment in an RI beam of ^{32}Al. In this paper, we focus on evaluating the magnitude of spin alignment realized in one-nucleon removal from ^{33}Al.

1. Two-step PF method with dispersion matching

The technique of spin orientation in radioactive-isotope (RI) beams has played an important role in nuclear physics especially through the measurement of nuclear electromagnetic moments. The mechanism of the spin orientation in a projectile fragmentation (PF) reaction to produce an RI beam was first revealed in 1990 [1, 2]. The fragment after PF has a momentum width from the Goldhaber distribution [3], owing to the Fermi motion of the nucleon removed from the nuclear surface. Qualitatively, when a nucleon with a position vector $\mathbf{R_0}$ and a Fermi momentum $\mathbf{p}$ is removed from the surface of a nucleus, the angular momentum transferred to the fragment is $(-\mathbf{p} \times \mathbf{R}_0)$. Hence, a specific ensemble with spin orientation can be extracted in accordance with the selected momentum region. Conventionally, spin orientation has been produced by single-step fragmentation. However, the applicable scope of a spin-oriented RI beam produced by single-step PF is limited to the vicinity of the primary beam. This limitation is a result of the magnitude of the spin orientation being reduced for PF, and excludes the removal of many nucleons from a projectile.

To overcome this difficulty, here we propose a novel method, the two-step PF method with dispersion-matching, for producing high spin alignment (i.e., orientation of rank 2) in any RI beam. In the proposed method, following primary PF, the nucleus of interest is produced in a tertiary beam via secondary PF. Here, the secondary PF is chosen to be the one-nucleon removal reaction in order that the spin alignment of the tertiary beam can potentially be maximized. The production yield of the tertiary beam is, however, low in a simple two-step PF scheme. Therefore, a technique of momentum-dispersion matching was combined with the method, where a tertiary beam with an equivalent relative momentum as the secondary beam was focused on the same lateral position in the focal plane, independent of the initial momentum. Fulfilling this dispersion-matching condition, yield enhancement can be achieved by extracting the same alignment component from the tertiary beam thereby avoiding cancelling alignment with alignment components of opposite sign. The principle of the proposed method is explained in Fig. 1.

An on-line experiment to produce a spin-aligned RI beam of ^{32}Al by the proposed method was carried out at RIKEN RI Beam Factory (RIBF) [5], and ^{32}Al was successfully produced from ^{48}Ca via ^{33}Al. In this paper, we briefly report on the procedure and the results of the experiment, and then focus on predicting the magnitude of spin alignment in RI beams.

