Vol. 45 (2014) *ACTA PHYSICA POLONICA B* No 2

NEUTRON RADIOACTIVITY*

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(Received November 6, 2013)

Studies of neutron radioactivity, a spontaneous break-up of atomic nucleus by emission of one or more neutrons are reviewed. Theoretical predictions of this still un-observed phenomenon and the recent experimental activity are presented. For example, the case of two-neutron decay of ^{26}O isotope is discussed. Prospective candidates for observation of neutron radioactivity and the related novel experimental methods are introduced. In particular, the fragment correlation method applied to neutron decays in-flight at intermediate energies is argued to be sensitive to decay energies down to 1 keV provided the corresponding neutron detector has sufficiently fine angular resolution. The design of such a neutron detector is suggested.

DOI:10.5506/APhysPolB.45.321
PACS numbers: 21.60.Gx, 21.10.Tg, 21.45.+v, 23.90.+w

1. Introduction

Nuclei with large excess of protons or neutrons become radioactive by emission of protons/neutrons. In past decades, impressive progress in studies of the proton-rich nuclei till limits of nuclear stability has been achieved. In particular, one-proton and two-proton ($2p$) radioactivities were predicted by Goldansky in 1960 [1]. Soon, proton radioactivity was first observed as a β-delayed process [2, 3], and about 20 years later the direct proton decay was discovered as radioactivity of an isomeric state, ^{53m}Co [4]. Later on, numerous one-proton decays were identified (see [5] for a recent review). It took about 42 years until two-proton radioactivity has been observed in ^{45}Fe [6, 7]. The specific feature of the latter phenomenon is that its mechanism, in general, cannot be reduced to a sequence of one-proton emissions (*i.e., true $2p$ decay*), and correlations between three decay fragments are important, which may be addressed by adequate few-body theory [8].

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[*] Presented at the XXXIII Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2013.

The direct analogue of true $2p$ decay across the isobaric line is the *true two-neutron ($2n$) decay*. With the progress in reaching experimentally the neutron drip-line, the interest to study nuclei beyond this limit is increasing. *E.g.*, some aspects of such processes were discussed by Thoennessen [9]. There is a possibility that neutron(s) emission may take the form of $2n$ radioactivity. The first theoretical estimates for searching of one-, two-, and four-neutron radioactivity which are expected for exotic extremely neutron-rich nuclei have been proposed in the paper of Grigorenko *et al.* [10]. Soon after this publication, the first indication on $2n$ radioactivity of isotope ^{26}O (whose lifetime is reported to be about 4.5 picoseconds) has been published [11]. The upper limit of the corresponding decay energy was measured to be less than 150 keV [12, 13]. Such a lifetime value of ^{26}O should correspond to a very small value of the decay energy of about 1 keV [14], which is very difficult to be measured by using the present neutron detectors.

The experiment which can prove the existence of the phenomenon of the neutron radioactivity requires a facility with the highest production of exotic nuclei (for example, the fragment separator Super-FRS which is the basis for all future experiments of the Collaboration NUSTAR@FAIR [15]). Moreover, a construction of a neutron detector with unique properties which make it suitable for measurements of neutron decays with very low energies is mandatory.

2. One-neutron radioactivity status

Like in the case of proton decay, neutron radioactivity was first observed as a β-delayed process, this disintegration mode playing an important role in reactor physics. Moreover, β-delayed one-, two-, and three-neutron emission have been identified in light nuclei (*e.g.*, see the recent review in Ref. [5]). As for the direct neutron emission, all known nuclear ground states (*e.g.*, ^{5}He, ^{10}Li, ^{13}Be *etc.*) are either very short-lived or exist as virtual states only. The reason of such a difference between a proton and neutron decay is the absence of a Coulomb barrier in the latter case. Thus, even small admixture of an s-wave configuration in the neutron precursor (*i.e.*, no centrifugal barrier) causes a dramatic reduction of its lifetime. Simple estimates of one-neutron decay widths [10] show that a chance to identify neutron radioactivity exists for the d-wave neutron configurations provided the decay energy should be smaller than 1 keV. There is a little chance that such a fine-located nuclide will actually be found. The more realistic opportunity to find one-neutron radioactivity exists only for f-wave or even higher-orbital-momentum configurations.

2.1. One-neutron radioactivity from an isomeric state

Special situation occurs if a neutron precursor has a collective structure with an extremely small admixture of one-neutron configuration. Then, it may have a half-life value in the radioactivity time range, more than 1 ps. It has long been speculated whether the direct neutron decay from a long-lived state may first be detected in an isomeric state, as was the case in the history of proton radioactivity. For illustration of such a possibility, the example of one-proton radioactivity from the high-spin isomer 21^+ of ^{94}Ag is presented in Fig. 1.

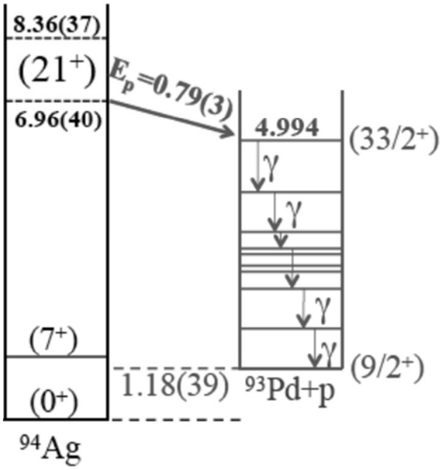

Fig. 1. Scheme of the one-proton decay branch of the high-spin isomer ^{94m}Ag(21^+), combining the proton data obtained in Refs. [16, 17] with the mass results presented in Ref. [18]. The energies of levels and emitted particles are given in MeV.

