ANL/PHY/CP-97688





# Coulomb Excitation of a $^{78}$Rb Radioactive Beam

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**Abstract.** In order to test the feasibility of Coulomb excitation of radioactive projectiles with low beam energies and intensities, we have produced a secondary radioactive beam of $^{78}$Rb and Coulomb re-excited it. The beam was produced in the fusion evaporation reaction $^{24}$Mg($^{58}$Ni,3pn)$^{78}$Rb at a beam energy of 260 MeV, using the Argonne National Laboratory ATLAS accelerator. The residues of interest were separated from other reaction products and non-interacting beam using the Fragment Mass Analyzer (FMA). The beam leaving the FMA was $^{78}$Kr and $^{78}$Rb$^{gs,m1,m2}$, which was refocused onto a $^{58}$Ni secondary target. We have extracted a spectrum of $\gamma$-rays associated with re-excitation of A=78 isobars. The re-excitation of stable $^{78}$Kr was observed, which serves as a reference. Gamma-rays associated with excitation of $^{78}$Rb$^{gs,m1,m2}$ were also seen. The measured yields indicate that all the $^{78}$Rb states are highly deformed.

## INTRODUCTION

Nuclei which lie far from the valley of beta stability are important for reaching a more complete understanding of nuclear structure physics and nucleosynthesis. In the intermediate mass region, studies of proton-rich nuclei with N≈Z can improve our understanding of the evolution of shape coexistence and shell stabilized deformation. These nuclei also lie along the rp-nucleosynthesis path, which is sensitive to shapes and binding energies. They can also shed light on issues of isospin purity and mixing of T=0 and T=1 pairing modes.

N≈Z nuclei can be produced and studied in fusion-evaporation and fragmentation reactions. However, these techniques mainly populate yrast configurations. In contrast, the production of radioactive beams of these nuclei and their subsequent Coulomb re-excitation can be a powerful probe into non-yrast collectivity. At present, radioactive beam accelerators are not widely available, so it is necessary to prepare the radioactive beam as part of any experiment. One method of production is to use the kinematic properties of a primary reaction to produce a secondary radioactive beam. Beams prepared in this manner generally have low intensity, poor emittance, low beam purity, and high backgrounds due to the natural radioactivity of the beam. There is also little control over the secondary beam energy. Nevertheless, it is an experimental challenge to investigate if new data can be obtained on non-yrast collectivity from experiments done with these modest secondary radioactive beams. To date, there have been rather few attempts at re-excitation following fusion-evaporation production of the radioactive beam [1–3]. The experiment reported here represents a considerable development in the technique.

A test experiment should involve nuclear states which can be strongly populated and easily re-excited. Several candidates can be found in the A=80 region. The Rubidium isotopes are known to be deformed, with $0.3 < \beta_2 < 0.4$. We chose to study the nucleus $^{78}$Rb which has been studied in atomic beam and fusion-evaporation experiments, through which the spin and parity of the ground state and excited states have been assigned [4,5]. The ground state of $^{78}$Rb has $J^\pi=0^+$ and $T_{1/2}$=17.66min. $^{78}$Rb also has two isomers: $^{78}$Rb$^{m1}$

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with $J^\pi=4^-$, $E^*=111$keV, and $T_{1/2}=5.74$min; and $^{78}Rb^{m2}$ $J^\pi=4^+$, $E^*=115$keV, $T_{1/2} \geq 7$ $\mu$sec. The spectroscopic quadrupole moment of $^{78}Rb^{m1}$ has been measured to be $Q_s$=-0.814eb [4]. Transition rates between yrast states have also been measured [5]. The goal of this experiment was to investigate the relationship between the shapes of these states.

A beam of $\sim$ 20pnA $^{58}$Ni at 260 MeV was used to produce $^{78}$Rb, through the reaction $^{24}$Mg($^{58}$Ni,3pn)$^{78}$Rb. The $^{24}$Mg target had a thickness of 0.82 mg/cm$^2$. This inverse reaction was particularly well suited to our requirements. The residues were produced with a cross-section of 239mb (29mb for $^{78}Rb^{gs}$, 83mb for $^{78}Rb^{m1}$, and 127mb for $^{78}Rb^{m2}$), in a recoil cone with $\theta_{1/2}^{max}$ $\sim 3^o$ with a mean energy of 150 MeV. The reaction had the added advantage that it provides a stable beam of $^{78}$Kr (98mb) for reference.