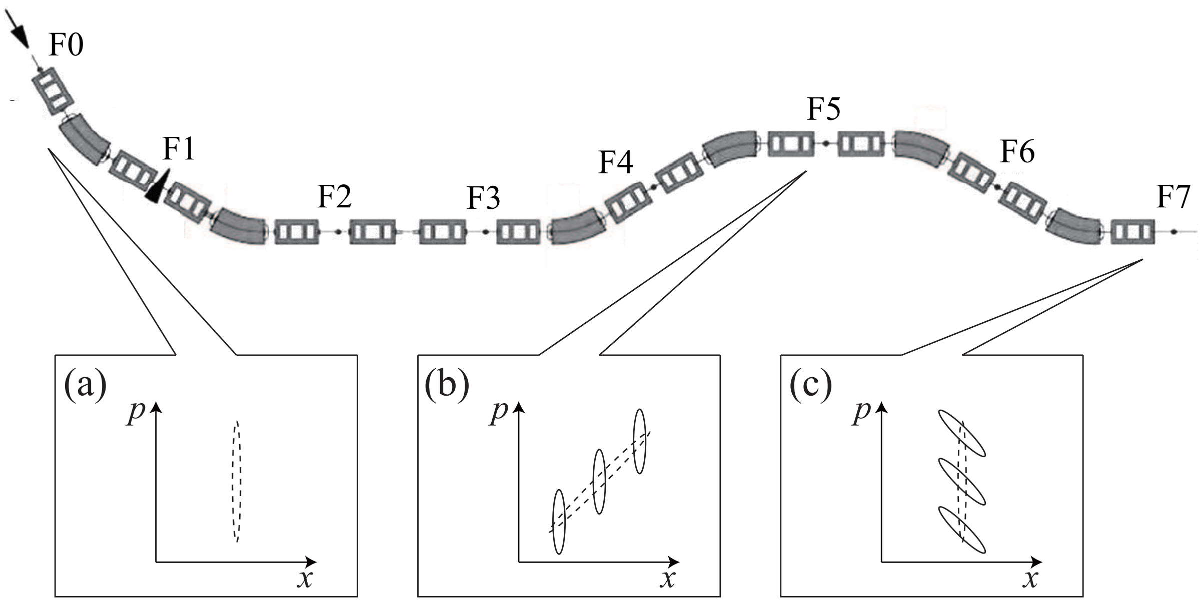

Figure 1. Principle of two-step PF method with dispersion matching, explained with BigRIPS beamline [4] at RIKEN RIBF [5]. F0, F2, F3 and F7 are double-achromatic focal planes. F1, F4, F5 and F6 are momentum-dispersive focal planes. Complementary figures (a), (b) and (c) represent two-dimensional spaces with horizontal axes of lateral position x and vertical axes of momentum p at F0, F5 and F7, respectively. Dashed and solid circles are schematic momentum distribution produced by primary PF and secondary PF, respectively. (a) Primary PF takes place at F0 with momentum spread dominated by fluctuation of energy loss from the primary target. (b) Transport to the momentum-dispersive focal plane corresponds to the rotation in the two-dimensional plane of x and p. Secondary PF takes place at each position of F5 with the momentum spread comparable with the Goldhaber width [3]. (c) Fulfilling the dispersion-matching condition, momentum dispersion for primary PF is cancelled, while that for secondary PF is generated. The slit at F7 extracts the equivalent momentum region for each distribution produced by the secondary PF.

2. Experiment at RIBF

An experiment to apply the proposed method to ^{32}Al was performed with the BigRIPS in-flight separator [4] at the RIKEN RIBF facility [5]. The BigRIPS beam line is shown in Fig. 1. In the primary reaction at the F0 focal plane, ^{33}Al was produced by the PF of a 345-MeV/nucleon ^{48}Ca beam on a primary target of ^{9}Be with a thickness of 1.85 g/cm^2, chosen to provide a maximum production yield of a secondary beam of ^{33}Al. The average beam intensity was approximately 150 pnA during the experiment. The reaction fragments were then collected and analyzed at the first dipole magnet of BigRIPS. A wedge-shaped aluminium degrader with a mean thickness of 221 mg/cm^2 was placed at the momentum dispersive focal plane F1 for isotope separation. The momentum acceptance at F1 was set to $\pm 3\%$. For particle identification of the fragments, the atomic number (Z) and mass-to-charge ratio (A/Q) of each fragment were found by the ΔE-TOF-$B\rho$ method, in which energy loss (ΔE), time-of-flight (TOF), and magnetic rigidity ($B\rho$) were measured with the focal-plane detectors in the beam line.

The secondary ^{33}Al beam was introduced to an aluminum wedge-shaped secondary target with a thickness of 2.70 g/cm^2, placed at the momentum dispersive focal plane F5. Here, ^{32}Al was produced through one-nucleon removal PF, its isomeric state ^{32m}Al [6] was populated, and the spin alignment was effectively produced at the same time in a “one-shot” reaction. The thickness of the secondary target was chosen such that the energy loss from the target was comparable with the Goldhaber width [3] of one-nucleon removal from ^{33}Al. A momentum width of $\sigma = 0.4\%$ was measured for ^{32}Al. The ^{32}Al beam was then transported to a double-achromatic focal plane F7, where the momentum dispersion for ^{32}Al from F5 to F7 was matched with that for ^{33}Al from F3 to F5. The slit at F7 was used to select a momentum region of $\Delta p/p = \pm 0.15\%$ around the center of the distribution.

Using the described method, we produced an RI beam of ^{32}Al with spin alignment of approximately 8%. The magnitude of the spin alignment was determined by the time-differential perturbed angular distribution (TDPAD) method. Spin alignment was observed through the change in anisotropy of the de-excitation γ-ray emission from ^{32m}Al synchronized with spin precession under an external magnetic field. A detailed description of the TDPAD method is given in another paper [7].

