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# Novel techniques to search for neutron radioactivity

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ABSTRACT

Two new methods to observe neutron radioactivity are presented. Both methods rely on the production and decay of the parent nucleus in flight. The relative velocity measured between the neutron and the fragment is sensitive to half-lives between ~1 and ~100 ps for the Decay in Target (DiT) method. The transverse position measurement of the neutron in the Decay in a Magnetic Field (DiMF) method is sensitive to half-lives between 10 ps and 1 ns.



## 1. Introduction

Nuclei with extreme neutron deficiency or neutron excess can decay by the emission of one or more protons or neutrons, respectively. The presence of the Coulomb barrier can significantly hinder the emission of a proton which can lead to fairly long lifetimes for this decay mode. The current status of one- and two-proton radioactivity has recently been reviewed by Pfützner [1]. In contrast, neutron emission typically proceeds on very short time scales ($\sim 10^{-21}$ s), primarily due to the absence of the Coulomb barrier. However, it has been postulated that in special cases one- or two-neutron radioactivity might occur due to the presence of an angular momentum barrier [2–4]. Lifetimes as short as $10^{-12}$ s can be considered as radioactivity [5] and only in the most extreme cases neutron emission is expected to reach these time scales. Thus traditional methods where the decaying nucleus is implanted in a detector and the subsequent decay is recorded are not applicable. With these methods the shortest measured lifetimes at present are 620 ns [6,7] and 1.9 μs [8–10] for α- and proton-decay, respectively.

Mukha et al. developed a new technique to measure the two-proton decay of $^{19}$Mg in flight by tracking the paths of the decay products and measured a half-life of 4.0(15) ps [11]. Voss et al. studied the same decay with an adaptation of the recoil distance method. The degrader foil of a plunger device was replaced by a double-sided silicon strip detector to measure the energy-loss of the decaying nucleus ($^{19}$Mg) and the resulting fragment ($^{17}$Ne). The lifetime was then extracted from the intensity ratio of the energy loss peaks as a function of target to detector distance [12].

In order to search for the corresponding decays of neutron-rich nuclei these or similar techniques have to be developed for neutron emission. Grigorenko et al. suggested one might adapt the tracking method by measuring the angular distributions of the neutron(s) and the fragment with high precision [3]. The reconstructed opening angle of the decay is then directly related to the decay energy. Caesar et al. extracted an upper limit of 5.7 ns for the decay of $^{26}$O by two-neutron emission by assuming the survival of $^{26}$O along the flight path in a magnetic field [13]. For future experiments they also proposed placing the target directly in front of a deflecting magnet and then deducing the lifetime from the horizontal position distribution of the neutrons. Most recently Kohley et al. applied another modification of the recoil distance method to analyze the previously reported ground-state two-neutron decay of $^{26}$O [14]. In this method the velocity difference between the neutrons and the fragments is sensitive to the lifetime if the decay occurs within the target. A half-life of $4.5^{+1.1}_{-1.5}$ (stat) ± 3(syst) ps was determined for the decay of $^{26}$O [15].

In the present paper we discuss calculations to extract the half-life sensitivities of the two methods mentioned above: the velocity difference method for the Decay in the Target (DiT) and the method to measure the horizontal neutron position distribution following the Decay in a Magnetic Field (DiMF).

## 2. Test case of $^{16}$B

In order to explore the feasibility of the DiT and DiMF methods for the measurement of neutron radioactivity, the single neutron decay of

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$^{16}$B was used as a test case. Although it is unlikely that neutron radioactivity will be observed in $^{16}$B, the reaction $^{17}$C(−p)$^{16}$B → $^{15}$B + n was simulated because the complications due to the emission of multiple neutrons, occurring in the potentially more interesting case of the two-neutron emitter $^{26}$O, are avoided.

$^{16}$B is unbound with respect to $^{15}$B plus a neutron [16,17] and the ground state resonance was reported at 40(60) keV [19] and 40(40) keV [18] from multiparticle transfer reactions. Such a low decay energy (which is consistent with 0 keV within the given uncertainty) is critical for the possible observation of a finite lifetime because of the small barrier which is only due to the angular momentum. For an $l=2$ transition, which is expected for the ground state of $^{16}$B, a decay energy of about 1 keV corresponds to a half-life of approximately 0.1 ps [2,4]. Subsequently, invariant mass measurements found a resonance at low decay energies of 85(15) keV [20] and 60(20) keV [21]. This resonance most likely corresponds to the ground state decay. However, it is still conceivable that it could be a transition to one of the bound excited states of $^{15}$B. In an attempt to search for neutron radioactivity of $^{16}$B an upper limit for the half-life of 132 ps (68% confidence level) was extracted from a proton stripping reaction from a radioactive $^{17}$C beam [2].

