Peculiar spin alignment of excited projectiles

D.E.M. Hoff,[1] J. Bromell,[1] K.W. Brown,[1] R.J. Charity,[1] J.M. Elson,[1] C.D. Pruitt,[1] L.G. Sobotka,[1,2]
T. Webb,[2] A. Saastamoinen,[3] and B. Roeder[3]
[1]*Department of Chemistry, Washington University in St. Louis, St. Louis, Missouri*
[2]*Department of Physics, Washington University in St. Louis, St. Louis, Missouri*
[3]*Cyclotron Institute, Texas A&M University, College Station, Texas*

In many nuclear reactions such as fusion, deep inelastic scattering and Coulomb excitation the total angular momentum of the resulting system is dominated by the entrance channel orbital angular momentum component. (If the target and projectile are both spin zero this is the only angular momentum.) In most reactions, the transfer of angular momentum from orbital to intrinsic spin of the reactants produces fragment spin alignment perpendicular to the beam axis. In such cases, i.e. exit channel fragments with their intrinsic spin largely aligned perpendicular to the beam axis, the fragments from sequential decay will exhibit a forward/backward focused angular distribution.

Recently reactions were observed for which the spin of excited ^{7}Be* ($J^{\pi} = 7/2^{-}$) projectiles were strongly aligned with (not perpendicular to) the beam axis [1]. In other words, the fragments of the decay of the unbound $J^{\pi} = 7/2^{-}$ state were found largely transverse to the beam axis. In this previous work (at NSCL at 70 MeV/u), the peculiar angular distribution of ^{7}Be* decay was for projectile excitation excited when the target, ^{9}Be ($J^{\pi} = 3/2^{-}$), remaining in its ground state. To explain this effect a reaction mechanism was proposed that depended on the "molecular" structure of ^{9}Be. ^{9}Be is well described by an α-α backbone with a valence neutron in one of two doubly degenerate "π-orbitals", analogous to molecular diatomic systems. In this reaction scenario, when the α-α backbone is aligned along the beam axis, the projectile could interact only with the distant valence neutron, flipping its spin (transfer of the neutron from one of the degenerate orbits to the other) and leaving the target in its ground state. Other orientations would more likely interact with α-α backbone, resulting in excitation and breakup of the target. This scenario would result in a net transfer of intrinsic spin from the target to the projectile along the beam axis.

To test this hypothesized reaction mechanism we studied the inelastic excitation of ^{7}Li ($J^{\pi} = 3/2^{-}$) at 24 MeV/u, provided by the TAMU K500 cyclotron in August 2015, with three different targets: ^{9}Be ($J^{\pi} = 3/2^{-}$), ^{12}C ($J^{\pi} = 0^{+}$), and ^{27}Al ($J^{\pi} = 5/2^{+}$). We expected to see a similar spin alignment phenomenon with the ^{7}Li beam on a ^{9}Be target as we observed at the NSCL with a ^{7}Be beam. On the other hand, the ground state of ^{12}C has zero spin, thus there can be no transfer of spin from target to projectile and while a spin-flip mechanism, with transfer of spin from target to projectile, is possible for the ^{27}Al, "molecular" structure mediated reactions are irrelevant.

The experimental setup was mounted on a rail system inside the TECSA chamber at the end of the MARS line. The CAD representation of the apparatus is shown in Fig. 1. Mounted on the rail were

