Nuclear Structure Studies in the $^{132}$Sn Region: “Safe Coulex” with Carbon Targets

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Abstract. The collective and single-particle structure of nuclei in the $^{132}$Sn region was recently studied by Coulomb excitation and heavy-ion induced transfer reactions using carbon, beryllium, and titanium targets. In particular, Coulomb excitation was used determine a complete set of electromagnetic moments for the first $2^+$ states and one-neutron transfer was used to probe the purity and evolution of single-neutron states. These recent experiments were conducted at the Holifield Radioactive Ion Beam Facility at ORNL using a CsI-HPGe detector array (BareBall-CLARION) to detect scattered particles and emitted gamma rays from the in-beam reactions. A Bragg-curve detector was used to measure the energy loss of the various beams through the targets and to measure the radioactive beam compositions. A sample of the Coulomb excitation results is presented here with an emphasis placed on $^{116}$Sn. In particular, the “safe Coulex” criterion for carbon targets will be analyzed and discussed.

1. Introduction

A powerful tool for probing shell structure and collectivity of both stable and radioactive nuclei is Coulomb excitation in inverse kinematics using particle-γ coincidence spectroscopy. The advantages of this technique include: (1) relatively large cross sections, (2) use of thick, pure, self-supporting targets, (3) excellent energy resolution from Doppler-corrected γ rays, and (4) abundant spectroscopic information from particle-γ correlations. Safe Coulomb excitation can be used to measure the electromagnetic moments of excited states, e.g., $B(E2; 2^+ \rightarrow 0^+)$, $Q(2^+_1)$, and $g(2^+_1)$, which probe the shape and coherent motion of the nucleons and provide a sensitive test of the excited-state wavefunctions. This technique was recently employed at the Holifield Radioactive Ion Beam Facility (HRIBF) of Oak Ridge National Laboratory (ORNL) to study several nuclei in the $^{132}$Sn region. Coulomb excitation results of $^{124,126,128}$Sn [1, 2] and

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Counts / 1.0 keV

| E (keV) | γ | Counts / 1.0 keV |
|--------|----|-----------------|
| 200    | 0  | 0               |
| 600    | 0  | 0               |
| 1000   | 0  | 0               |
| 1400   | 0  | 0               |
| 1800   | 0  | 0               |
| 2200   | 0  | 0               |
| 2600   | 0  | 0               |
| 3000   | 0  | 0               |
| 3400   | 0  | 0               |
| 3800   | 0  | 0               |
| 4200   | 0  | 0               |

Figure 1. γ-ray spectra following Coulomb excitation of a stable 116Sn beam on a carbon target for (a) 293.1-, (b) 336.4-, and (c) 382.7-MeV beam energies. Population of the 3− state is most prominent at the highest beam energy.

130,134Te [3] were recently published, and results for the entire chain of stable tin isotopes will be published shortly [4]. These studies were based on seminal single-step Coulomb excitation studies of radioactive Te isotopes by Radford et al. [5] and Stone et al. [6]. A sample of the recent Coulomb excitation results is presented here with an emphasis placed on 116Sn. In particular, the “safe Coulex” criterion for carbon targets will be analyzed and discussed.

2. Experiment

The experimental setup included a HPGe clover array, CLARION [7], a 2π CsI array, BareBall [8], and a Bragg-Curve detector; the setup was identical to that in Ref. [9], which provides further detail. By measuring the absolute cross sections and particle-γ angular correlations of excited states following Coulomb excitation, a complete set of electromagnetic moments can be determined, cf. Refs. [1, 2, 3]. The absolute cross sections can be obtained by measuring the Coulomb excitation to Rutherford yield, i.e., particle-γ to particle yield.

The γ-ray spectra following Coulomb excitation of a stable 116Sn beam on a 1-mg/cm² carbon target are given in Fig. 1 for (a) 293.1-, (b) 336.4-, and (c) 382.7-MeV beam energies. The spectra are dominated by single-step excitation of the 2+ state. Population of the 3− state from single-step (i.e., E3) excitation, followed by E1 decay, is most prominent for the highest beam energy. Two-step (i.e., E2 plus E1) excitation of the 3− state is significantly smaller according to calculations with the Coulomb-excitation code GOSIA [10].
The energy loss of an ion beam through a target, which can be measured with a Bragg-curve detector, is a critical component of absolute cross section measurements and comparison with theory. A Bragg detector at zero degrees was used to measure the energy loss of the beam through the target. The Bragg detector was calibrated by measuring direct beam from the 25-MV tandem at multiple energies, which was achieved quickly by changing charge states while keeping the magnetic rigidity fixed (i.e., using analog beams). The energy loss through the 1-mg/cm$^2$ carbon target was measured with a $^{114}$Sn beam and was determined to be 78.4(17) and 78.0(17) MeV for beam energies of 2.53 and 2.9 MeV/u, respectively.

