19Mg two-proton decay lifetime

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The ground state two-proton decay lifetime of 19Mg, populated by the one-neutron knockout of an intermediate-energy 20Mg radioactive beam, was measured utilizing a new experimental technique. A thin silicon detector positioned at varying distances (0.0–1.0 mm) downstream of the reaction target measured the energy loss of 19Mg and the two-proton decay product 17Ne. The lifetime was deduced from fits to the measured energy-loss line shapes and depended upon the contribution of prompt reaction processes to the yield of 17Ne. For relative 17Ne prompt contributions from 82% to 92%, the extracted lifetimes ranged from 1.75±0.42 to 6.4±2.4 ps. The results are consistent with the previously reported 19Mg lifetime measurement and serve as both an important complementary study and a validation of this new technique, which can provide lifetime information for short-lived states beyond the proton drip line.

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I. INTRODUCTION

Mapping the limits of nuclear existence and performing precise spectroscopy of rare atomic nuclei with extreme proton-neutron asymmetries requires the development of sensitive experimental techniques to surmount short lifetimes, low production cross sections, and large background signals. The exotic two-proton (2p) decay of even-Z nuclei beyond the proton drip line exemplifies such challenges; more than 40 years passed between prediction [1] and experimental confirmation [2,3].

Lifetime measurements have proven to be an important probe of the decay properties of these short-lived 2p-emitting nuclei. For example, the 2p-emission lifetimes of 45Fe [2–5], 48Ni [4,6], and 54Zn [7] have been measured to be several milliseconds. In comparison with theoretical predictions, these relatively long lifetimes provided strong evidence for the necessity of a three-body quantum mechanical description of the decay process; modeling the decay as the tunneling of a diproton (2He nucleus) typically yielded lifetimes several orders of magnitude too short (cf. Refs. [8–10]). Subsequently, direct visual evidence in support of a true three-body decay was observed in 45Fe [5] and 48Ni [6] using the optical time-projection chamber technique. For lighter nuclei, both the Coulomb and the centrifugal barriers are reduced with respect to the aforementioned, medium-mass 2p emitters, and the lifetimes are correspondingly shorter. Therefore, to access the wealth of nuclear structure information beyond the proton drip line, a wide variety of experimental techniques are required. In this work, we present an adaptation of the well-established recoil distance method used in γ-ray spectroscopy [11] for lifetime measurements of proton emitters with lifetimes from 10−13 to 10−10 s. The 2p emitter 19Mg was chosen for the first application of this new technique. The ground state 2p-decay mean lifetime was previously measured to be τ = 5.8 ± 2.2 ps (T1/2 = 4.0 ± 1.5 ps) via trajectory reconstruction of all three decay components (17Ne + p + p) [12]. The results fell well within the predicted 0.5 to 60 ps lifetime range of a three-body decay calculation [13] and near the upper limit of the 0.06 to 8.2 ps lifetime range assuming a diproton emission model [14,15]. Both models favored a dominant d2 configuration for the 19Mg valence protons. However, spectroscopy of the unbound intermediary nucleus 18Na uncovered unexpected low-lying broad s-wave resonances; 19Mg lifetime estimates via sequential 1p decays through these states were as low as 1 ps [16]. This wide range of predicted lifetimes warrants an independent confirmation of the measured results using a new and complementary method. Hence, a particle plunger variant of the Köl/Nscl plunger [17] for lifetime measurements beyond the proton drip line was developed. In this technique, a double-sided silicon strip detector (DSSD) is installed in place of the plunger degrader to measure the energy loss of reaction and decay residues (19Mg and 17Ne, respectively) emerging from the target in coincidence with ion identification in the S800 Magnetic Spectrograph [18]. Lifetime information can then be extracted from the variation of 19Mg and 17Ne energy-loss peak intensities at various target-DSSD distances.