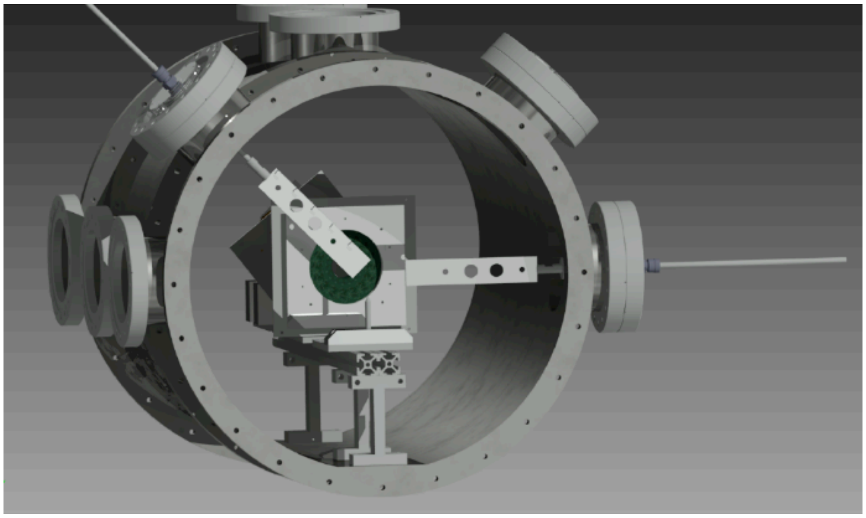

FIG. 1. CAD representation of the experimental setup in the TECSA chamber. Only the first of the annular Si telescopes can be seen from this downstream perspective.

two annular Si-CsI telescopes. We measured α-t coincidences to access the particle unbound states of ^{7}Li. In particular, we looked at the first particle unbound state at 4.63 MeV ($J^{\pi} = 7/2^{-}$), the strong peak in the invariant mass spectrum shown in Fig. 2. One goal of this experiment was to improve the energy resolution (relative to ref. [1]) of the reconstructed target energy. In that prior work (at the NSCL), the FWHM of the ground-state peak was about 10 MeV. With our apparatus at TAMU, we were able to reduce this to under 3 MeV. This was enough to strongly bias the data set with events where the ^{9}Be target stayed in its ground state (the first excited state of ^{9}Be is at 1.7 MeV) and generate a clean data set

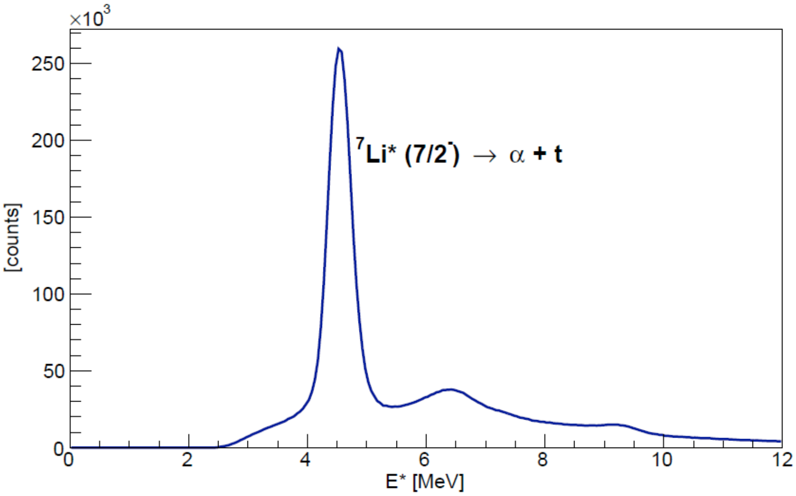

FIG. 2. Invariant mass excitation spectrum of ^{7}Li.

where the ^{12}C target stayed in its ground state. The reconstructed energies of the three targets are shown in Fig. 3.

