Spin polarization of ^{37}K produced in a single-proton pick-up reaction at intermediate energies

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Abstract

Spin polarization of ^{37}K nuclei produced via single proton pick-up from a ^{9}Be target by a beam of 150 MeV/nucleon ^{36}Ar has been observed. Positive spin polarization with magnitude $8.5\pm0.6\%$ was deduced near the peak of the ^{37}K momentum distribution. The variation of the spin polarization as a function of outgoing ^{37}K momentum is explained by a classical conservation model, as previously applied to describe the induced spin polarization observed for fragments produced in intermediate-energy heavy-ion reactions, with the condition that the picked-up proton has an average momentum equal to the Fermi momentum and aligned along the incident beam direction.

Spin polarized nuclei have proven a highly useful tool for the study of nuclear structure, nuclear reactions and fundamental interactions, in addition to condensed matter physics through the hyperfine interaction between implanted polarized nuclei and the surrounding lattice. Nuclear spin polarization is required, for example, in the determination of nuclear ground state moments by nuclear magnetic resonance combined with beta spectroscopy (the β-NMR technique). Owing to the simple and well-known form of the magnetic dipole operator, measurement of nuclear dipole moments can provide stringent tests of current nuclear structure models. At the extremes of nuclear stability, determination of nuclear magnetic moments can provide insight into new features of nuclear structure attributed to low nuclear binding. The extension of magnetic moment measurements to drip-line nuclei will require simultaneous optimization both of rare isotope production and spin polarization production.

In this Letter we report a new aspect of spin polarization in intermediate-energy heavy-ion reactions. We have deduced the spin polarization of ^{37}K nuclei produced in the single proton pick-up reaction ^{9}Be(^{36}Ar,^{37}K) at 150 MeV/nucleon. *Positive* spin polarization of ^{37}K pick-up products has been observed at the *peak* of the ^{37}K momentum yield curve. The results prove that the nucleon is preferentially picked-up when its momentum vector matches the Fermi momentum and is aligned along the direction of the incident projectile. We show that polarization in intermediate energy reactions, whether pick-up or fragmentation, can be understood in terms of the same kinematical conservation model.

Intermediate-energy heavy ion reactions, in combination with in-flight separation methods, have provided a means to produce a variety of short-lived nuclei [1]. Spin polarization of fragments produced in intermediate-energy heavy-ion reactions was first observed by Asahi *et al.* [2]. For the reaction ^{197}Au(^{14}N,^{12}B) at 40 MeV/nucleon, the largest spin polarization of ^{12}B fragments ($\sim 20\%$) was deduced at the wings of the ^{12}B momentum distribution, where the yield is lowest. Zero spin polarization was observed at the peak of the ^{12}B momentum distribution. Due to the high Z of the target, these peripheral reactions were dominated by a Coulomb trajectory. Zero spin polarization at the peak of the fragment momentum distribution was also observed for fragmentation reactions involving low-Z targets, where the attractive nucleus-nucleus potential determines the far-side trajectory of the outgoing particle [3, 4]. Systematic investigations of the spin polarization induced in fragmentation reactions were carried out by Okuno *et al.* [4]. Negative spin polarization at the peak in the momentum yield curve was observed for nuclei produced in reactions involving intermediate mass targets, where a balance is achieved between the repulsive Coulomb and attractive nucleus-nucleus potentials. Asahi *et al.* [2] developed a model based on the classical treatment of linear and angular momentum to explain the reaction mechanism governing the spin polarization of fragments produced in intermediate-energy heavy-ion reactions.

The kinematical model of Asahi *et al.* suggests that spin polarization occurs in systems when there is a significant momentum mismatch between the incoming projectile and outgoing fragment because this mismatch implies momentum transfer near the surface of the fragment parallel (or antiparallel) to the beam axis. Nuclei produced by nucleon pick-up from a target at intermediate energies experience a large momentum shift relative to the incident beam momentum [5, 6], and it is anticipated that these nuclei may show significant spin polarization. The mechanism would be fundamentally the same as in fragmentation, but as the picked-up nucleon on average has the Fermi momentum in the beam direction, positive spin polarization is expected at the peak of the momentum distribution.