3. Evaluation for magnitude of spin alignment

The one-nucleon removal reaction is advantageous in terms of the feasibility of predicting the magnitude of spin alignment. The theoretical maximum spin alignment is quantitatively estimated based on Hüfner and Nemes model [8]. The cross section, $d\sigma/dp_{\|}$, required for production of a fragment with longitudinal momentum $p_{\|}$ is expressed as

$$\frac{d\sigma}{dp_{\|}} = \int d^2\mathbf{s}D(\mathbf{s}) \int dz \int d^2p_{\|} W(\mathbf{s}, z, \mathbf{p}_{\perp}, p_{\|} - \langle p_{\|}\rangle), \tag{1}$$

where the momentum vector $\mathbf{p} = (\mathbf{p}_{\perp}, p_{\|})$ of the removed nucleon is decomposed into the aforementioned longitudinal component $p_{\|}$ parallel to the beam and a transverse part $\mathbf{p}_{\perp}$. The position vector $\mathbf{R} = (\mathbf{s}, z)$ at which the nucleon removal takes place, is decomposed into z and $\mathbf{s}$ in the same manner. The value of $p_{\|}$ that corresponds to the beam velocity is denoted $\langle p_{\|}\rangle$ in Eq.1, and the Wigner transform $W(\mathbf{R};\mathbf{p})$ of the one-body density matrix $\langle \mathbf{r}|\rho|\mathbf{r}'\rangle$,

$$W(\mathbf{R};\mathbf{p}) = \int \frac{d^3\mathbf{x}}{(2\pi)^3} \exp(-i\mathbf{p}\mathbf{x}) \langle \mathbf{R} - \frac{\mathbf{x}}{2}|\rho|\mathbf{R} + \frac{\mathbf{x}}{2}\rangle, \tag{2}$$

represents the “probability” of finding a particle at position $\mathbf{R}$ with momentum $\mathbf{p}$. Finally, the weighting function $D(\mathbf{s})$ constrains the collision dynamics and confines the process of nucleon removal to the nuclear surface. In the following, $D(\mathbf{s}) = \delta(|\mathbf{s}| - s_0)$ has been assumed for the weighting function.

For the sake of simplicity, we take the removal of a neutron from the $0d_{3/2}$ orbital in ^{33}Al Describing this orbital by a harmonic-oscillator wave function, we obtain the following expression for the longitudinal momentum distribution:

$$\frac{d\sigma_0}{dp_\parallel} = \frac{s_0^4}{3\pi^{3/2}b^5}\left(\frac{2p_\parallel^2}{\Gamma^2} + 1 - \frac{2b^2}{s_0^2}\right)^2 \exp\left\{-\frac{s_0^2}{b^2}\left(1 + \frac{p_\parallel^2}{\Gamma^2}\right)\right\}, \tag{3}$$

$$\frac{d\sigma_{\pm 1}}{dp_\parallel} = \frac{2s_0^4}{\pi^{3/2}b^5}\frac{p_\parallel^2}{\Gamma^2} \exp\left\{-\frac{s_0^2}{b^2}\left(1 + \frac{p_\parallel^2}{\Gamma^2}\right)\right\}, \tag{4}$$

$$\frac{d\sigma_{\pm 2}}{dp_\parallel} = \frac{s_0^4}{2\pi^{3/2}b^5} \exp\left\{-\frac{s_0^2}{b^2}\left(1 + \frac{p_\parallel^2}{\Gamma^2}\right)\right\}, \tag{5}$$

where $d\sigma_m/dp_\parallel$ is the cross section of component m of the orbital angular momentum $l = 2$. The width, Γ, of the distribution can be expressed in the form $\Gamma = s_0/b^2$, where b is the oscillator parameter of the wave function. The momentum distribution for component m_n of the removed neutron's angular momentum, $j = 3/2$, is expressed as

$$\frac{d\sigma_{m_n}}{dp_\parallel} = \sum_m \langle 2, m, 1/2, m_n - m|3/2, m_n\rangle^2 \frac{d\sigma_m}{dp_\parallel}, \tag{6}$$

where $\langle 2, m, 1/2, m_n - m|3/2, m_n\rangle$ are the Clebsch-Gordan coefficients corresponding to the combination of an orbital angular momentum of $l = 2$ and a neutron intrinsic spin of $s = 1/2$. The total nuclear spin $I^{pi} = 4^+$ of ^{32m}Al is composed of a neutron hole in the $d_{3/2}$ orbital and a proton hole in the $d_{5/2}$ orbital. The momentum distribution for component M in ^{32m}Al is

$$\frac{d\sigma_M}{dp_\parallel} = \sum_{m_n} \langle 5/2, M - m_n, 3/2, m|4, M\rangle^2 \frac{d\sigma_{m_n}}{dp_\parallel}, \tag{7}$$

where $\langle 5/2, M - m_n, 3/2, m_n|4, M\rangle$ are the Clebsch-Gordan coefficients for combining a proton hole with $j_1 = 5/2$ and a neutron hole with $j_2 = 3/2$ to produce a total spin $I^\pi = 4^+$. The calculated momentum distribution is shown in Fig. 2 (a).