## 3. Decay in Target (DiT)

The DiT technique was recently applied for the first time in the decay of $^{26}$O into $^{24}$O and two neutrons [15]. A schematic overview of this technique is shown in Fig. 1 for the decay of $^{16}$B as an example. In this figure it is assumed that the one-proton removal reaction $^{17}$C(-p)$^{16}$B occurs at the beginning of the target and the outgoing fragment continues with essentially the same velocity as the incoming beam. As mentioned before, in order for long lifetimes to occur the decay energy for the subsequent decay of $^{16}$B into $^{15}$B and a neutron has to be very low and therefore recoil effects can be neglected. Panel (a) of the figure depicts the situation where the decay of $^{16}$B into $^{15}$B and a neutron proceeds instantaneously. While the neutrons continue at beam velocity through the target and into the neutron detectors, the $^{15}$B fragments lose energy as they traverse the target before the final energy is measured with charged-particle detectors. The fragment velocity at the interaction point can then be reconstructed from the measured final energy [E($^{15}$B)] and the energy loss through the target [$\Delta E$($^{15}$B)] which can be calculated with the above assumptions from the incoming beam energy and the target thickness. The velocity difference $v_n - v_f$ for this case is then equal to zero. If the decay occurs at a later time, when the $^{16}$B fragment has traveled through a fraction of the target, the calculated velocity difference will be less than zero as shown in Fig. 1(b). As the location of the decay is unknown, the fragment velocity is calculated with the assumption that the decay occurred at the beginning of the target, the same as in panel (a). The neutron velocity, however, will be reduced due to the energy loss of the $^{16}$B in the target before its decay to $^{15}$B and the neutron. The signature for a finite lifetime of the decay is thus a shift towards negative values of the velocity difference $v_n - v_f$.

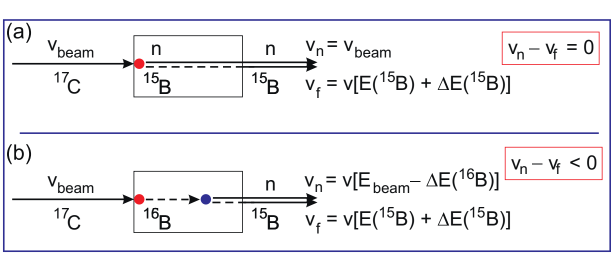


**Fig. 1.** Schematics of the DiT technique. Panel (a) shows the production of $^{16}$B and decay to $^{15}$B and a neutron at the beginning of the target, while in panel (b) $^{16}$B is produced at the beginning of the target but decays to $^{15}$B and a neutron at a later time in the target. Because the position of the decay is unknown, $\Delta E$ ($^{15}$B) is calculated assuming it traverses the whole target. The calculations of the relevant velocities are explained in the text.

The various effects contributing to the measured distributions are demonstrated in Figs. 2–5. Fig. 2 shows the calculated velocity difference assuming that $^{16}$B is produced at the beginning of the target. Distributions for half-lives of 1 ps (black/solid line), 10 ps (red/dotted line), and 100 ps (blue/dashed line) are shown for a 700 mg/cm$^2$ thick $^9$Be target and an incoming $^{17}$C beam energy of 80 MeV/u. For the calculation of the velocity difference the energy loss through the full target was added back to the final fragment energy. The exponential decrease of the velocity difference translates directly to the half life. The beam energy corresponds to a velocity of 11.7 cm/ns and with a target thickness of 0.38 cm, the traversal time through the target is ~32 ps. The decay rate for a half-life of 10 ps drops by about an order of magnitude during this time, consistent with the decrease shown by the red/dotted line in the figure. The sharp increase at the left edge of the distributions is due to the integral of decays outside of the target which is larger for the longer half-lives.

More realistic calculations have to take into account that the reaction can take place anywhere in the target. Because the exact interaction point is unknown, the velocity difference broadens due to the varying energy losses by the fragments in the target. This effect is shown in Fig. 3 for target thicknesses of 200 mg/cm$^2$ (black/solid line), 700 mg/cm$^2$ (red/dotted line), and 1500 mg/cm$^2$ (blue/dashed line). The beam energy was 80 MeV/u and it was assumed that the subsequent decay occurs at the same time/place as the reaction ($t_{1/2} = 0$ ps). In order to center the distributions at $v_n - v_f = 0$, only the energy loss through half the target thickness was added back to the final fragment energy.

The combined effect of finite half-lives and uniform distribution of the reaction within the target is shown in Fig. 4 for the same three half-lives and conditions as in Fig. 2. Finally, the results of the simulations have to be folded with realistic resolutions of the detectors. The corresponding curves displayed in Fig. 5 were calculated with an overall resolution of 0.2 cm/ns which assumed resolutions (FWHM) of 2% and 3% for the neutron and charged particle detectors, respectively [15]. The distributions for the half-lives shown in the figure demonstrate the approximate limits of the method. While the velocity difference distribution for a half-life of 1 ps is essentially centered around zero, the distribution for a half-life of 100 ps is centered at the edge of the target and distributions for longer half-lives are very similar.

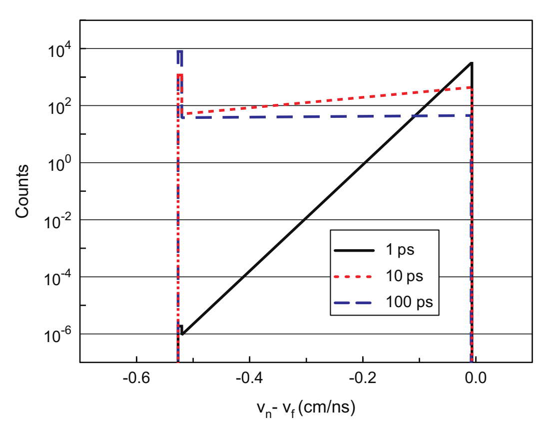


**Fig. 2.** Velocity difference distributions for the decay of $^{16}$B into $^{15}$B and a neutron at 80 MeV/u for three different half lives. The production of $^{16}$B is assumed to occur at the beginning of a 700 mg/cm$^2$ $^9$Be target. The fragment velocity was calculated after adding the energy loss of the fragment through the whole target to the final measured energy.