In the present experiment ^{37}K secondary particles were produced from a primary beam of ^{36}Ar accelerated to 150 MeV/nucleon using the coupled cyclotrons at the National Superconducting Cyclotron Laboratory at Michigan State University. The primary beam, with an average intensity of 11 pnA, impinged on a 578 mg/cm^2 ^{9}Be target at the entrance to the A1900 fragment separator [7]. The beam was set at an angle of $+2^\circ$ relative to the normal beam axis using two dipole magnets immediately upstream of the A1900 target position. The measured angular acceptance of the A1900 is 60 mrad in the horizontal direction and 40 mrad in the vertical direction. The full momentum acceptance of the A1900 was limited to 0.5% using a slit at the second intermediate image. A 971 mg/cm^2 acrylic wedge was also placed at this location to separate secondary particles based on relative energy loss. The momentum distribution for ^{37}K pick-up products was measured using a pair of parallel-plate avalanche counters (PPACs) placed at the second intermediate image of the A1900. Secondary beam particles were identified based on standard energy loss and time-of-flight measurements. ^{37}K products constituted the majority of the secondary beam, with two other species present: ^{36}Ar, which is β stable, and ^{35}Ar.

The secondary beam was delivered to the NSCL β-NMR apparatus, which is described in detail elsewhere [8]. The beam exited the evacuated beam line through a Kapton window, traversed 20 cm of air, passed through an Al collimator, and was deposited in a KBr crystal located at the center the β-NMR dipole magnet. The spin-lattice relaxation time, T_1, for ^{37}K in KBr is several seconds at room temperature [9], and compares favorably to the β-decay half-life of ^{37}K, which is 1.226 s [10]. The 4 mm thick KBr crystal had a diameter of 22 mm, and was placed at a 45° angle relative to the beam axis to minimize the amount of material β particles would traverse before reaching the β telescopes.

The secondary beam particles were implanted continuously into the KBr crystal. The magnetic holding field was switched between the field on, $B_{\text{app}} = 0.30$ T, and off, $B_{\text{app}} = 0.00$ T, conditions every 60 seconds. Polarization was deduced using the pulsed magnetic field method outlined by Anthony *et al.* [11]. The double ratio $\mathcal{R}$ is determined from the counts observed in the 0° and 180° β detectors for magnetic field on and off:

$$\mathcal{R} = \frac{[N(0)/N(180)]_{\text{field on}}}{[N(0)/N(180)]_{\text{field off}}} = \frac{1+AP}{1-AP} \tag{1}$$

where $N(0)$ and $N(180)$ are the counting rates in the 0° and 180° β telescopes, respectively, A is the asymmetry in the β decay, and P is the polarization. The A value was deduced to be $+0.48 \pm 0.03$ from the known level scheme [10] using the relations in Refs. [12, 13]. Anthony *et al.* noted that only 60% of the full spin polarization as measured using β-NMR was observed for ^{12}B fragments implanted into a Pt host material [11] using the pulsed magnetic field method. It is expected that the use of KBr, where the catcher shares a common ion with the implanted impurity, should permit observation of the full ^{37}K spin polarization [14].

Polarization was deduced for ^{37}K pick-up products at fixed values of outgoing fragment momentum p relative to p_0, the momentum corresponding to the peak of the ^{37}K momentum distribution. A summary of the results is listed in Table I and Fig. 1(a). The momentum distribution for ^{37}K pick-up products is shown in Fig. 1(b). The counting rates in the 0° and 180° β telescopes were evaluated by integrating the counts in the two-dimensional $\Delta E/E$ spectrum with an energy above 700 keV for the E detectors. The β-decay properties of ^{35}Ar [$T_{1/2} = 1.77$ s, $Q_\beta = 5.97$ MeV, $A = +0.46$] are comparable to that of ^{37}K [$T_{1/2} = 1.226$ s, $Q_\beta = 6.15$ MeV, $A = +0.48$]. However, the ^{35}Ar contamination was only a few percent of the total secondary beam intensity for all A1900 momentum settings (see Table I).

