The TRIPLE PLunger for EXotic beams TRIPLEX for excited-state lifetime measurement studies on rare isotopes

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Abstract

A new device, the TRIPLE PLunger for EXotic beams (TRIPLEX), has been developed for lifetime measurement studies with rare isotope beams. This plunger device holds up to three metal foils in the beam path and facilitates the recoil distance Doppler-shift technique to measure lifetimes of nuclear excited states in the range of 1 ps – 1 ns. The unique design allows independent movement of the target and second degrader with respect to a fixed first degrader in between, enabling advanced experimental approaches, such as the differential recoil distance method and the double recoil distance method. The design and control of the device are presented in this paper, together with simulated performances of the new applications. As an example of actual experiments, results from the lifetime measurement of the neutron-rich ^{17}C isotope performed at the National Superconducting Cyclotron Laboratory are shown.

Keywords: Plunger, Lifetimes, Recoil distance Doppler-shift method, Rare isotope beams

1. Introduction

In this paper, we report on the development of a new plunger device for lifetime measurements of exotic nuclei based on the Recoil Distance Doppler-Shift method (RDDS) using intermediate-energy rare isotope beams. Excited-state lifetimes have been extensively studied to determine transition rates among nuclear levels which offer useful information to quantify deformation of atomic nuclei, characterize collective modes, and understand wave functions of the states. Experimental studies to determine lifetimes have been performed with a variety of reaction mechanisms involving stable and rare isotope beams at low and relativistic energies. A recent review of the related works can be found in Ref. [1].

The limiting factors for precision in recoil distance studies are predominantly the experimental yields in γ -ray spectra and the necessity for measurements with various distance settings. These are particularly relevant for experiments with rare isotope beams when nuclei of interest are located far from stability and therefore can be produced only in a limited amount with low cross sections. In order to perform lifetime experiments under these conditions, we have designed and developed a new plunger device, the TRIple PLunger for EXotic beams (TRIPLEX), which incorporates a target and two degrader foils. This design allows the independent movement of the target and the second degrader with respect to the fixed first degrader, thus simultaneously covering regions of sensitivity for two different lifetimes.

A recoil distance setup using more than the standard target and stopper foil was first proposed in Ref. [2], the so-called differential plunger, where an additional foil, called a retardation (degrader) foil, is placed upstream of the stopper foil at a small distance. This foil only reduces the recoil velocities of nuclei produced and excited in the target but does not stop them completely. Depending on the locations where γ -ray decays occur along the beam path, three different γ -ray peaks should appear in the spectra. Those are termed fast, reduced, and stopped (slow) components, each of which corresponds to the γ -ray

31 decay behind the target, behind the degrader, and in the stopper, respectively.
 32 With this configuration, it is possible to determine directly the derivative of
 33 the decay function. In practice, this can be approximately done by dividing the
 34 reduced-peak yield I^r by the time $\Delta t = \Delta x/v$ it takes for reaction products with
 35 the speed v to travel over the degrader-stopper distance Δx . Combined with the
 36 amplitude of the decay curve, which can be obtained from the stop-peak yield
 37 I^s , the level lifetime (τ) can be extracted directly from quantities measured only
 38 at one degrader-stopper distance setting as expressed in the following equations:

$$\tau = \left| \frac{\exp(-t/\tau)}{\frac{d}{dt}(\exp(-t/\tau))} \right| \quad (1)$$

$$\approx \frac{I^s}{\frac{1}{\Delta t} I^r} = \frac{\Delta x}{v} \frac{I^s}{I^r}. \quad (2)$$

39 Although this experimental setup in principle has potential advantages, it
 40 has never been successfully applied in the past. One reason was the poor separa-
 41 tion of the three peaks in low-energy beam experiments with recoil velocities up
 42 to only a few percent of the speed of light (c). However, the situation changed
 43 when RDDS experiments were applied to rare isotope beams and performed at
 44 intermediate beam energies of 100-200 MeV/nucleon [3, 4, 5]. In these exper-
 45 iments, a foil combination of the target and degrader is used (instead of the
 46 target and stopper) to identify reaction products coming out of the degrader
 47 and final recoiling velocities (v/c) are as high as 20-40%. This triggered the idea
 48 of using multiple-foil setups for RDDS experiments and the first attempt was
 49 made at GSI measuring γ -ray decays from ^{36}K at around 130 MeV/nucleon with
 50 three target foils separated at fixed distances [6]. The striking idea of measuring
 51 a decay curve at different flight times simultaneously is hampered by the fact
 52 that the total statistics of a transition are distributed among different peaks,
 53 and normally no real gain in terms of signal-to-noise ratios is obtained from such
 54 a setup. Therefore the result was not suited to demonstrate the advantage of a
 55 multi-foil plunger setup compared to the standard one. As a result, subsequent
 56 RDDS experiments at intermediate energies were focused on the standard two-
 57 foil setup and successfully applied to various exotic nuclei [7, 8, 9, 10, 11, 12, 13].