II. EXPERIMENTAL METHOD

The lifetime measurement was performed at the National Superconducting Cyclotron Laboratory (NSCL). A 170 MeV/nucleon 24Mg12+ primary beam was accelerated

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by the Coupled Cyclotron Facility and impinged upon a 1081 mg/cm² ⁹Be production target. A radioactive ²⁰Mg secondary beam was selected from the fragmentation reaction products by the A1900 Fragment Separator [19]. Three significant beam contaminants—²⁰O (29%), ¹⁷F (11%), and ¹⁸Ne (19%)—were distinguished from ²⁰Mg (36%) by their time of flight between two thin plastic scintillators at the A1900 focal plane and the S800 object position, as illustrated in Fig. 1. The ¹⁰C contaminant, with the same charge-to-mass ratio as ²⁰Mg (and hence the same time of flight), was separated by energy-loss differences in the S800 ionization chamber [20].

The ²⁰Mg secondary beam was delivered to the Köln/NSCL particle plunger at the S800 target position with an energy of 91 MeV/nucleon and an average intensity of 1600 pps. States in ¹⁹Mg were populated via a one-neutron knockout reaction on a 110 mg/cm² ⁹Be target and the nucleus decayed by ²p emission to ¹⁷Ne after a flight distance governed by the lifetime and beam velocity. The energy-loss profile of each ion emerging from the target was detected in a 69 mg/cm² (0.30 mm) DSSD mounted perpendicular to the beam axis immediately downstream of the target. Knockout-reaction and decay residues were identified on an event-by-event basis by the S800 Spectrograph tuned for acceptance of ¹⁷Ne⁰⁺. The region surrounding the ¹⁹Mg energy-loss peaks (shaded red) for the production of ¹⁷Ne, both in the target. The small enhancement at higher energy corresponds to magnesium energy loss—from the production of ¹⁹Mg in the target or detector and ²p decay farther downstream. The broad plateau between these extremes corresponds to events with mixed neon and magnesium energy losses.

III. EXPERIMENTAL RESULTS

¹⁷Ne-gated DSSD energy-loss spectra were collected at target-DSSD distances of 0.0, 0.1, 0.2, 0.5, and 1.0 mm. In addition to the delayed ground state ²p decay of ¹⁹Mg, three indistinguishable prompt processes, occurring on a time scale (t < ~10⁻¹⁵ s) well below our experimental sensitivity, contributed to the observed ¹⁷Ne yield: the ²p ¹¹n breakup of the ²⁰Mg secondary beam, the ¹p ¹⁰n breakup followed by prompt proton emission from unbound ¹⁸Na [16,21,22], and sequential ¹p emissions of ¹⁹Mg excited states through broad resonances in ¹⁸Na. Furthermore, the ²⁰Mg beam had sufficient energy to pass unreacted through the target and undergo knockout reactions on the DSSD. Together, the combination of delayed and prompt ¹⁷Ne production processes and reactions on both the target and the DSSD yielded the energy-loss line shape shown in Fig. 3(a). There, the prominent peak corresponds to neon energy loss—from the ²p decay of ¹⁹Mg and the prompt production of ¹⁷Ne, both in the target. The small enhancement at higher energy corresponds to magnesium energy loss—from the production of ¹⁹Mg in the target or detector and ²p decay farther downstream. The broad plateau between these extremes corresponds to events with mixed neon and magnesium energy losses.
IV. SIMULATIONS AND ANALYSIS

Fitting the DSSD energy-loss data with simulated line shapes generated with various input lifetimes and then applying a $\chi^2$ goodness-of-fit test yields the best-fit lifetime. The DSSD line-shape simulations and statistical analysis were performed within the GEANT4 [23] and ROOT [24] toolkits and were modified from $\gamma$-ray line-shape simulation software used extensively for recoil distance method lifetime analyses [25–27]. Obtaining accurate energy-loss line shapes required a parametrization of the experimental details impacting the observed reaction- and decay-residue momentum distributions. In particular, the simulations accurately reproduced the S800 momentum acceptance and the DSSD detector response, as well as the $^{20}\text{Mg}$ secondary beam emittance, the knockout-reaction kinematics, and the subsequent energy and angular straggling of both $^{19}\text{Mg}$ and $^{17}\text{Ne}$ in the target and detector. Figure 4 illustrates the quality of select fits to the data.

