PREDICTING SPIN POLARIZATION FROM INTERMEDIATE-ENERGY HEAVY-ION FRAGMENTATION REACTIONS

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Nuclear magnetic resonance of β-emitting nuclei (β-NMR) is a sensitive technique for probing the structure of nuclei far from the valley of stability. Knowledge of the nuclear magnetic dipole moment yields detailed information on the ground state wave function of the nucleus. However, in order to make measurements of ground state magnetic dipole moments using the technique of β-NMR, the nuclei under investigation must be polarized. These measurements have been hampered by the fact that the induced fragment spin polarization cannot be accurately predicted, because the mechanism for producing spin-polarized nuclei off the central beam axis in intermediate-energy heavy-ion fragmentation reactions is not well understood.

A simple kinematical model based on the conservation of linear and angular momentum has been developed by Asahi *et al.* [1]. In this model, the polarization of the fragment as the ratio of the z-component of angular momentum to the total angular momentum ($l_z / |\boldsymbol{l}|$) is calculated using the relation $\mathbf{J} = \mathbf{R} \times \mathbf{P}$, where $\mathbf{R}$ is the position of the removed group of nucleons and $\mathbf{P}$ is the linear momentum of the group of removed nucleons. Okuno [2] subsequently demonstrated a systematic behavior in the spin polarization as a function of target, beam energy and incident beam angle. Using Asahi's simple framework, Okuno developed a Monte Carlo code to reproduce the polarization of his experimental data. His code reproduces the gross features of the spin polarization as a function of fragment momentum rather well, although the calculated $l_z/|\boldsymbol{l}|$ values were scaled by a factor of 0.25 for all reactions.

Work has shown that heavy targets like ^{197}Au and light targets like ^{27}Al produce zero polarization at the peak of the momentum yield curve, only giving appreciable polarization in the wings of the distribution. Whereas, intermediate mass targets like ^{93}Nb can produce significant polarization at the peak of the momentum yield. This is associated with the competition between the attractive nuclear potential and the repulsive Coulomb potential between the target and the projectile. When one or the other dominates, appreciable polarization is only seen in the wings of the momentum distribution. If the Coulomb potential and the nuclear potential effectively cancel each other, polarization can be observed at the peak of the yield curve. It is desirable to be able to predict the spin polarization resulting from particular projectile/target combinations in order to maximize the polarization at the peak of the momentum yield.

With this is mind, we have started with Okuno's code and improved upon it to correctly account for the absence of spin polarization at a beam angle of 0°. Two major modifications to Okuno's code were necessary to accomplish this improvement. First, changes were made in the method to calculate the removal position of the abraded nucleons. Essentially, a removal position is calculated for each nucleon by selecting a random position within the overlap region of two spheres (the target and the projectile) and these positions are then averaged together to give the position of the group of removed nucleons. This is necessary to maintain the integrity of Asahi's polarization model; a group of nucleons is removed and it is this group that has a position and an angular momentum, not each individual nucleon. Determining the removal position in this fashion differs from Okuno's method. Okuno's use of $X = R_0 \cos \Theta$ and $Y = -R_0 \sin \Theta$, where $\Theta > 0$ is the rotation angle and R_0 is the radius of the projectile insured that the removed nucleons only came from the surface of the projectile. Furthermore, a single angle Θ was unsatisfactory because the removal position was exactly the same for each and every event. The new method allows for the removed nucleons to come from anywhere in the overlap region and provides a new position for each event, in true Monte Carlo fashion.

The second modification involves the physical interaction of the target and the projectile. In the intermediate energy heavy-ion fragmentation reactions we are trying to model, the target and projectile experience a peripheral collision where the impact parameter is greater than zero. In other words, the projectile and target collide in an orientation other than head-on. In a situation of peripheral collisions, the projectile can interact with the target in two configurations: one where the projectile is on the left side of the target and one where the projectile is on the right side of the target. This allowance of right- or left-side collisions coupled with near- or far-side collisions correctly accounts for the observed absence of spin polarization at an incident beam angle of 0°. This is understandable because half of the events detected at 0° are from a right-sided interaction, and the other half are from left-sided interactions which will give fragments with polarization equal in magnitude to the right-sided events but opposite in sign, for an overall average of zero polarization. Okuno's code did not allow particles to interact on both sides of the target which made his calculations unable to predict zero polarization at 0°. Our calculation for the fragmentation of ^{18}O in a ^{93}Nb target at 80 MeV/A to produce ^{12}B with collection of events at 0° is shown in Figure 1.

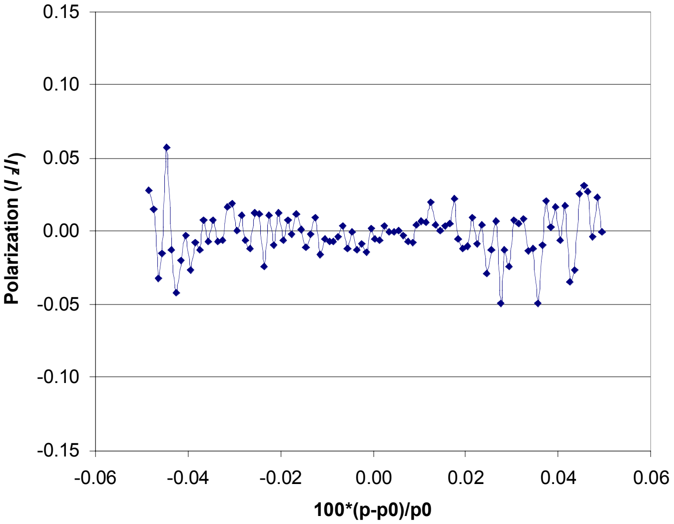

Figure 1: Plot of polarization as a function of momentum for ^{12}B resulting from the fragmentation of ^{18}O in a ^{93}Nb target at 80 MeV/A with a beam angle of 0°. In the figure, *p* is the outgoing fragment momentum, *p0* is the incident projectile momentum and the polarization is given by $l_z / \boldsymbol{l}$ as explained in the text.