Figure 1: Simulated spectra with a three-foil plunger for ^{17}C . The distance (d_1) between the target and the first degrader and the distance (d_2) between the first and second degraders are varied from $(d_1, d_2) = (3 \text{ mm}, 25 \text{ mm})$ in the solid (red) histogram to $(1 \text{ mm}, 10 \text{ mm})$ in the dashed (black) histogram. Lifetimes of the first $1/2^+$ excited state and the second $5/2^+$ excited state are assumed to be $\approx 500 \text{ ps}$ and $\approx 20 \text{ ps}$, respectively. Three different peaks for each transition are denoted as fast (f), reduced (r), and slow (s) components.

58 Despite the negative results obtained with the three-foil RDDS setup in the
59 past, the idea of taking advantage of the high recoil velocity especially in rare
60 isotope beam experiments was further pursued. Indeed, there are special exper-
61 imental conditions where a three-foil setup can be advantageous, for instance in
62 cases when lifetimes of two different levels have to be measured with considerably
63 different foil separations. As an example of such cases, lifetime measurements
64 of the neutron-rich nucleus ^{17}C are considered where two independent γ -ray
65 decays are known for the $1/2^+ \rightarrow 3/2^+_{g.s.}$ and $5/2^+ \rightarrow 3/2^+_{g.s.}$ transitions with sub-
66 stantially different lifetimes ($\tau \approx 500 \text{ ps}$ for $1/2^+$ and $\approx 20 \text{ ps}$ for $5/2^+$ [14, 15]).
67 The experimental situation was simulated based on our original code based

on GEANT4 [16, 17] which incorporates modifications to include the three-foil
 plunger [18, 19]. The results are shown in Fig. 1 together with the partial level
 scheme of ^{17}C . For the $5/2^+$ state (at ~ 330 keV) with a shorter lifetime, the
 fast and reduced components provide a useful measure of the lifetime, while
 the reduced and slow components are much more suited for the lifetime mea-
 surement of the longer-lived $1/2^+$ state (at ~ 220 keV). The advantage of the
 multi-foil setup is clearly shown in the simulated results, demonstrating that
 two different sensitive regions in lifetime measurements can be covered in a sin-
 gle experimental setup. This was our motivation to build a new plunger device
 where two independent foils (the target and the second degrader) can be used
 and positioned at different distances with respect to the fixed first degrader.

2. Design of the three-foil plunger device TRIPLEX

The TRIPLEX consists of a dedicated plunger vacuum chamber and the
 inner plunger structure, where the device itself is illustrated in Fig. 2. The
 design of the device is based on three concentric tubes, where the outer and
 the inner tubes can be moved precisely along the beam direction with respect
 to the immobile middle tube, ensuring a parallel motion of the target/degrader
 foils. Technical specifications are summarized in Table 1. The whole system is
 comprised of three main parts:

- the support structure
- the bearing unit
- the foil unit.

In the following subsections, details of each component are described.

2.1. Support structure

The plunger vacuum chamber, as shown in Fig. 3 (a), hosts the plunger
 device and is designed to fit into the center of a multi Ge detector array such as
 SeGA (Segmented Germanium Array) [20] or GRETINA (Gamma-Ray Energy
 Tracking In-beam Nuclear Array) [21]. The main part of the chamber consists of

96 a 6 inch wide Al tube which is used as a beam pipe and allows positioning of the
97 bare plunger device at an appropriate position inside the γ -ray spectrometer.
98 The plunger chamber should be quite transparent for γ radiation especially in
99 the parts of the solid angle which are covered by the Ge detectors. The actual
100 plunger chamber was designed especially for the specific geometries of the SeGA
101 array as well as GRETINA. Figure 4 shows the plunger setup coupled with
102 GRETINA. The plunger device can be aligned by six special screws attached to
103 the plunger chamber tube (Fig. 3 (b)).