The kinematical model used by Asahi *et al.* [2] to explain the spin polarization of fragments produced in intermediate-energy heavy-ion reactions considered a fast peripheral collision between a projectile nucleus having a straight-line trajectory and a stationary target, and the removal of nucleons in the overlap region between projectile and target. If the removed nucleons are assumed to come from a fixed location at distance R from the center of the projectile (Fig. 2(a)), then from conservation considerations the angular momentum imparted to the spectator portion of the projectile (the selected fragment) is $\boldsymbol{L} = -\boldsymbol{R}\times\boldsymbol{K}$, where $\boldsymbol{K}$ is the linear momentum of the removed nucleons. The momentum of the selected fragment p is connected to K through the conservation relation $\boldsymbol{p} = \boldsymbol{p}_p - \boldsymbol{K}$, where $\boldsymbol{p}_p$ is the momentum of the incident beam. The spin polarization is defined as the ratio ℓ_z/L, where ℓ_z is the z-component of the angular momentum and L is the magnitude of the total angular momentum. ℓ_z can be expressed in terms of the longitudinal K_y and transverse K_x components of the momentum of the removed nucleons, $\ell_z = -K_y R\cos\Theta + K_x R\sin\Theta$, where Θ identifies the location of nucleon removal within the overlap region [4].

If nucleon removal occurs uniformly in the overlap region, then Θ=0 and $\ell_z = -K_y R$. The spin polarization will vary as the longitudinal momentum of the removed nucleons. At the peak of the momentum yield curve of the spectator portion of the projectile, $K_y = p - p_p = 0$ and hence $\ell_z/L = 0$. The absence of spin polarization at the momentum corresponding to peak fragment production was observed by Asahi *et al.* [2] for reactions with high-Z targets, where the peripheral reactions are dominated by Coulomb interactions. It was proposed in Ref. [4] that a nucleon rescattering effect may produce a backward shift in the removal position, resulting in $\Theta < 0^\circ$. This would lead to a *negative* polarization at the peak of the momentum yield curve, as the contribution $K_x R\sin\Theta$ would have a negative value. Such behavior of the spin polarization was noted by Okuno *et al.* [4] for fragments produced in reactions involving intermediate mass targets, where a balance is achieved between the repulsive Coulomb and attractive nucleus-nucleus potentials.

The centroids of the momentum distributions for neutron pick-up products were studied for light projectiles at energies $\sim$ 80 MeV/nucleon by Souliotis *et al.* [5]. From the shifts in the centroids relative to the initial projectile momentum, they concluded that the picked-up neutrons have an average momentum equal to the Fermi momentum (typically 230 MeV/c in their study) oriented parallel to the incident projectile direction. Pfaff *et al.* [6] observed similar shifts for proton pick-up reactions at intermediate energies using ^{78}Kr projectiles. Although the ^{9}Be(^{36}Ar,^{37}K) reaction was carried out at a projectile energy nearly twice that reported in Refs. [5, 6], the momentum shift observed in our measurements is consistent with these conclusions. Specifically, the ratio of the centroid of the parallel momentum/nucleon of ^{37}K to the momentum/nucleon of the ^{36}Ar projectile was deduced to be 0.981, after considering corrections due to the thick ^{9}Be target employed. This ratio is consistent with measurements by Souliotis *et al.* [5] for neutron pick-up reactions on ^{27}Al and ^{181}Ta targets. The use of a ^{9}Be target should not greatly influence the observed centroid shift, as there is relatively little variation in Fermi momentum between targets [15].