We have continued with this line of research and incorporated our improved Monte Carlo code into a fragmentation code that includes the evaporation of nucleons similar to that done for high-energy fragmentation reactions [3]. Evaporation is the process where a nucleus energetically excited during the abrasion process will eject nucleons as a means to reducing this excitation energy. Each evaporated nucleon will carry with it some of the linear (and thus angular) momentum of the parent nucleus thus changing the polarization of the parent nucleus. Within the code, the fragment immediately after the abrasion step gets 13.3 MeV of excitation energy for each abraded nucleon, and each evaporated nucleon requires 20 MeV of the fragment's excitation energy [4]. The total number of evaporated nucleons is calculated by dividing the excitation energy by 20 MeV while allowing for statistical uncertainties. This allows some events to have higher or lower excitation energy then the average and it also insures that not every particle that can evaporate will evaporate. Each evaporated nucleon is then assigned a linear momentum derived from a Gaussian distribution centered at zero with an arbitrary width, and a random position on the surface of the fragment. The position and momentum are then used to calculate an angular momentum for each evaporated nucleon which is then subtracted from the fragment's angular momentum. The polarization of the fragment is recalculated with the fragment's new values for angular momentum. Inclusion of this evaporation process should make the polarization predictions more realistic, perhaps removing the need for a scaling factor to get the magnitude of the polarization right.

Including evaporation, our code correctly reproduces the polarization data of Okuno within a scaling factor of 0.25. Furthermore, Figure 2 is a plot of several experimental data points from the fragmentation of ^{18}O in a ^{93}Nb target at 80 MeV/A. The solid line represents our prediction for the polarization, and it is scaled by 0.04.

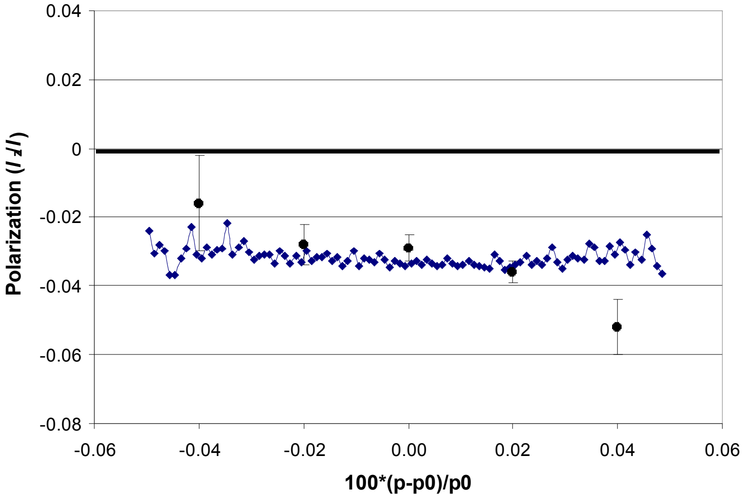

Figure 2: Plot of polarization as a function of momentum for ^{12}B resulting from the fragmentation of ^{18}O in a ^{93}Nb target at 80 MeV/A with a beam angle of 3°. The line is the calculation scaled by a factor of 0.04 using an optical potential of 80 MeV.

That we cannot reproduce the magnitude of polarization is indicative of an incomplete or inaccurate model. We have not included the intrinsic spin of the nucleons, and we treat protons and neutrons identically. Perhaps including the spin of the nucleons will add the component of angular momentum necessary to get the magnitude of the polarization correct. Furthermore, our code uses the real part of the optical model potential to calculate mean deflection angles. This is problematic due to the limited nucleus-nucleus scattering data available to formulate accurate and realistic values for the potential. In addition, our code assumes a pure fragmentation reaction mechanism, where in intermediate energy fragmentation reactions there is usually a coexistence of competing reaction mechanisms. Perhaps the presence of competing reaction mechanisms explains why our incorporation of evaporation seems to have little impact on the polarization. These issues are not clear; thus, we are still working.

As the result of a previous experiment of ^{18}O fragmented in ^{93}Nb at 80 MeV/A, we have momentum distributions for almost all of the fragmentation products produced in this reaction. Preliminary comparisons between our calculations and this experimental data show that the momentum distribution widths compare somewhat favorably, but the peaks of the distributions do not match up. From our calculations, it seems that changing the optical model potential has essentially no effect on the momentum distribution. Furthermore, evaporation does not appreciably affect the momentum distributions, nor does the average position of the removed nucleons. The removal position part and the optical model part make sense. A change in the optical model potential only changes the mean deflection angle which will only change the trajectory of the fragment. This could conceivably affect the momentum, because it is the x-component of momentum that determines the ‘kick’ the fragment gets and this determines whether the fragment makes it into the detector window. Apparently the change in trajectory resulting from changing the optical model potential has a negligible effect on the momentum distribution. That the removal position has little effect is also not surprising, because the removal position only affects the calculation of angular momentum through the cross product – it has no bearing on the momentum distribution, only the polarization.

Proposed changes to treat the evaporation process differently within the code are underway.

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