104 It is intended that the downstream flange be permanently fixed to the down-
105 stream part of the experimental setup, which is normally attached to a recoil
106 detection system such as a magnetic spectrometer. The plunger chamber also
107 provides several electrical feedthroughs for the cabling of the motors and dis-
108 tance sensors as well as for the electrical connections to the target and degrader
109 foils. The feedthroughs are hosted in two separate chambers which are welded
110 to the plunger chamber tube. The inner plunger structure has to be inserted
111 from the upstream flange of the chamber. In order to do so, the beam tube
112 has to be opened so that at least 50 cm of free space is available. After having
113 the plunger device inserted and aligned to the beam axis, all cables of specific
114 electrical devices have to be connected to the feedthroughs.

115 The inner plunger structure is built upon the basic support structure which
116 consists of a support ring and an outer support frame. The support ring, which
117 is connected to the outer support frame, is a basis for all immobile components
118 such as the middle plunger tube, piezoelectrical motors, and connectors. The
119 screws used for the alignment of the plunger device inside the plunger cham-
120 ber go radially up to the support frame (Fig. 3 (b)). The distance control is
121 performed by two motors directly attached to the support ring, and inductive
122 transducers are used to measure the movements of the foils.

123 *2.2. Bearing unit*

124 The bearing unit consists of three stainless steel concentric tubes (Fig. 5)
125 which are separated and held by four sliding bearings attached to the middle

126 tube (Fig. 6). This bearing unit is the most crucial part of the plunger device and
127 has to be built with high precision. The spindles of the motors are mechanically
128 connected to the two movable tubes. This connection has to be made such that
129 no radial forces are introduced on the moving tubes. In practice, this is realized
130 by using a short piece of elastic wire (see Fig. 7) to connect the motor and a ring
131 which is clamped to the movable tube. Special care has to be taken to avoid
132 deformation of the tube by the clamped ring and minimize any force onto the
133 slide bearings.

134 2.3. Foil unit

135 Opposite the clamp ring, a brass ring is fixed to the end of each tube which
136 allows the foil unit to be mounted. The foil unit consists of three thin Al
137 frames which are attached to the brass rings of the tubes and, at the other end,
138 have a provision to mount the target and degrader foils. The foils are glued to
139 mounting cones, which are in turn connected to the Al frames by three screws.
140 The cones are electrically insulated by dedicated boron nitride pieces to enable
141 a capacitance measurement between the foils which is required to evaluate the
142 foil separation. Hard springs are introduced for the connection so that the
143 screws can press and release to align the three foils parallel to each other and
144 perpendicular to the beam axis. Since the beam has to pass through the inner
145 tube to reach the target, the width of the target and degrader foils was chosen to
146 be ≈ 5 cm (Table 1) which is essential especially for measurements with fast rare
147 isotope beams where the beam spot size can be as large as a few centimeters.

148 To mount the three target or degrader foils, three independent cones are
149 necessary. As shown in Fig. 8, two cones are positioned face to face, while the
150 third cone needs to enter into the second cone which requires different dimen-
151 sions for the foils. Therefore, the cone for the second degrader is prepared in
152 a special shape (Fig. 8) and the second degrader in a circular shape has to fit
153 into the inner diameter of the first degrader cone. The alignment of the foils
154 is done by adjusting the screws which mount the cones and the optimal setting
155 can be achieved by maximizing the capacitance between foils. However, the

three-foil structure of the TRIPLEX requires a two-step procedure for the foil alignment: first, the target is aligned with respect to the fixed degrader and next, the second degrader is aligned with respect to the aligned target with the first degrader removed. By inserting the first degrader again in its fixed place, the capacitance measurement between the target and first degrader can be repeated and, if the capacitance is comparable to the previous measurement, the three foils are aligned.

3. Control software

The Plunger Feedback Control software for Linux (PFCL) was initially developed to control the Cologne plunger [1]. The programs were also adopted to work with other plunger devices, such as DPUNS [22]. From a software point-of-view, the TRIPLEX can be considered to some extent as two different plunger devices accommodated within one housing. Existing frameworks are therefore expanded into a modular concept so that multiple devices can be handled in parallel to fulfill comparable tasks.