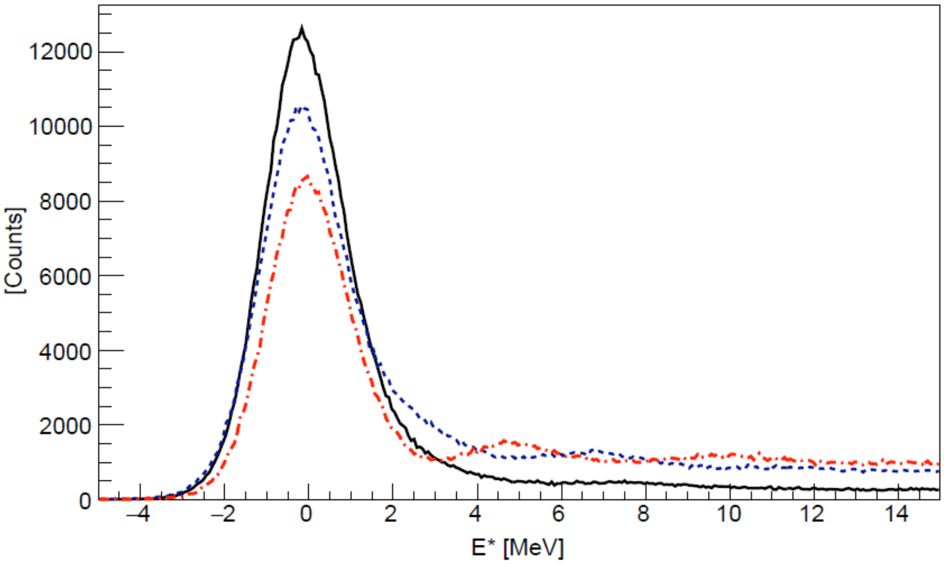

FIG. 3. Reconstructed target energy for ^{9}Be (dash/blue), ^{27}Al (solid/back), and ^{12}C (dot-dash/red).

This experiment was also the first use of the latest HINP chip system [2]. The new chip features active dual-gains allowing for a dynamic range of 0.5-400 MeV. This new system also includes remote and distributed digitization allowing for faster readout.

By measuring the angle between the relative velocity of the fragments and the beam axis, ψ, we can extract information on the spin alignment of the excited projectile (see [1] for more details). It should be noted that the fragments found at $\psi=90^{o}$, or $\cos(\psi)=0$, are transverse decays. Fig. 4 shows the

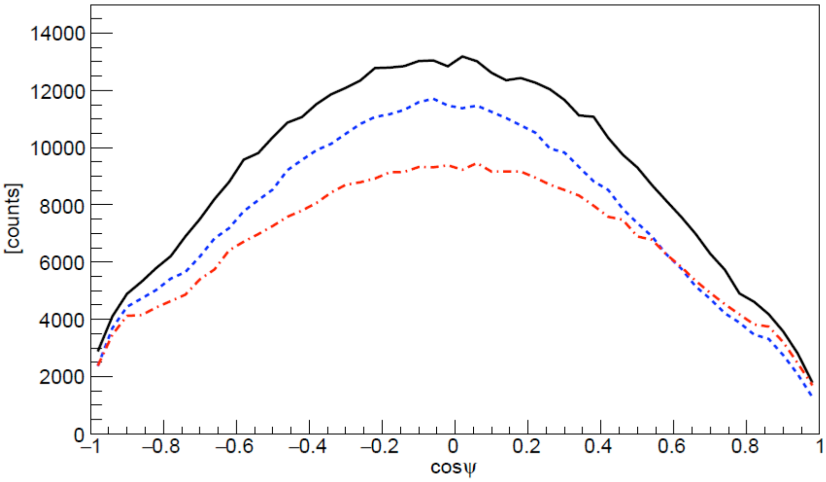

FIG. 4. $\cos(\psi)$ distrbutions for the three different targets: ^{9}Be (dash/blue), ^{27}Al (solid/black), and ^{12}C (dot-dash/red).

preliminary distributions for the three different targets: ^{27}Al (solid/black), ^{9}Be (dash/blue) and ^{12}C (dot-dash/red). These were all generated by gating on the 4.63 state of ^{7}Li and the target ground-state peak. These distributions do not include simulated efficiency corrections. However, the simulations done to date suggest that the shape of these angular distributions are largely independent of the efficiency for the detector. A significant position dependence of the CsI(Tl) light output was accounted for. At present we do not understand the asymmetry about cos(ψ)=0, but it may be due to the inferred triton calibration, extrapolated from p and d data.

In all cases, the fragment decay distributions suggest a spin alignment of the excited ^{7}Li projectile along the beam axis. This is inconsistent with our expectations and proposed reaction model. This peculiar decay, now observed for all targets, could find an explanation in the clustered structure of ^{7}Li/^{7}Be. We are presently pursuing calculations from FRESCO in an attempt to understand this observed spin alignment, along the beam axis, that these reactions seem to produce.

[1] R.J. Charity *et al.*, Phys. Rev. C **91**, 024610 (2015).

[2] G. Engel *et al.*, Nucl. Instrum. Methods Phys. Res. **A573,** 418 (2007). The updated chip was designed as part of a RIKEN/TAMU/WU collaboration. A paper on this revised chip is in preparation.