After the production target, the recoiling reaction products passed through a charge resetting foil of 0.02mg/cm$^2$ $^{12}$C to equilibrate their charge-state distribution. The residues of interest were separated from the direct beam and other reaction products using the Argonne Fragment Mass Analyzer (FMA) [6]. The FMA separated recoils by A/q in a mode that was non-dispersive in energy. The central A/q setting was chosen to be A=78, q=25, with $E_R$=150 MeV. The efficiency of the FMA was $e^{3pn}_{FMA} \approx 77\%$ for $^{78}$Rb, $e^{4p}_{FMA} \approx 52\%$ for $^{78}$Kr. The fraction of recoils with q=25 was $\sim$ 24% for $^{78}$Rb and $\sim$ 21% for $^{78}$Kr . The setting of the FMA was adjusted to provide a beam which was parallel beyond the focal plane. Suppression of the primary beam was $\geq 10^7$. A 2.5cm square aperture allowed only particles with A/q=78/25 to enter the secondary beam-line. Particles were detected in two 9cmx8cm multi channel plate (MCP) detectors which were position sensitive in two dimensions with a resolution of 2.2mm, and which were placed 20cm apart. The two-MCP combination was used to characterize the secondary beam at the re-excitation target, placed 92cm behind MCP1. The MCP system could handle event rates $\geq 10^5$/sec. The position of each ion impinging on the target was determined by applying a beam tracking method. The beam spot size at the secondary target was determined to have a FWHM of 2.24cm (Fig. 1). In the data analysis, ions were required to pass through a circle of diameter 3.7cm, centered on the beam-line.

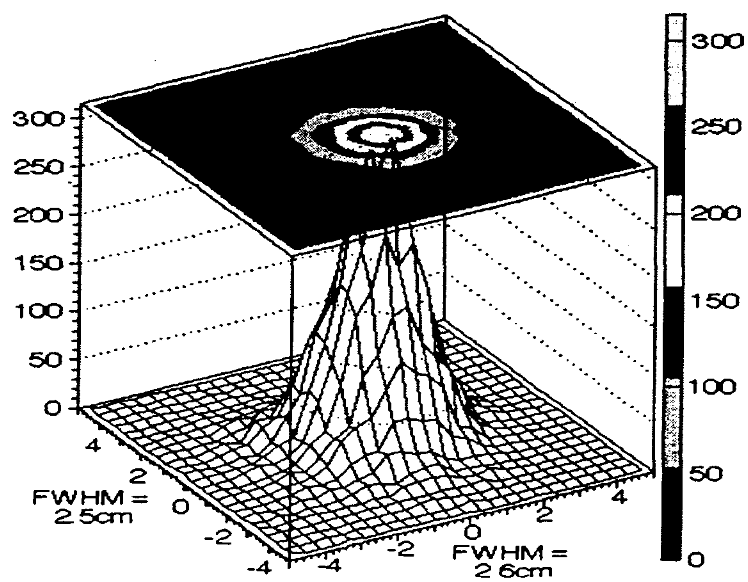


**FIGURE 1. Figure 1.** *The reconstructed beam profile at the re-excitation foil. The profile had a FWHM of 2.5cm, of which 1.1 cm was due to the tracking procedure.*

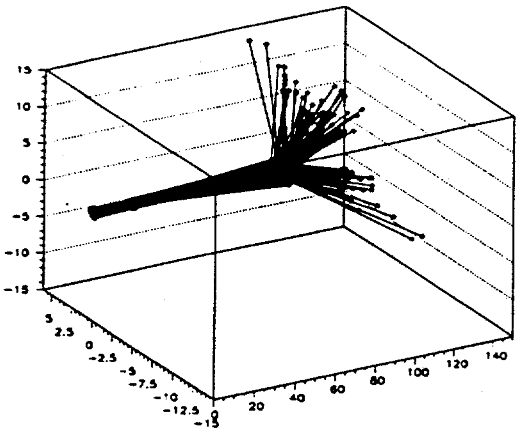

**Figure 2.** *Event-by-event ray-tracing of A=78 ions along the secondary beam-line. For clarity, only ions scattering into the beam-right and upper MWPC's are shown.*

The re-excitation target was 1.1mg/cm$^2$ $^{58}$Ni, 4.3cm in diameter. Inverse kinematics were again selected in the re-excitation reaction to insure a high probability of detecting the scattered particles downstream. $^{58}$Ni was a mechanically convenient re-excitation foil, which was not easily Coulomb excited, and from which A=78 ions were scattered in a recoil cone with $\theta_{lab}^{max} = 48^o$. The scattered ions were detected in a 4-quadrant, position sensitive multi-wire proportional counter (MWPC), placed 19cm beyond the target and subtending laboratory angles $6^o \leq \theta_{det} \leq 45^o$. Each quadrant of the MWPC was a separate detector, with all four quadrants sharing a common gas volume of isobutane at 3 Torr. The scattered-ion rate was ~3/sec. The detection of a scattered ion provided the main experimental trigger. Ions scattering at angles less than 3$^o$ in the laboratory frame were not intercepted and passed into a beam dump 20cm behind the MWPC. Photons associated with Coulomb excitation were detected in two 70% HPGe detectors, which were a distance of ~ 7cm from the target, and at an angle $\theta_{Ge} \sim 112^o$ with respect to the beam axis. From these data, complete event reconstruction was possible, allowing Doppler correction (Fig. 2). A $\gamma$-ray singles spectrum from the experiment is shown in figure 3. The spectrum is dominated by beta decay of $^{78}$Rb ions which stopped in the target chamber. The suppression of these background events, and the extraction of the $\gamma$-rays associated with Coulomb excitation of the beam came from analysis of space and time correlations between scattered ions and $\gamma$-rays.

