Precision Lifetime Measurement of 2_1^+ State in ^{120}Te

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Abstract. The lifetime of the ^{120}Te first-excited 2^+ state is measured using the recoil distance Doppler shift (RDDS) method after population by inverse-kinematics Coulomb excitation. The resulting mean lifetime of 10.4(2) ps provides a factor of ten improvement in precision relative to the previously accepted value. A number of necessary corrections are discussed stemming from relativistic effects due to large recoil velocities.

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For many even-even nuclei, the lifetime of the first 2^+ states is known only from measured Coulomb excitation cross sections. Systematic errors in lifetimes extracted in this way can sometimes arise from assumed quadrupole moments and unobserved or virtual feeding. The recoil distance Doppler shift (RDDS) method provides a simple, model-independent means of measuring lifetimes. The RDDS method is applied in a novel way for the present measurement, using Coulomb excitation in inverse kinematics well below the Coulomb barrier to excite the 2_1^+ state directly. The large recoil velocity ($\sim$6% c) and simple reaction employed here yield a very clean γ-ray spectrum with large Doppler shifts. While this is conducive to precise and accurate lifetime measurements, the more relativistic recoil velocity introduces effects, primarily in the angular distribution of emitted γ-rays, which must be addressed to accurately deduce a lifetime.

The measurement was performed at the Wright Nuclear Structure lab on the campus of Yale University using the New Yale Plunger Device (NYPD) [1] and the SPEEDY array [2]. A 300-MeV beam of ^{120}Te was produced in the 20-MV ESTU Tandem Van de Graaff. Excited states in ^{120}Te are produced by Coulomb excitation in a target foil consisting of a 400 μg/cm^2 layer of carbon and a 40 μg/cm^2 gold backing. After exiting the target, the beam recoils through a fixed distance and comes to rest in a stopper foil consisting of a single 14 mg/cm^2 layer of copper. Gamma-rays were detected in eight HPGe clover detectors mounted in the SPEEDY array: four forward-angle detectors at 41.5°and four backward-angle detectors at 138.5° relative to the beam axis. A cylindrical silicon particle detector was mounted at 0° relative to the beam axis and subtended a scattering angle of $\sim$30-40°. Data were acquired event-by-event with the acquisition

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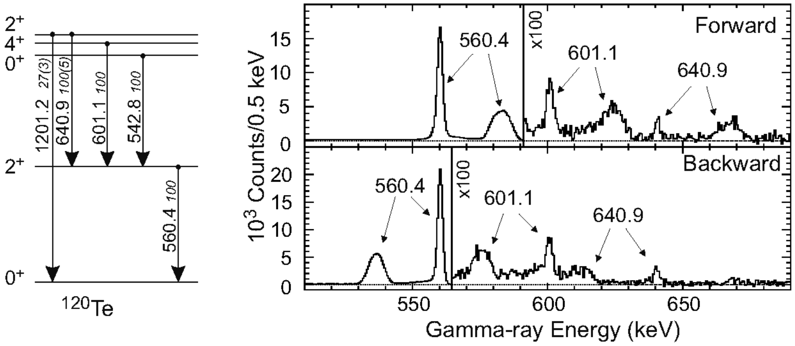

FIGURE 1. Sum spectra for all distances. Data from the 41.5° and 138.5° rings are shown in the upper and lower panels, respectively.

system triggered on a coincidence between the particle detector and any one of the γ-ray detectors. Foil thicknesses are chosen such that essentially only Coulomb scattered carbon nuclei reach the particle detector, yielding a very clean γ-ray spectrum for the Coulomb excitation reaction.

Gamma-ray spectra for the forward- and backward-angle groups of detectors summed over all target-stopper distances are shown in Fig. 1. The 560.4-keV $2_1^+ \rightarrow 0_1^+$ transition dominates the spectrum due to a mid-target beam energy of only $\sim$50% of the Coulomb barrier. Higher-lying states are populated with γ-ray intensities of 1.06(16)% for the 601.1-keV $4_1^+ \rightarrow 2_1^+$ transition and 0.424(37)% for the 640.9-keV $2_2^+ \rightarrow 2_1^+$ transition relative to the 560.4-keV intensity. The 542.8-keV $0_2^+ \rightarrow 2_1^+$ transition was not observed and an upper limit for the γ-ray intensity of 0.08% is estimated.