3.1. Controlled components

The software package is written in LabVIEW and is able to control both active (position control elements such as motors and piezoelectric elements) and passive elements (distance measurement). In the TRIPLEX, both the target and second degrader are aligned with respect to the first degrader at a fixed position between these two foils. The N-381 NEXACT linear actuator manufactured by Physik Instrumente (PI) [23] is employed as a motor to handle well-defined linear displacements of the target and second degrader. The linear actuator is equipped with a linear encoder which provides the distance information with sub- μm resolution. The inductive-working micrometer probe GTL21 manufactured by TESA group [24] is used to precisely measure relative changes in the foil separations with sub- μm resolution. These measurements done by the encoder and micrometer offer a relative distance information (Table I). In

low-energy beam experiments [22, 25, 26], thermal effects may affect the foil separations, if large beam powers are dissipated in the foils. In this case, a feedback function based on the capacitance measurement is mandatory to compensate small changes in the foil separation (usually in the μm range) and keep the separation constant during measurements. For a potential use in reaccelerated rare isotope beam experiments as envisioned by other plunger systems for different facilities [25, 26], the TRIPLEX device is equipped with a feedback function which can be performed either by using the motor or an additional piezoelectric element. Since the capacitance feedback needs to translate the measured capacitance into the position information, a calibration of the relative foil separation is necessary prior to experiment.

3.2. Usage of control software

The current control program PFCL is object-orientated and follows a modular concept so that several hardware components can be grouped into classes according to their tasks. Classes for the following tasks are currently prepared: Major ($>10\mu\text{m}$) linear displacements (by motors), minor (on the order of μm) linear displacements (by piezoelectric elements or by the motors), distance measurements, and a triggered voltage readout. The circuit diagram between the TRIPLEX device and the control PC is illustrated in Fig. 9. The modular software concept allows handling of multiple devices of the same class, while an external configuration file is used to specify the configuration for each experiment. For practical usage of the current software, several graphical user interfaces (GUI) are prepared to control the plunger in an intuitive way. The Micrometer GUI (Fig. 10 (a)) is used to read out the relative position information provided by the micrometer probe. The Motor GUI (Fig. 10 (b)) is used to drive the motor with various velocity settings ($v \approx 0.5\mu\text{m/s}$ – 0.2mm/s) and display the distance information from the embedded linear encoder. Finally, if a pulser signal is injected to the fixed degrader, induced signals can be measured from the target and the second degrader (Fig. 9). The induced signals go through NIM modules as shown in Fig. 9 and their amplitudes can be measured

with the multichannel analyzer using the MCA GUI (Fig. 10 (c)). A linear gate and stretcher is used to accommodate a possible time jitter between the pulser signal and the start timing of the ADC conversion and measure a proper induced signal by MCA. The distance calibration is made by recording the amplitudes of the induced signals for different separations, and the feedback, if needed during experiments, is applied based on the measured pulse heights of the induced signals. For a practical operation, the position of the electrical contact between foils is defined as a zero distance setting, while it could include a finite offset on the order of 10 μm (Table I). To determine the absolute foil separation, it is necessary to know this offset, which is normally evaluated based on the capacitance measurement [27] by comparing the distance calibration data to an analytical form of the parallel-plate capacitance.

4. Simulations and experimental results

Based on its unique design, the TRIPLEX allows advanced approaches in excited-state lifetime measurements with fast rare isotope beams. In this section, two new applications of the recoil distance Doppler-shift technique are discussed. Since the TRIPLEX setup allows the independent motion of the target and second degrader foils, two quantities are defined for the separation (d_1) between the target and the first degrader and the separation (d_2) between the first and second degraders. The dynamic range for the foil separation is between 0 mm and 25 mm for both d_1 and d_2 (Table 1). Firstly, the differential recoil distance method is discussed in detail, which is based on the measurement of the differential and integral values of the decay curve using the reduced and slow peaks, respectively [2]. Secondly, the double recoil distance method is described, where the distance setting with small d_1 and large d_2 separations enables a simultaneous measurement of two different lifetimes using a single experimental setup. Characteristics and sensitivities of the above two methods are discussed based on existing GEANT4 simulations [17, 18] which have already been used in recent lifetime studies performed at the National Superconducting Cyclotron