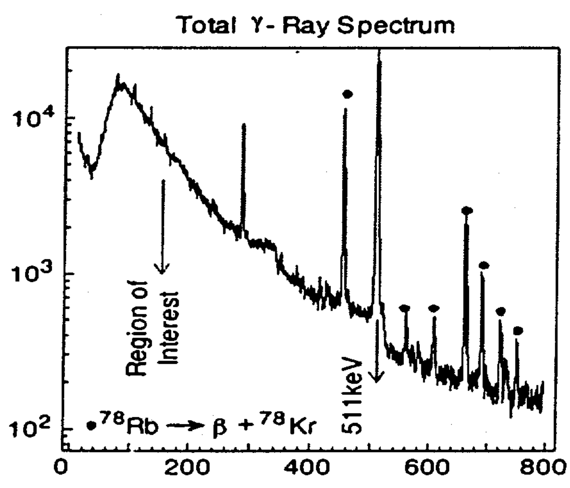


**Figure 3.** *A scaled-down singles spectrum from both of the 70% HpGe detectors. It is dominated by radioactive decay of the stopped $^{78}$Rb beam particles and room-background radioactivity.*

Figure 4 shows a time-correlation spectrum in which the real coincidences are evident above a flat background of random events. After time-random subtraction, a clean $\gamma$-ray spectrum was obtained, which is shown in figure 5. This spectrum is devoid of characteristic 511keV $\gamma$-rays associated with the $\beta^+$ decay of the beam. Coulomb excitation of $^{78}$Kr and $^{78}$Rb$^{gs,m1,m2}$ are evident. The very intense peak at ~154keV corresponds to the excitation and decay of states built on both $^{78}Rb^{m1}$ and $^{78}Rb^{m2}$ isomers. Preliminary Coulomb excitation calculations indicate that states built on the $^{78}Rb^{gs}$ have a similar collectivity to that measured for $^{78}Rb^{m1}$. The collectivity of $^{78}Rb^{m1}$ and $^{78}Rb^{m2}$ also appear to be similar, in agreement with recent in-beam measurements [5]. A quantitative analysis is in progress.

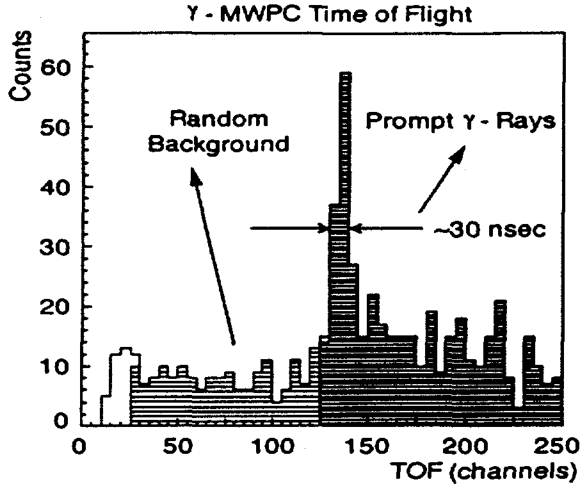


**Figure 4.** *Time correlations between scattered heavy-ions and gamma-rays. The events to the right of the prompt peak correspond to slow rise-time (low energy) pulses in the large Ge detectors.*

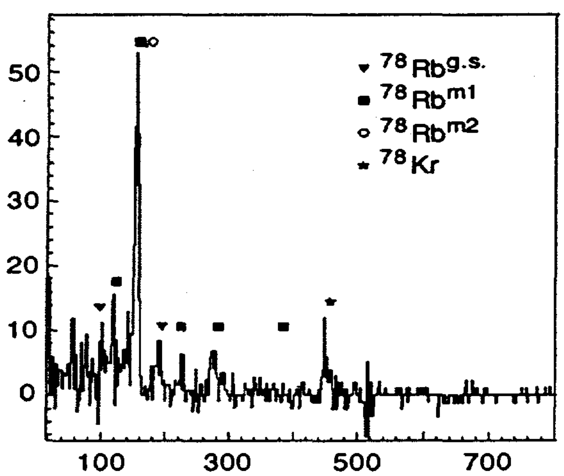


**Figure 5.** *The time-random subtracted spectrum of γ-rays associated with re-excitation of A=78 ions. Peaks associated with re-excitation of $^{78}Kr$ and $^{78}Rb^{gs,m1,m2}$ are all evident.*

This work is supported by the US Department of Energy, under contract nos. W-31-109-ENG-38 and DE-FG-91-40609, as well as grants from the NSF and U.K. EPSERC.

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