The recoil velocity is determined from the Doppler shift between γ-rays emitted in-flight and at-rest. Analysis of the Doppler shift in individual "leaves" (clover elements) of both forward and backward angle detectors yields a recoil velocity of 5.62(5)% c.

The vast majority of the Coulomb excitation cross section directly feeds the 2_1^+ state (see Fig. 1). Ignoring the $\sim$1% indirect feeding, the probability that the 2_1^+ state decays in-flight for a fixed target-stopper separation d is given by

$$P(d) = 1 - exp(-\frac{d}{\tau v}) \tag{1}$$

where τ is the mean lifetime of the state and v is the recoil velocity.

From the data, the probability P is taken from the intensity of the Doppler-shifted peak normalized by the summed intensity of the transition. The summed intensity includes the shifted and non-shifted peaks and additionally a small Doppler-shift attenuation (DSA) continuum between the shifted and non-shifted peaks caused by γ-ray emission during stopping. To extract intensity ratios from the spectra, peak areas are corrected for the difference in photopeak detection efficiency and angular distributions between the shifted and non-shifted peaks. Efficiency corrections are taken from measurements with a standard ^{152}Eu source. Angular distribution corrections are discussed below.

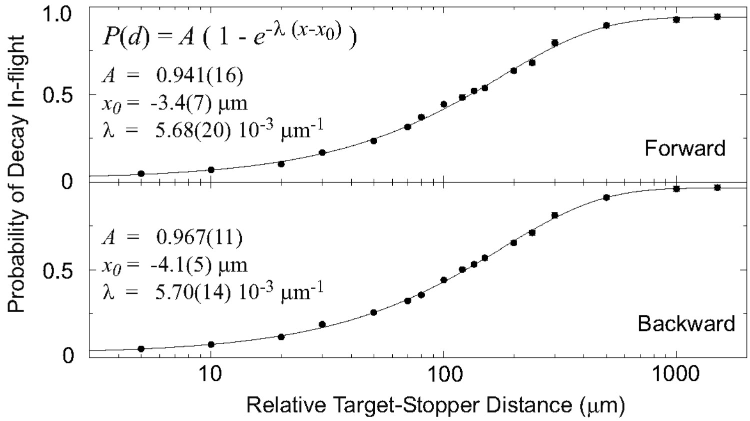

FIGURE 2. Probability (P) of decay while in flight vs. relative target-stopper distance (d). Error bars are plotted but, for many points, are hidden by the plot symbol.

At high recoil velocities, the angular distribution of γ-rays emitted from rest and in-flight differ. The in-flight angular distribution is more forward-focused in the lab frame of reference due to the Lorentz boost. The Lorentz transformation of the angular distribution consists of a transformation of the emission angle as well as a multiplicative factor J given by the Jacobian of the transformation:

$$J = \frac{d\Omega_{CM}}{d\Omega_{lab}} = \frac{1-\beta^2}{(1-\beta cos\theta_{lab})^2} \tag{2}$$

Due to the relative flatness of the $2_1^+ \rightarrow 0_1^+$ angular distribution at 41.5° and 138.5°, the transformation of the emission angle has a nearly negligible effect on the angular distribution. However, even for relatively low recoil velocities, the Jacobian of the transformation leads to a significant difference in angular distributions between shifted and non-shifted peaks. In the present analysis, a correction of $\sim$8% is applied to the shifted peak areas, leading to a change of approximately the same magnitude in the extracted lifetime.

Higher recoil velocities also lead to time dependence in the angular distribution due to a stronger hyperfine interaction between the nucleus and the atomic electrons during recoil in vacuum [3]. This interaction causes a de-orientation of the aligned nuclear state, thereby attenuating asymmetry in the angular distribution of emitted γ-rays. A time-dependent attenuation coefficient $G_k(t)$, which presently can only be determined empirically, is included in the angular distribution to account for this effect.