243 Laboratory (NSCL) with GRETINA [13, 15, 19].

244 In the present simulation, the following conditions are considered. The
245 inelastic scattering of an incoming beam AZ with $A = 60$ and $Z = 32$ at
246 90 MeV/nucleon on a Be target is employed in inverse kinematics to popu-
247 late excited states of interest. It is assumed that the reaction populates two
248 excited states at 300 keV and 800 keV in the differential recoil distance method
249 (at 300 keV and 500 keV in the double recoil distance method) which have
250 different lifetimes τ_1 and τ_2 , respectively. The lifetime values are changed to
251 study features of each method. The foil configuration of the TRIPLEX is a
252 1-mm-thick Be target, a 0.1-mm-thick Ta degrader, and a 0.1-mm-thick Ta de-
253 grader. In general, nuclear reactions to populate the excited states of interest
254 can occur both in the target and the degraders. However, a proper choice of the
255 degrader materials [4] as well as an additional momentum selection of reaction
256 products by means of a magnetic spectrometer helps to reduce or eliminate the
257 background contributions due to the reactions in the degraders. In the present
258 setting, the areal density is about twenty times larger for the Be target than that
259 of the Ta degrader so that the excited-state population is dominated by reac-
260 tions in the target. In actual experiments, background contributions due to the
261 reactions in the degraders are evaluated by measuring the yield ratios among
262 the three different γ -ray peaks at a largest possible foil separation. Typical
263 background levels are around 20-30% [7, 19] with respect to the target reaction
264 yields. Other experimental parameters such as the spot size and emittance of
265 incoming and outgoing beams are assumed to be the same as observed in recent
266 measurements at NSCL [13, 15, 19], because the impacts of these parameters
267 on present results are rather marginal.

268 4.1. *Differential recoil distance measurement*

269 As performed in recent works with the TRIPLEX [13, 15, 19], lifetimes are
270 determined through the least-squares analysis by comparing data to detailed
271 simulations [17]. The advantage of this approach is that the simulation can take
272 into account various experimental details such as feeding contributions, finite

target/degrader effects, and γ -ray decays occurring in the foils, which can not be fully represented by the simple analytical approach based on the reduced/slow yield ratio as shown in Eq. (2). However, as discussed below, an estimate based on the differential equation provides a transparent interpretation of the data, which is useful at the initial stage of the analysis and ensures the reliability of final experimental results from the differential recoil distance method.

The systematic uncertainties in recoil distance lifetime measurements are mainly due to unknown feeding contributions from higher-lying states. If such a transition is known or observed in experiments, the feeding effects can be carefully taken into account in the analysis. However, if the origin of the feeding and its effective lifetime are unknown, the treatment of the feeding contributions becomes very difficult unless the experimental statistics are large enough to apply the gamma-gamma coincidence to eliminate the influence of the feeding [28, 29]. To realize a transparent approach in lifetime measurements, the Differential Decay-Curve Method (DDCM) [2] has been applied so far (examples can be found in Refs. [1, 30]), in which a number of data points are taken with various distance settings and a phenomenological decay curve is determined. The derivative of the curve is obtained analytically and the original data points for the decay curve are divided by its derivative value, yielding the mean lifetime as expressed in Eq. (1). Although this technique offers a powerful tool to obtain an accurate result, it requires taking data with various foil separations, which is often not possible in experiments with rare isotope beams. Therefore, the new TRIPLEX device has been developed such that a single distance measurement allows the determination of both the decay integral $\exp(-t/\tau)$ and its derivative $\frac{d}{dt}\exp(-t/\tau)$ from the measured slow and reduced peak yields, respectively, and hence achieves the differential recoil distance measurement.

Figure 11 shows simulated spectra for the differential recoil distance measurement. The distance setting of $(d_1, d_2) = (2 \text{ mm}, 2 \text{ mm})$ is considered to show a specific example of actual applications. Compared to the double recoil distance method depicted in Fig. 1, the major difference is given by the short separation for d_2 . In the present case, a cascade decay is considered where the

304 reaction populates exclusively the second excited state at 800 keV and the first
 305 excited state at 300 keV can be populated only through the feeding from the
 306 second excited state. In Fig. 11 (a), a mean lifetime of 20 ps is considered for the
 307 first excited state, whereas a very short lifetime of 0.1 ps is taken for the second
 308 excited state to minimize feeding effects. In such a case, γ decays could occur
 309 inside of the thick target. Therefore, the spectral shape of the fast component
 310 reflects the large energy loss of the projectile ($Z=32$) through the target, which
 311 results in the broadened or asymmetric peak. A smaller separation for d_2 is
 312 ideal for getting the differential value, however d_2 needs to be sufficiently large
 313 to ensure statistical significance for the reduced peak. By following Eq. (2), the
 314 lifetime information can be obtained from the ratio between the reduced I^r and
 315 slow I^s peak yields. From Gaussian fits to the spectrum in Fig. 11 (a), the I^s/I^r
 316 ratio of ~ 0.6 is obtained for the 300-keV state, which yields the mean lifetime
 317 of ~ 12 ps after multiplying the time of flight Δt of ≈ 20 ps (with $v/c \approx 0.3$) over
 318 the second separation of 2 mm. The result is much shorter than the assumed
 319 lifetime of 20 ps, and the difference is ascribed to the approximation to calculate
 320 the first derivative of the decay curve based on the reduced component. The
 321 analytical form of the derivative is given (if a normalization factor is neglected):