The spin alignment in ^{32m}Al was calculated by using the momentum distribution of each substate M:

$$A \equiv \sum_M \alpha_2(M)\frac{d\sigma_M}{dp_\parallel} / \sum_M \frac{d\sigma_M}{dp_\parallel}. \tag{8}$$

Here,

$$\alpha_2\,(M) = \frac{3M^2 - I(I+1)}{I(2I-1)}, \tag{9}$$

is the weighting factor required for substate M to deduce the alignment with rank 2. The expected spin alignment is shown in Fig. 2 (b). In this experiment, the momentum acceptance was $dp/p = \pm 0.15\%$ around the center of the distribution and gave a theoretical maximum alignment of 30%, 4-fold greater than the realized magnitude. This reduction from the maximum is considered to be a result of de-excitation from higher excited states produced by the PF, for example, states with spin-parity of (4^-) [9] and 1^+ [10]. The production of spin alignment is related to both the reaction mechanism and the nuclear structure including various parameters. Under these conditions, we suggest that a realized alignment magnitude of 1/4 of the maximum is good, despite the reaction path to the isomeric states not being unique. If we choose a nucleus produced by a unique reaction path, a spin alignment magnitude closer to the expected maximum would be realized.

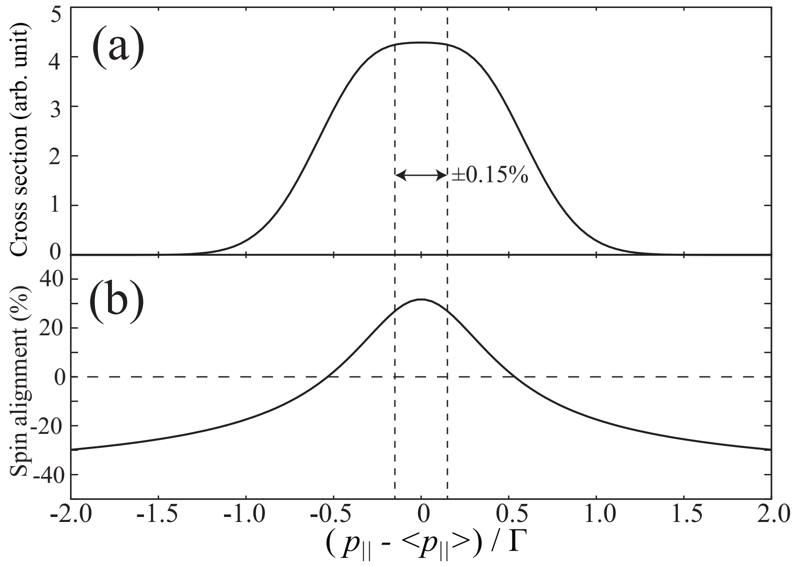

Figure 2. (a) Momentum distribution and (b) expected spin alignment in ^{32m}Al. The width, Γ, of the distribution is expressed in form $\Gamma = s_0/b^2$, for oscillator parameter b of the wave function.

4. Summary

We have developed a new method to produce highly spin-aligned RI beams by combining two-step PF and a dispersion-matching technique. To test the validity of the method, an on-line experiment was conducted using the RIKEN BigRIPS, where an RI beam of ^{32}Al was produced from a primary beam of ^{48}Ca via ^{33}Al. The produced ^{32}Al beam had approximately 8% spin alignment. The magnitude of the achieved spin alignment was 1/4 of the theoretical maximum. Spin alignment of similar magnitude, approximately 10%, could potentially be realized in other isomeric states in any nuclear region. By applying the proposed method, which utilizes the characteristics of a next-generation facility such as RIBF, the available scope of spin-aligned RI beams is substantially broadened beyond the two-dimensional region in the nuclear chart.

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