Optical pumping model of the polarization for the TRINAT experiment

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The TRIUMF Neutral Atom Trap (TRINAT) has an active experimental program to measure angular correlations in the β^+ decay of spin-polarized ^{37}K. An overview of our recent progress including a successful run in December 2012 is described in our other report. This report will focus on our progress in developing a better model of the optical-pumping process that polarizes the trapped atoms.

Optical pumping uses circularly polarized laser light to drive the potassium atoms' single valence electron to an extreme Zeeman sublevel which, due to the hyperfine coupling of atomic and nuclear angular momenta, corresponds to complete atomic and nuclear polarization. An atom in a ground state absorbs a circularly polarized photon, which promotes it to an excited state and imparts an additional unit of angular momentum to the atom. Once in the excited state, the atom quickly decays; the emitted photon can have any polarization. Through a series of repeated absorptions and emissions, the atom undergoes a biased random walk to an extreme sublevel. Once in this sublevel, called the stretched state, the atom can no longer absorb a photon as there is no excited state with the appropriate quantum numbers to conserve angular momentum. A schematic diagram of this process is shown in the Fig.1. Once an atom reaches the stretched state, it is both trapped in that state and completely polarized, an ideal combination for our polarized decay studies.

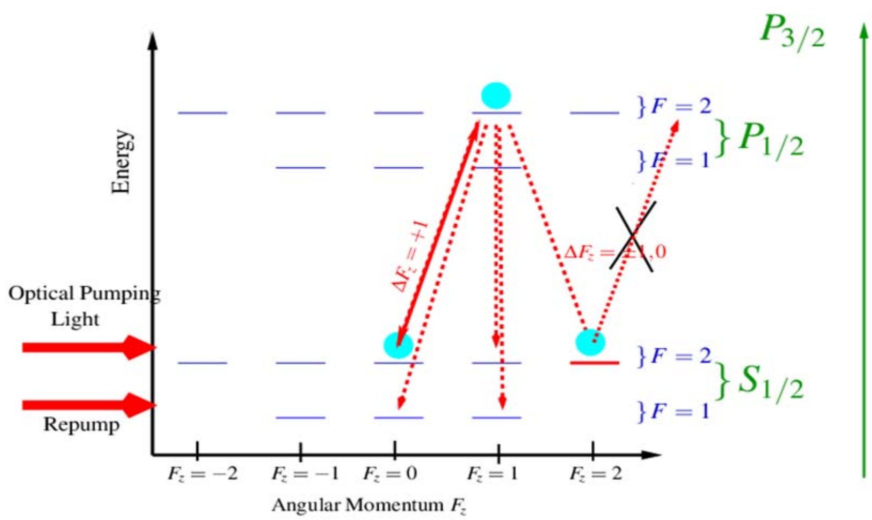

FIG. 1. Outline of the optical pumping process including the steps in the biased random walk. The quantum number F is the combined nuclear and atomic angular momentum. The stretched state is highlighted in red.

Using our current apparatus we are able to achieve polarization of 99%. To measure the polarization with the necessary precision (< 1%) requires a detailed atomic model of the process. The excited state population is monitored experimentally by photoionizing only atoms in these states and observing the resulting photoions. As atoms accumulate in the stretched state, they are no longer able to be excited and possibly photoionized. Therefore, a decrease in photoionization implies an increase in nuclear polarization, and an accurate model is required to quantitatively relate the two.

In the last year, we have improved our model to correctly account for effects that could have a negative impact on the degree of nuclear polarization. Previous models have used the rate-equation approach that essentially treats the atoms classically [1, 2]. Our improved model uses the density matrix formalism to treat the atoms quantum mechanically [3]. One important effect that is now included is the existence of coherently trapped populations, or CPT states [4]. These states arise from a coherence between two ground states with the same F quantum number but different F_Z when the main optical-pumping laser and repump laser (see figure above) have an energy difference exactly equal to the energy difference of the two states. The result of this coherence is a state that does not absorb the optical-pumping light and is also not polarized. Since atoms in this state are not available to be photoionized, we cannot experimentally distinguish unpolarized atoms trapped in the CPT states from polarized atoms trapped in the stretched state and we must rely on our model to correctly relate the decreasing fluorescence to increasing polarization. Our improved density matrix model correctly considers CPT states whereas the previous rate-equation approach was unable to include them.

Another important advantage of this approach is that any magnetic field transverse to the optical pumping axis can be precisely modeled [5]. A transverse magnetic field causes atoms to precess out of the stretched state and become depolarized. Although this misalignment is estimated be less than 2°, it can have a significant impact on the degree of nuclear polarization and is now included in our theoretical model.

The improved optical-pumping model allows for a more precise determination of the nuclear polarization, an important systematic uncertainty in previous versions of the experiment [1]. For the December 2012 run, we have too few photoion events to use this technique to determine the polarization, but the improved model will still be useful in off-line studies of stable ^{41}K as well as in recommending ideal frequencies for the optical-pumping lasers. In the future, we plan to increase the power of the photoionization laser in order to create enough photoions to measure the nuclear polarization of radioactive ^{37}K as described above. In April 2013, Benjamin Fenker successfully presented this model for a non-thesis option M.S. Degree.

In order to measure the polarization for our recent run, we will rely on a measurement of the position asymmetry of recoiling Ar ions on a micro-channel plate using a delay line anode for the necessary position sensitivity. The recoil asymmetry along the polarization axis is only sensitive to tensor interactions which are well constrained by other experiments [6, 7]. Therefore, the standard model prediction is well known and an experimental measurement of the asymmetry can be used to extract information about the degree of polarization. We are currently performing this analysis and will complete it in the upcoming year.

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