$$\left. \frac{d}{dt}(\exp(-t/\tau)) \right|_{t=t_2} = -\frac{1}{\tau}(\exp(-t_2/\tau)). \quad (3)$$

322 On the other hand, the derivative can be approximately obtained from the
 323 measured spectrum as:

$$-\frac{1}{\Delta t} I^r = (\exp(-t_2/\tau) - \exp(-t_1/\tau))/(t_2 - t_1), \quad (4)$$

324 where t_1 and t_2 specify times when recoiling nuclei leave the first degrader (t_1)
 325 and enter the second degrader (t_2), respectively. The difference between the
 326 above two quantities is not negligible for the finite foil separation and amounts
 327 to as large as a factor of 1.7 for the present case where the time of flight Δt ($=$
 328 $t_2 - t_1 = 20$ ps) is comparable to the lifetime τ . However, the ratio of Eq. (4) to
 329 Eq. (3) defines a correction factor $C(\tau, \Delta t)$:

$$C(\tau, \Delta t) = \frac{\exp(\Delta t/\tau) - 1}{\Delta t/\tau}, \quad (5)$$

330 and a correct lifetime can be deduced as follows:

$$\tau^{cor} = \Delta t \frac{I^s}{I^r} C(\tau, \Delta t). \quad (6)$$

331 In actual cases, the lifetime information is unknown, while it is required to
 332 calculate $C(\tau, \Delta t)$. Therefore, an iteration process is taken to use Eq. (6).
 333 Initially, an estimated lifetime based on Eq. (2) can be used for $C(\tau, \Delta t)$ to
 334 obtain a corrected lifetime. This result gives, in the next turn, a new correction
 335 factor and hence a revised lifetime. After several iterations (typically more
 336 than 10), the results converge to an accurate value. As shown in Eq. (5),
 337 the correction factor depends only on the ratio between the time-of-flight Δt
 338 over the second separation d_2 and the lifetime τ and it approaches unity when
 339 $\Delta t/\tau \ll 1$. In experiments, a finite value of $\Delta t/\tau$ can be chosen so that sufficient
 340 yields are obtained for both the reduced and slow peaks, whereas $\Delta t/\tau$ should
 341 be smaller than ≈ 1.5 to have convergence through Eq. (6). In the present
 342 case, the correction factor is about 1.7 for $\Delta t/\tau = 1$ and the final result can
 343 be calculated to about 20 ps ($= 12 \text{ ps} \times 1.7$), which agrees very well with the
 344 original lifetime assumed in the simulation.

345 To study impacts of feeding contributions, in Fig. 11 (b), the lifetime for
 346 the second excited state is changed to 10 ps. The feeding effects in the cascade
 347 decay can be easily seen in the modified spectral shape of the 300-keV peak,
 348 particularly in its fast component. Notably, the reduced/slow peak ratio remains
 349 unchanged compared to Fig. 11 (a), showing the ability of the present differential
 350 method to control and reduce the feeding effects, particularly in this specific
 351 example. The I^s/I^r ratio of ~ 0.7 estimated in this case corresponds to the
 352 initial estimate of the lifetime of 14 ps, which yields the final result of 23 ps
 353 after corrections based on Eq. (6). It should be noted that the final result is
 354 still in reasonable agreement with the original lifetime of 20 ps even with the
 355 significant feeding from the second excited state as is evident in the altered
 356 fast/reduced ratio in Fig.11 (b).

357 4.2. Double recoil distance measurement

358 As briefly discussed in the introduction, the TRIPLEX measurement with
359 two movable foils can cover two different sensitive regions of lifetimes simulta-
360 neously. At the typical recoil velocity of $v/c \approx 0.3$ at NSCL, beams travel a
361 distance of about 1 mm in 10 ps. Therefore, two different lifetimes in the ranges
362 of 10 ps and 100 ps can be covered by setting the first separation $d_1 \approx 1$ mm and
363 the second separation $d_2 \approx 10$ mm in the TRIPLEX. In this application, life-
364 times are determined by varying both separations around the sensitive regions
365 as shown in Fig. 1.