Adopting the notation of Souliotis *et al.* [5], the outgoing pick-up product has an average momentum $\langle p \rangle$ that is the sum of the incident projectile average momentum $\langle p_p \rangle$ and the average momentum of the picked-up nucleon $\langle p_t \rangle$. At the peak of the fragment momentum distribution $p_0 = p_p + p_{\mathrm{Fermi}}$, where p_{Fermi} is the Fermi momentum of the picked-up nucleon aligned along the direction of the projectile motion. In the projectile rest frame, the Fermi momentum of the picked-up nucleon can be represented by a momentum vector $\boldsymbol{K}$ that lies anti-parallel to p_{Fermi}. Assuming a peripherial interaction, angular momentum can be generated in the outgoing product as the vector product of the projectile radius $\boldsymbol{R}$ and $\boldsymbol{K}$. This arrangement is shown schematically in Fig. 2(b). The angle $\bar{\theta}_{def}$ is the mean deflection angle, which in Fig. 2(b) represents a far-side trajectory that will be followed by ^{37}K pick-up products due to the use a low-Z ^{9}Be target where the attractive nucleus-nucleus potential is predominant. The cross product of $\boldsymbol{R}$ and $\boldsymbol{K}$ will ensure an angular momentum vector directed out of the page as shown in Fig. 2(b). The polarization is therefore positive, since the angular momentum vector is parallel to the vector $\boldsymbol{p}_{in} \times \boldsymbol{p}_{out}$, where $\boldsymbol{p}_{in}$ and $\boldsymbol{p}_{out}$ are the momentum vectors of the incoming and outgoing particles, respectively.

The systematic variation of the spin polarization as a function of the outgoing ^{37}K momentum can also be qualitatively understood based on kinematical arguments. Since the momentum matching conditions for simple surface-to-surface pick-up [16] are best met for the two data points on the high momentum side of the peak of the yield we discuss these points first. For a pure pick-up reaction, the zero crossing of polarization as a function of outgoing product momentum is expected to occur when the velocity of the projectile matches the velocity of the picked-up nucleon, $p_p/A_p = p_t/A_t$, where A_p and A_t are the mass numbers of the projectile and picked-up nucleon, respectively. Since the momentum of the outgoing particle is the sum of the projectile momentum and the momentum of the picked-up nucleon, at the zero crossing $p = [(A_p + 1)/A_p]p_p$. Accounting for the thickness of the target, the zero crossing of the ^{37}K spin polarization should occur at $(p - p_0)/p_0 = 1.9\%$. The calculated zero crossing point is marked for reference in Fig. 1(a). A linear increase in the spin polarization, as expected from simple kinematical arguments, is observed with a decrease in the momentum of the outgoing pick-up product.

On the low momentum side of the peak of the product yield curve the picked-up nucleon has a momentum p_t much less than p_{Fermi} (in the projectile rest frame, K much greater than p_{Fermi}) and the momentum matching conditions [16] for direct pick-up are poorly satisfied. More complex transfer mechanisms are therefore required on the low momentum side of the yield peak, which can be expected to increasingly reduce the observed spin polarization of ^{37}K products as their momentum decreases.

In summary, positive spin polarization of ^{37}K nuclei produced in a single proton pick-up reaction has been observed at the peak of the ^{37}K momentum yield curve. A kinematical model based on conservation of linear and angular momentum, previously applied to explain polarization of fragments produced via intermediate-energy heavy-ion fragmentation reactions, was used to explain the observed qualitative variation in spin polarization produced by proton pick-up at similar energies. These new spin polarization results for proton pick-up reactions at intermediate energies confirm that the nucleon picked up from the target has an average momentum equal to the Fermi momentum, with the momentum vector preferentially aligned along the direction of the incident projectile. The scientific cases for the next generation radioactive beam facilities around the world include applications to condensed matter physics and the life sciences which will require intense beams of highly polarized exotic nuclei. There are theoretical indications that even larger polarizations than those reported here might be achieved if the kinematical conditions for pick-up are optimized [17]. Our new results represent a major advance towards realizing these theoretical expectations. The presence of spin polarization at the peak of the pick-up product yield distribution, where the origin of the spin polarization can be rationalized based on kinematical arguments, will afford new opportunities to study nuclear magnetic moments and other spin-related phenomena for nuclei far from the valley of β stability.

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FIG. 1: (a) Polarization and (b) ^{37}K ion yield at the A1900 intermediate image as functions of relative fragment momentum, $(p-p_0)/p_0$ for ^{37}K, where p_0 is the momentum corresponding to the peak of the ^{37}K momentum distribution. The momentum acceptance for the data in (a) was 0.5%.