De-orientation due to recoil in vacuum has been extensively studied for tellurium isotopes recoiling at $v \sim 6\%$ c [4]. The time dependence of the attenuation coefficient is assumed to arise from interaction of the nucleus with an ensemble of electronic configurations in the static limit giving an exponential dependence (see Eqs. 11 and 12 of [4]). The time dependence is parametrized by α_k, C_k, and the magnitude of the

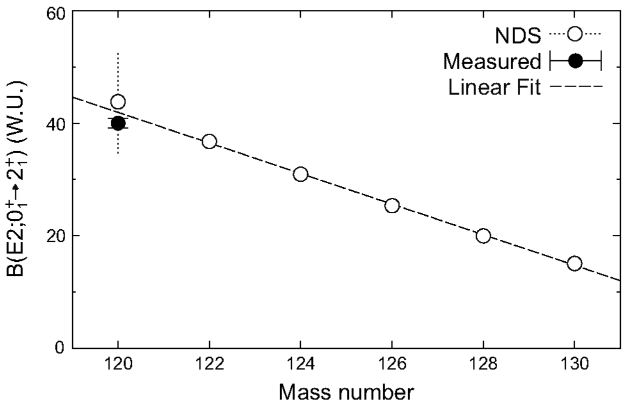

FIGURE 3. Reduced transition probabilities for the stable tellurium isotopes.

g-factor for the 2_1^+ state. As discussed in [4], we adopt the parametrization $\alpha_k = 0$, $C_2 = 2.14(11)$ ps, and $C_4 = 1.18(5)$ ps. The g-factor for the 2_1^+ state is +0.56(8) [5].

For a fixed target-stopper distance d, γ-rays emitted at rest are subject to maximal de-orientation. The attenuation coefficient $G_k(t)$ is integrated over the range $t = 0$ to $t = d/v$:

$$G_k^{(rest)}(d) = exp\left(-\frac{|g|d}{vC_k}\right) \tag{3}$$

For γ-rays emitted in-flight, emission may occur at any time between $t = 0$ and $t = d/v$. Therefore, $G_k(t)$ must be folded with the decay probability over this range:

$$G_k^{(in-flight)}(d) = \frac{1}{1+\frac{|g|\tau}{C_k}} \frac{1-exp\left(-(1+\frac{|g|\tau}{C_k})\frac{d}{v\tau}\right)}{1-exp\left(-\frac{d}{v\tau}\right)} \tag{4}$$

Gamma-ray angular distributions are calculated with statistical tensors taken from a modified version of the Winther-de Boer multiple Coulomb excitation code [6]. In addition to the recoil-in-vacuum coefficient, an attenuation coefficient due to the finite size of the γ-ray detector is included. Corrections of 0-5% (depending on target-stopper distance) are applied to in-flight intensities based on the ratio of the stopped to in-flight angular distributions at 41.5° and 138.5°. This correction gives a 4% increase in the extracted lifetime.

Results from this analysis with all corrections included are summarized in Fig. 2. The weighted average of forward- and backward-angle results gives a mean lifetime of $\tau = 1/v\lambda = 10.4(2)$ ps. This corresponds to a reduced transition probability of B(E2;$0_1^+ \rightarrow 2_1^+$) = 0.703(14) e^2b^2. This value is consistent with the accepted value of 0.77(16) e^2b^2 listed in the Raman compilation [7]. However, the precision is improved by a factor of ten.

Reduced transition probabilities from the ground state to the 2_1^+ state for the even-even stable tellurium isotopes are shown in Fig. 3 [7]. The previously accepted B(E2;$0_1^+ \rightarrow$

2_1^+) value of ^{120}Te is the only point with an error bar that is not negligible compared to the size of the plot symbol. The B(E2;$0_1^+ \rightarrow 2_1^+$) values of the even-even tellurium isotopes from $A = 122$ to $A = 130$ lie on a straight line in good agreement with predictions of the U(5) limit of the IBA-1 assuming a constant effective charge for the chain [8]. The B(E2) value of ^{120}Te now clearly deviates from this trend, suggesting a change in structure near mid-shell for the tellurium isotopes.

These results should be considered preliminary. While most corrections have been included, a significant correction arises from indirect feeding of the first-excited 2^+ state from higher-lying excited states. The resulting correction, if any, will lower the deduced lifetime of the 2_1^+ state. An initial estimate, assuming lifetimes of 5 ps for these states, suggests a reduction of approximately 1%. Actual lifetimes for these higher-lying states will be obtained from the present data by analysis of relative Coulomb excitation cross sections.

In conclusion, the RDDS method has been employed in a novel way to yield a precision measurement of the ^{120}Te 2_1^+ state. The technique was shown to produce very clean spectra with lifetimes extracted through a straight-forward analysis. However, large recoil velocities introduce relativistic effects primarily in the angular distribution of emitted γ-rays. Necessary corrections are applied to the data to yield a mean lifetime of 10.4(2) ps. This technique should also be applicable to radioactive ion beams by replacing the zero-degree detector with an annular one.

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