366 Figure 12 shows simulated spectra for the double recoil distance measure-
367 ments. Lifetimes assumed in Fig. 12 (a) (and also in dashed lines of Fig. 12 (b)
368 and (c)) are $\tau_1 = 100$ ps for the first excited state at 300 keV and $\tau_2 = 10$ ps for
369 the second excited state at 500 keV. Both of the excited states decay directly
370 to the ground state. The same population cross section is assumed for the two
371 states. To depict a feature of this method, in Fig. 12 (b) and (c), lifetime values
372 are changed from (50 ps, 5 ps) (thick red), to (100 ps, 10 ps) (black dashed), and
373 to (150 ps, 15 ps) (thin blue) for the first and second excited states, respectively.
374 Effects due to the lifetime are evident in the yield distribution among three dif-
375 ferent Doppler-shift components, which are shifted toward the reduced or slow
376 components for longer lifetimes. More importantly, the three γ -ray peaks have
377 different sensitivities: for a longer lifetime, the reduced/slow peak ratio provides
378 a useful means for lifetime measurements (Fig. 12 (b)), while the fast/reduced
379 peak ratio is more sensitive to the shorter lifetime as indicated in Fig. 12 (c),
380 demonstrating the important feature of the three-foil configuration for multiple
381 lifetime measurements. If a broadened or asymmetric spectral shape is evident
382 for the fast component as shown in Fig. 12 (c), it also provides an additional
383 means to determine lifetimes in the 1-5 ps range [19]. The advantage of the
384 three-foil approach is also demonstrated by comparing Fig. 12 (a) and Fig. 13,
385 where the latter shows simulation results for the traditional two-foil plunger
386 measurements. The experimental conditions are the same except for the ab-
387 sence of the second degrader in Fig. 13. The three-foil setup can cover a wider

range of lifetimes and provide two distance data at the same time, while the two-foil setup requires two independent measurements with different distances to get equivalent information.

As an example of experimental results, the γ -ray spectrum observed for ^{17}C is shown in Fig. 14 and compared to the simulation. The experiment was performed at the Coupled Cyclotron Facility at NSCL using a 74 MeV/nucleon ^{18}C secondary beam onto a 2-mm-thick ^9Be target followed by 1-mm-thick Ta degrader and 0.57-mm-thick Ta degrader. De-excitation γ -rays were measured by GRETINA [21] in coincidence with outgoing ^{17}C particles identified by the S800 spectrograph [31]. Only forward-angle detectors are used in the lifetime analysis and simulation with a further angular cutoff ($\theta_{lab} < 40^\circ$) applied. Four different recoil distance measurements were performed with various distance settings, and the result from one setting ($d_1 = 3$ mm, $d_2 = 22.8$ mm) is shown in the spectrum. The detailed description of the experiment and discussion of obtained results will be published elsewhere [15].

As shown in Fig. 14, the well-separated peak structure is evident for both the $1/2^+ \rightarrow 3/2^+_{g.s.}$ transition at 220 keV and the $5/2^+ \rightarrow 3/2^+_{g.s.}$ transition at 330 keV. Due to the sizable degrader reaction contributions in this specific experiment, additional yields are present for the reduced and slow components. Therefore, the measured yield distribution among the three peaks is slightly different from that expected from the simulation (the solid curve in Fig. 1). Nevertheless, it is clearly shown that the TRIPLEX setup can cover two independent lifetime regions in a single experiment. Results obtained [15] are consistent with the previous work [14]. This demonstrates the feasibility and usefulness of the double recoil distance method for efficient lifetime measurements using rare isotope beams.

5. Summary

In summary, the three-foil plunger device TRIPLEX has been developed to enable advanced recoil distance techniques in excited-state lifetime measure-

ments with fast rare isotope beams. The unique design and control software allow the independent motion of the two foils and also facilitate the stable operation of this new device during experiments. As new techniques for which the TRIPLEX is ideally suited, the differential recoil distance method and the double recoil distance method are discussed in detail based on the simulation results. The TRIPLEX device has already been used in several lifetime experiments at NSCL in the standard two-foil configuration [12, 13, 32] and the new three-foil configuration [15, 19]. The result presented for the neutron-rich ^{17}C isotope demonstrates the promising performance of the new lifetime measurement techniques realized by the three-foil plunger.