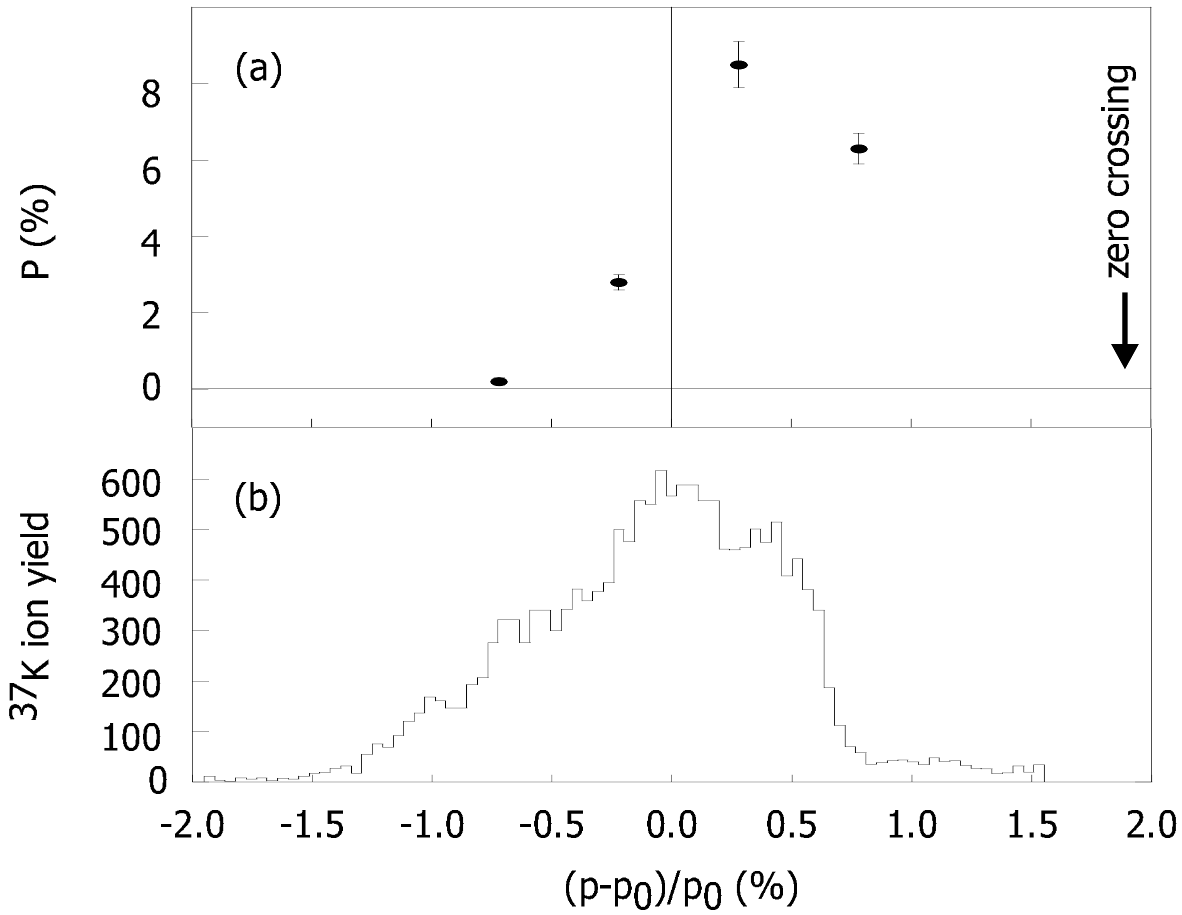
FIG. 2: (a) Schematic representation of the variables defining the polarization produced via projectile fragmentation. As shown, the near-side fragmentation product will show positive polarization when $K_y < 0$. At the peak of the momentum distribution, $K_y \sim 0$ and the polarization may be negative due to the positive K_x contribution, attributed to rescattering, to the outgoing fragment momentum. (b) Schematic representation of the polarization produced via pick-up of a target nucleon. $\boldsymbol{R}$ is the position of the picked up nucleon and $\boldsymbol{K}$ is the linear momentum of the picked up nucleon in the projectile rest frame.