There are several advantages to performing Coulomb excitation in inverse kinematics with a low-$Z$ carbon target, particularly for measuring high-precision absolute $B(E2; 0^+_1 \rightarrow 2^+_1)$ values, which include: (1) the excitation process is predominately single step, (2) the reorientation effect is minimized, (3) the target doesn’t contribute to the gamma-ray background, (4) the uncertainties are not limited by a target $B(E2)$ uncertainty (typical of relative measurements), and (5) the recoiling target nuclei are measured at backward center of mass angles where the Rutherford cross section is less sensitive to angle. Back angles in the center of mass frame minimize uncertainties related to geometry, and also maximize the ratio of Coulomb excitation to Rutherford scattering, which minimizes the non-prompt (or random) particle-$\gamma$ component.

3. Results

A leading concern with using Coulomb excitation to extract accurate electromagnetic moments is the role of Coulomb-nuclear interference on the measured cross sections. Near the barrier the Coulomb-nuclear interference is destructive, which reduces the inelastic cross sections at large center of mass scattering angles [11, 12]. For a $B(E2)$ measurement, this would result in values that are systematically too small. For a $Q(2^+_1)$ measurement, it would result in values that are overly prolate deformed. The influence of Coulomb-nuclear interference is typically mitigated by using the “safe” energy or distance criterion [11, 12], which states that the projectile and target should maintain a separation of $\geq 5$ fm. This can be achieved by selecting smaller center of mass scattering angles or by selecting a beam energy that is “safe” for all angles. However, a separation of $\geq 5$ fm is only a rule of thumb, which should be tested for each specific target-projectile system if possible.

The extracted $\langle 0^+_1 | M(E2) | 2^+_1 \rangle$ matrix elements from Coulomb excitation of a stable $^{116}$Sn beam on a 1-mg/cm$^2$ carbon target are given in Fig. 2 for beam energies of 293.1, 336.4, and 382.7 MeV, i.e., 2.53, 2.9, and 3.3 MeV/u. Virtual excitations to higher-lying states and population of the $3_1^-$ state were included in the analysis using the Coulomb-excitation code GOSIA [10]. For $\theta_{cm} = 180^\circ$ scattering, these beam energies correspond to separations of 6.76, 4.74, and 3.08 fm. However, the data were taken over $\theta_{cm} \approx 99 - 152^\circ$ and with a thick target. For $\theta_{cm} = 152^\circ$ scattering, the beam energies correspond to a separation of 7.01, 4.95, and 3.27 fm at the front of the target and 12.81, 9.15, and 6.37 fm at the back of the target. The $\langle 0^+_1 | M(E2) | 2^+_1 \rangle$ values extracted from the two lower beam energies are consistent with each other and the Raman evaluation [13]. However, the $\langle 0^+_1 | M(E2) | 2^+_1 \rangle$ value extracted from the higher beam energy at 3.3 MeV/u shows a deviation that is consistent with a destructive Coulomb-nuclear interference effect.

In order to better understand the impact of quantum corrections and Coulomb-nuclear interference on the extracted $\langle 0^+_1 | M(E2) | 2^+_1 \rangle$ matrix elements, calculations with the quantum code PTOLEMY [15] and the semi-classical code GOSIA [10] were compared for various optical potentials, cf. Fig. 3. These calculations only consider excitation of the first $2^+_1$ state. The
Figure 2. Extracted $\langle 0^+_1||M(E2)||2^+_1 \rangle$ matrix elements from Coulomb excitation of a stable $^{116}$Sn beam on a 1-mg/cm$^2$ carbon target for (a) 293.1-, (b) 336.4-, and (c) 382.7-MeV beam energies. The statistical and total uncertainties are given as red and black error bars, respectively. For comparison, the adopted value of 0.457(7) eb from the Raman evaluation [13] is shown with a dashed (shaded) horizontal line. A recent lifetime measurement by Jungclaus et al., [14] reported 0.409(12) eb, which is not shown here.

4. Conclusions

From the present results, it is concluded that the $\geq 5$-fm separation rule of thumb for “safe” Coulomb excitation is reasonably upheld by the tin isotopes on a carbon target. Furthermore, the quantum corrections to the semi-classical approximation is less than 2%. Testing the “safe” criterion for each specific target-projectile system is particularly important when conducting high-precision, i.e., $< 5\%$, Coulomb excitation measurements. However, if slightly “unsafe” energies are used, the destructive Coulomb-nuclear interference effect can be mitigated to some degree by selecting smaller center of mass scattering angles and thicker targets.

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Figure 3. Ratio of calculated $2^+_1$ cross sections from the quantum code PTOLEMY [15] and the semi-classical code GOSIA [10] for various optical potentials. Real potentials from $V = 0$ to 80 MeV and imaginary potentials from $W = 0$ to 100 MeV were used. The experimental $B(E2; E_{beam})/B(E2; E_{beam} = 2.9)$ ratios with statistical uncertainties are shown for comparison, where $B(E2) = \langle 0^+_1 | |M(E2)||2^+_1 \rangle ^2 \propto \sigma(2^+_1)$.

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