DSSD energy-loss spectra in coincidence with incoming $^{20}\text{Mg}$ on the target and outgoing $^{18}\text{Ne}$ in the S800 (see Fig. 2) were used to properly account for the high-energy background extending beyond the $^{19}\text{Mg}$ energy-loss region evident in Fig. 3. These events originated from the $2p$ knockout of the $^{20}\text{Mg}$ secondary beam or the proton decay of the $1p$-knockout residue $^{19}\text{Na}$. Shell model calculations of the proton-decay width indicate that the unbound $^{19}\text{Na}$ ground state has an approximately 1 fs decay lifetime [28]. Both processes contributing to these $^{18}\text{Ne}$ energy-loss line shapes are thus prompt, allowing the high-energy background to be parametrized without the presence of lifetime effects. The background parameters were determined from the simulated best-fit to the $^{18}\text{Ne}$-gated energy-loss line shapes at a fixed lifetime of $\tau = 0$ ps and were subsequently applied to the $^{19}\text{Mg}$ analysis.

The contribution of prompt processes to the observed $^{17}\text{Ne}$ yield was parametrized by a production mechanism ratio, $R_p$, given by

$$R_p = \frac{N_{\text{prompt}}}{N_{\text{delayed}} + N_{\text{prompt}}}.$$  \hspace{1cm} (1)

Here, a value of 0 corresponds to 100% delayed production of $^{17}\text{Ne}$ by the $2p$ decay of the $^{19}\text{Mg}$ ground state and $N_{\text{prompt}}$ is the sum of the three processes discussed above. Similarly, the ratio of knockout reactions on the target to those on the detector, $R_\sigma$, was parametrized as

$$R_\sigma = \frac{N_{\text{tar}}}{N_{\text{det}}}.$$  \hspace{1cm} (2)

Therefore, with the simulation parameters systematically fixed to reproduce the observed momentum distributions and high-energy background, DSSD energy-loss line shapes were constructed within the three-dimensional parameter space of $\tau$, $R_p$, and $R_\sigma$. We have performed knockout-reaction cross section calculations to constrain $R_\sigma$. Assuming $p$-wave neutron removal from $^{20}\text{Mg}$ at beam energies between 80 and 90 MeV/nucleon, we obtained a reaction ratio of $R_\sigma = 3.2$. Additional calculations using EAPAX 2.15 [29] and Abration Ablation [30,31] fragmentation parametrizations within LISE++ [32] yielded ratios of $R_\sigma = 2.9$ and 3.3, respectively. Finally, similar LISE++ cross section estimates were obtained for the $1p$ knockouts, producing $^{19}\text{Na}$, and the best-fit simulations of its subsequent prompt $1p$-decay data were obtained within the well-constrained range $R_\sigma = [3.0,3.4]$. We have therefore adopted the values $R_\sigma = 3.0$, 3.2, and 3.4 for the $^{19}\text{Mg}$ analysis.

In contrast, we have taken a twofold approach for the constraint of the $^{17}\text{Ne}$ production mechanism ratio. First, the ratio was left unconstrained and lifetimes were determined in 10% intervals within the range $R_p = [0.05,0.95]$. These results highlight the effect of an increasing $^{17}\text{Ne}$ prompt production on the best-fit $2p$-decay lifetime of $^{19}\text{Mg}$; in general, larger values of $R_p$ require longer lifetimes to properly fit the data. In addition, tighter constraints were placed on the $^{17}\text{Ne}$ production mechanism ratio in an effort to compare our results.
of 20Mg on a thick beryllium target at 450 MeV

restrict target compositions for the two measurements in order to ratios were calculated using the proper beam energies and $\chi$ bars are due largely to the cubic polynomial fits to the distributions of $R_p$ with statistical uncertainties (solid black line) and simulated over the same energy range as the plots in Figs.3(b)–3(d). The best-fit $\tau$ for three lifetimes: $\tau = 0.50$ ps (a), $\tau = 2.14$ ps (b), and $\tau = 4.50$ ps (c). Background contributions are shown in gray. The data and lifetime of 2.14 ps is taken from the minimum of the black curve for $\tau$ for three lifetimes: $\tau = 0.50$ ps (a), $\tau = 2.14$ ps (b), and $\tau = 4.50$ ps (c). Background contributions are shown in gray. The data and

τ

with those of the complementary technique presented in detail in Refs. [12,33,34]. There, a one-neutron knockout reaction of 20Mg on a thick beryllium target at 450 MeV/nucleon was used to populate states in 19Mg. The energy and angles of all three 19Mg decay products were measured independently, and from the reconstructed decay vertex profile, a lifetime of $\tau = 5.8(22)$ ps was deduced. Prompt contributions to the decay vertex profile had to be accounted for as their impact on the lifetime analysis was identical to that of $R_p$ on the present analysis. From the measured proton–17Ne angular correlations, the authors determined the prompt contribution of the 17Ne yield to be 89(1)% [35] from the analysis presented in Ref. [36].