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Figure 2: The TRIPLEX device (top : photograph, bottom : drawing). The components are labeled in the bottom panel as follows: (A) The outer casing (support frame) of the TRIPLEX. (B) One of the piezoelectric motors (linear actuators) for positioning the target foil. (C) The outermost movable tube, to which the second degrader is attached. (D) The central, immobile tube to which the first degrader is attached. (E) The innermost movable tube to which the target is attached. (F) The target, positioned by the movable tube E. (G) The first degrader, held at a fixed position. (H) The second degrader frame, on which the second degrader (obscured by the first degrader) is mounted. In the top photograph, the target and degraders are removed to show a frame structure of the device.

Table 1: A summary of technical details of the TRIPLEX device. The origin of the movable range is at the fixed first degrader and the axis is defined toward the direction of the beam. For the geometry setting labeled with (a), typical values in experiments are listed.

Movable range for the target	-25–0 mm
Movable range for the second degrader	0–25 mm
Clearance in the beam path	$\geq \varnothing$ 45 mm
Dimension of the target/the first degrader	50×50 mm ²
Dimension of the second degrader	$\varnothing$ 47.5 mm
Length of the device	$\sim$ 50 cm ^(a)
Precision of the relative distance measurement	1 μ m
Offset for the foil separation	$\lesssim$ 30 μ m ^(a)

Figure 3: The plunger chamber holding the TRIPLEX device inside is shown in (a), together with a close-up view (b).

Figure 4: The TRIPLEX chamber installed with GREYINA [21].

Figure 5: The structure of the three tubes connected to each plunger target/degrader frame is shown. The outer and inner tubes are movable with respect to the stationary middle tube. See also Fig. 8 for a close-up view.

Figure 6: A schematic view of the middle tube which is clamped to the support ring. Four sliding bearings (light grey) are placed on both the inner and outer sides of the middle tube.

Figure 7: An example of the connection between the movable tube and the head of motor through a thin wire. For the TRIPLEX, the piezoelectric element is embedded in the ring for the movable tube and connected with the motor through the wire.

Figure 8: The close-up view of the TRIPLEX device showing three cones to mount the target and degrader foils.

Figure 9: A schematic diagram of the electronic modules to control the TRIPLEX.

Figure 10: Examples of graphical interfaces (GUI) for user control: (a) position measurement based on the micrometer (Micrometer GUI), (b) control and position monitoring of the motor (Motor GUI), and (c) induced signal measurement with the multi-channel analyzer (MCA GUI). Graphical interface windows to control a single plunger are shown in the figure, while the same control panel is duplicated in each device window when two motors are operated for the TRIPLEX.

Figure 11: Simulated spectra are shown for the differential recoil distance measurements with the distance setting $d_1 = 2 \text{ mm}$ and $d_2 = 2 \text{ mm}$. The mean lifetimes for the first and second excited states (τ_1 , τ_2) are assumed to (20 ps, 0.1 ps) in (a) and (20 ps, 10 ps) in (b), respectively. In (b), the different Doppler-shift components (f : fast, r : reduced, and s : slow) are indicated by the arrows.

Figure 12: Simulated spectra are shown for the double recoil distance measurement with a distance setting $d_1 = 1$ mm and $d_2 = 10$ mm. The arrows indicate the different Doppler-shift components (f : fast, r : reduced, and s : slow). In (a), mean lifetimes of 100 ps and 10 ps are assumed for the first (I_1) and second (I_2) excited states, respectively, while they are varied in (b) and (c). The bottom panels focus on each transition and the lifetimes for the (I_1 , I_2) states are changed to (50 ps, 5 ps) (shown in thick red solid curves), (100 ps, 10 ps) (black dashed), and (150 ps, 15 ps) (blue solid), respectively.

Figure 13: Simulated spectra are shown for the two-foil recoil-distance setup with the target-degrader separation $d_1 = 1\text{ mm}$ (black solid) and 10 mm (red bold).

Figure 14: Measured spectrum for the ^{17}C isotope with the TRIPLEX device. Data (black points) are shown with error bars and compared to the simulated curve (red). See also the caption of Fig. 1.

Figure 13 eps

COUNTS/keV

Figure 14 eps

COUNTS/2keV