TABLE I: A1900 magnetic rigidity settings, relative fragment momentum, and polarization for ^{37}K pick-up products.

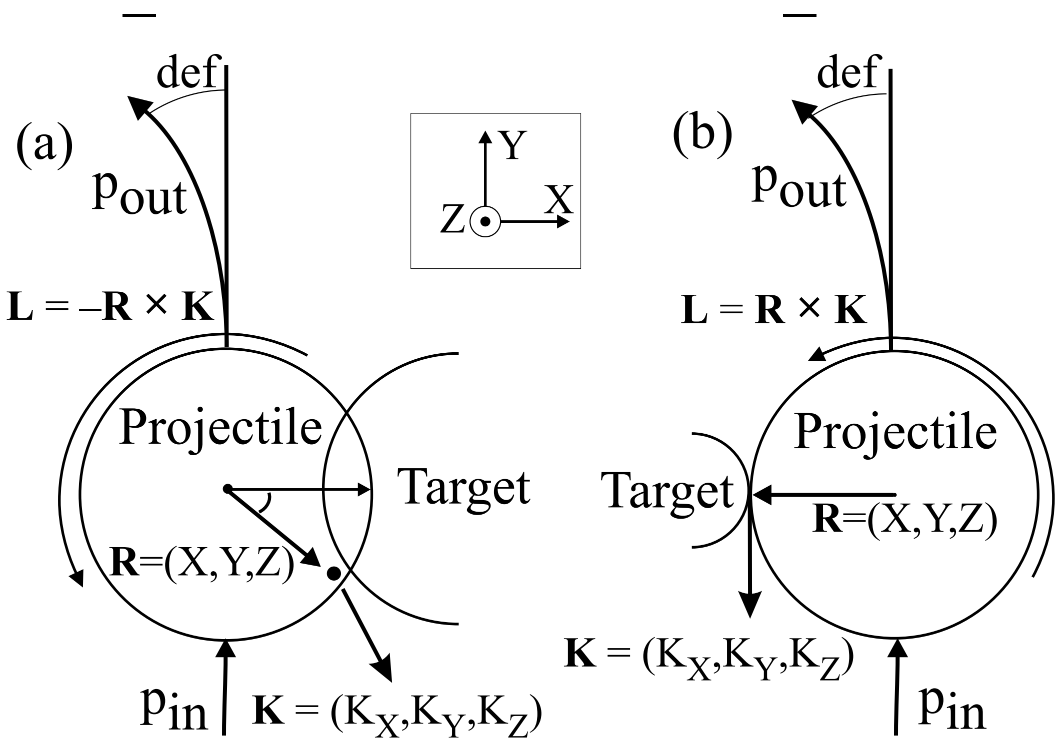
				Beam Composition (%)		
Bρ_1 (Tm)	p (MeV/c)[a]	$(p-p_0)/p_0$[b] (%)	P(%)	^{37}K	^{36}Ar	^{35}Ar
3.1421	17763	-0.72	$+0.2 \pm 0.1$	99	0.5	0.5
3.1579	17853	-0.22	$+2.8 \pm 0.2$	98	1.6	0.4
3.1737	17942	$+0.28$	$+8.5 \pm 0.6$	94	5.0	1.0
3.1895	18031	$+0.78$	$+6.3 \pm 0.4$	73	19	8.0

[a] p determined relativistically after correcting the A1900 $B\rho$ setting by factor 0.9925.

[b] $p_0 = 17892$ MeV/c determined from the peak of the momentum yield curve in Fig. 1(b).



(a)
P (%)
0
2
4
6
8
zero crossing
(b)
^{37}K ion yield
0
100
200
300
400
500
600
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
(p-p$_0$)/p$_0$ (%)



(a)
def
p_out
L = –R × K
Projectile
Target
R=(X,Y,Z)
p_in
K = (K_X,K_Y,K_Z)
Y
X
Z
(b)
def
p_out
L = R × K
Projectile
Target
R=(X,Y,Z)
K = (K_X,K_Y,K_Z)
p_in