With this value in mind, knockout-reaction cross section ratios were calculated using the proper beam energies and target compositions for the two measurements in order to restrict $R_p$ for the present work. First, calculations of $p$-wave neutron removal from the 20Mg secondary beam to the 1/2– ground state and low-lying 3/2– excited states in 19Mg [36] were performed. The results indicated a modest 4% increase in both 19Mg ground state production—the only source of delayed 17Ne—and excited state production—one source of prompt 17Ne—for our work compared to Ref. [12]. Next, multinucleon-removal calculations of the 2p1n breakup of 20Mg to 17Ne and the 1p1n breakup to 18Na—both prompt processes producing 17Ne—were performed. The calculations treated all valence nuclei as uncorrelated and equally available for removal and then computed the geometric probability that 2p1n or 1p1n groupings would be struck and removed by the target; this uncorrelated model is discussed briefly in Refs. [37,38]. The results indicated 7% less production of prompt 17Ne from these channels in our work compared to Ref. [12]. From this information, we calculate $R_p = 0.87$ for our measurement. Attaching a conservative uncertainty of ±5%, we arrive at the constrained range $R_p = [0.82, 0.92]$ and have investigated the best-fit lifetime at the additional values of 0.82, 0.88, 0.90, and 0.92.

Hence, simulated energy-loss line shapes were generated over a broad lifetime range for all $R_p$,$R_\sigma$ pairs. A varying normalization factor accounted for statistical differences between the simulations and data. The 0.0 mm energy-loss data were found to be the most sensitive to lifetime effects due to the dominance of prompt 17Ne production mechanisms along with the short 19Mg lifetime. We have therefore only used these data for the full analysis. Distributions of $\chi^2$ values from the fits of simulated and experimental spectra were constructed for each $R_p$,$R_\sigma$ pair. The best-fit lifetimes and statistical errors ($\delta\tau_{\text{min}} + 1$) were taken from cubic polynomial fits to these distributions for $R_p$ values in the range 0.05 to 0.90. The distributions obtained for $R_p = 0.92$ and 0.95 were quite broad and best fit with phenomenological power laws. Samples of nine such fits are provided in Fig. 5 for $R_p = 0.35, 0.55,$ and 0.85 and all three $R_\sigma$ values. The sensitivity to small changes in lifetime is enhanced for small values of $R_p$ as expected; with limited contributions from prompt 17Ne production processes, the intensity ratio of the small 19Mg and prominent 17Ne energy-loss peaks is heavily dependent upon the ground state 2p-decay lifetime. Figure 6 illustrates the sensitivity of the simulated line-shape features to changes in lifetime. These simulations were generated using $R_p = 0.85$ and $R_\sigma = 3.2$. The superior fit of the $\tau = 2.14$ ps simulation is clear; this lifetime value was extracted from the minimum of the black curve in Fig. 5(c).

Figure 5 demonstrates that the spread in best-fit lifetimes introduced by the variation of $R_\sigma$ is insignificant compared to that from the variation of $R_p$. Therefore for each $R_p$, the best-fit lifetime is taken from the central value $R_\sigma = 3.2$ and

![](image.png)

**FIG. 6. (Color online) The 0.0 mm experimental DSSD spectra in coincidence with incoming 20Mg on the target and outgoing 17Ne in the S800 with statistical uncertainties (solid black line) and simulated line shapes (dashed red line) generated with $R_p = 0.85$ and $R_\sigma = 3.2$ for three lifetimes: $\tau = 0.50$ ps (a), $\tau = 2.14$ ps (b), and $\tau = 4.50$ ps (c). Background contributions are shown in gray. The data and simulated line shapes (0.50 ps, dotted blue line; 2.14 ps, dashed red line; and 4.50 ps, dashed blue line) are replotted for comparison (d) over the same energy range as the plots in Figs. 3(b)–3(d). The best-fit lifetime of 2.14 ps is taken from the minimum of the black curve for $R_p = 0.85$ in Fig. 5(c).**

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<td>3.7</td>
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<td>+0.14</td>
<td>+0.16</td>
<td>+0.18</td>
<td>+0.21</td>
<td>+0.25</td>
<td>+0.33</td>
<td>+0.43</td>
<td>+0.49</td>
<td>+0.68</td>
<td>+1.0</td>
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<td>—</td>
</tr>
<tr>
<td>$\delta\tau_{\text{total}}$</td>
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<td>−0.12</td>
<td>−0.14</td>
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<td>−0.18</td>
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<td>−2.7</td>
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TABLE I. 19Mg ground state 2p-decay lifetime (in ps) as a function of the 17Ne production mechanism ratio $R_p$. The asymmetric error bars are due largely to the cubic polynomial fits to the distributions of $\chi^2$ values in Fig. 5; there it is clear that the third-order term’s coefficient becomes more significant at large $R_p$. 

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and outgoing $^{17}\text{Ne}$ in the S800 with statistical uncertainties (solid black line) and simulated line shapes (dashed red line) generated with $R_p = 0.85$ and $R_\sigma = 3.2$ for the best-fit lifetime of $\tau = 2.14$ ps extracted from fits to the 0.0 mm energy-loss data. Background contributions are shown in gray.

those from simulations of the upper and lower $R_\sigma$ limits form the main contribution to the systematic error. Discrepancies between the experimental and the simulated reaction- and decay-residue momentum distributions affect energy losses and comprise a second source of uncertainty. The impact of this systematic error was investigated with small variations in both the target and detector thickness and the S800 momentum acceptance. These changes were found to contribute only half as much as the uncertainties of $R_p$. The sum of these two systematic errors was adopted for the final results as all other sources were found to be negligible. Table I summarizes the best-fit lifetime results with the total systematic and statistical errors summed. No clear minimum was obtained for the distribution of $\chi^2$ values at $R_p = 0.95$; the distribution flattened at 8.1 ps and this has been taken as a lower limit on the lifetime.

As a consistency check, the simulated energy losses for the best-fit lifetime of 2.14 ps at $R_p = 0.85$ and target-DSSD distances of 0.1 and 0.5 mm are plotted against the corresponding experimental DSSD spectra in Fig. 7. The compatibility in shape indicates that using the 0.0 mm energy-loss data for the full line-shape analysis did not bias the results. Figure 8 summarizes the best-fit lifetimes and total uncertainties in Table I to illustrate the lifetime trend as a function of increasing $^{17}\text{Ne}$ prompt production (red squares) with statistical and systematic uncertainties summed. Dashed horizontal lines indicate the 1σ lower- and upper-limit best-fit lifetimes for the $R_p = 0.82$ and $R_\sigma = 0.92$ bounds, respectively. The literature result (black circle) from Ref. [12] is plotted for comparison.

V. CONCLUSION AND OUTLOOK

In summary, we have developed an adaptation of the recoil distance method for lifetime studies of short-lived proton-emitting nuclei beyond the drip line. We report the results of the first application of this particle plunger technique that provides a complementary measurement of the ground state $2p$-decay lifetime of $^{19}\text{Mg}$. A range of lifetimes was deduced as a function of the prompt contribution of the observed $^{17}\text{Ne}$ decay-residue yield. With guidance from the previous measurement and knockout-reaction cross section calculations, we have determined a range for the prompt $^{17}\text{Ne}$ contribution from 82% to 92%, corresponding to lifetimes between $1.75^{+0.43}_{-0.42}$ and $6.4^{+2.4}_{-2.7}$ ps, respectively. These results are consistent with the previously reported $^{19}\text{Mg}$ lifetime measurement and serve as an important validation of this new method for measuring lifetimes of exotic, short-lived proton emitters. Few direct experimental approaches for picosecond-ordered proton-emission lifetime measurements exist, thus the method introduced in this paper offers a valuable experimental addition. Future precision lifetime measurements with the technique introduced here, especially coupled with a simultaneous constraint of the prompt contribution to the yield of the $2p$-decay residue, would be of great interest.

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