The isomer half-life value is about 0.5 s, and the branching value of the one-proton decay branch of 1.2%. From the figure one may see that the excitation energy of the isomer is around 7 MeV, which points into a possibility of detection of neutron radioactivity in neutron-bound isotopes located before the neutron drip line, not beyond it. Such a high excitation energy allows for observation of other exotic decay mode, two-proton radioactivity [19]. Though there is no direct analogue of such an isomer structure on neutron-rich side of the nuclear chart, isomers with other collective configurations may show similar properties. Fission isomers are of particular interest in respect to this issue.

3. Two-neutron and four-neutron radioactivity studies

Recently, a simplified few-body method was applied for estimates of properties of one-, two-, and four-neutron decays of light nuclei [10]. It was shown that the half-lives of $2n$ emission are about 10 times longer than those of one-neutron emitters at the same decay energy. The reason of such an effect is in an enhanced three-body centrifugal barrier which is non-zero even for s-wave $2n$ configurations. The trend toward longer lifetimes continues for $4n$ emission, which is predicted to be strongly hindered compared to $2n$ emission with the same energy. Therefore, the existence of $2n$ and, especially, $4n$ radioactivity is plausible, since the energy windows corresponding to the radioactive timescale is estimated to be reasonably broad for ^{7}H, ^{18}Be and ^{28}O, the two last isotopes remaining unobserved so far.

Though the true $4n$ emission is found to be the most prospective phenomenon for an experimental search, broad boundaries were also established in the "lifetime *versus* decay energy" plane for existence of radioactive true $2n$ emitters. In particular, it was done for the ^{26}O system, information on which has appeared recently. The upper limits were found experimentally for the decay energy of ^{26}O: of 150^{+50}_{-150} keV [12] and of < 120 keV [13]. For the known ^{25}O ground-state decay energy of 770^{+20}_{-10} keV [20], the ^{26}O can clearly be ascribed as a true $2n$ emitter.

Recently, the half-life time of ^{26}O was reported to be within the radioactivity time scale, namely of $4.5^{+1.1}_{-1.5}$(stat.)±3(syst.) ps [11]. Taking into account experimental uncertainties and novelty of the method applied (which is shortly described below), the authors express a cautious optimism about the possibility of $2n$ radioactivity observation in their work. Prospects of the discovery of this new type of the radioactive decay call for a further focused experimental search and deeper theoretical insights providing the guideline for such a search.

The detailed three-body ^{24}O$+n+n$ studies of the long-lived true $2n$ emitter, the ^{26}O isotope have been performed very recently [14]. This work concludes that the fine few-body effects play an extremely important role in the decay dynamics of the true $2n$ emitter ^{26}O. In particular, the sensitivity of its decay width to *(i)* configuration mixing due to core (*i.e.* ^{24}O) recoil, *(ii)* sub-barrier configuration mixing caused by n–n final state interaction FSI, and *(iii)* occupied-orbital effect far exceed the corresponding effects in true $2p$ decays. For illustration, see Fig. 2 where the width of ^{26}O is shown as a function of its decay energy in different model calculations. Unexpectedly, the lifetime systematics of ^{26}O with $[d^2]$ internal structure keeps to the typical $[s^2]$ behavior due to configuration mixing caused by n–n FSI. From the comparison of the experimental data and theoretical calculations in Fig. 2, one may conclude that the decay energy of ^{26}O has to be at least 200 times smaller that the measured upper limit of 150 keV, less than of 1 keV.

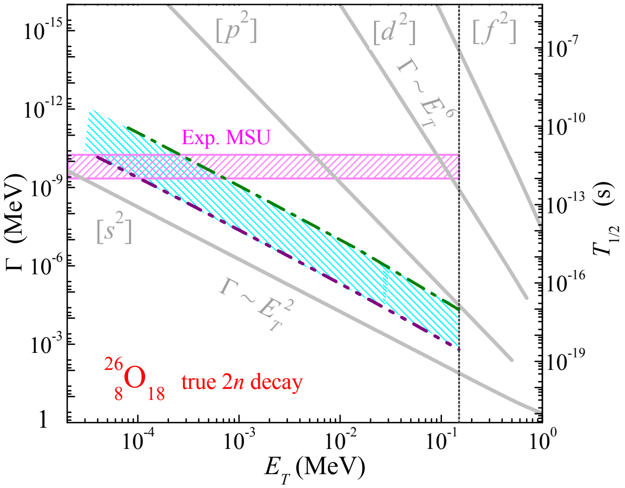

Fig. 2. Width (half-life time) of ^{26}O as a function of its decay energy according to different model calculations in Ref. [14]. The gray curves show the simple estimates of Ref. [10] for decay via pure orbital [ℓ^2] configurations coupled to the total angular momentum of zero. The dash-dotted and dash-double-dotted curves correspond to the three-body model calculations with the assumed d-wave valent neutrons plus neutron–neutron final state interaction, and in addition with the "strong repulsion" and "moderate repulsion" in s- and p-waves in ^{25}O, respectively. The hatched areas give the experimental limits from Refs. [11, 12] and the realistic theoretical limits from the work [14].

4. Prospective experimental techniques

Measurements of very small decay energies of neutron precursors (*e.g.*, of 1 keV for the $2n$ decay of ^{26}O) require special experimental methods. For such small relative energies of the decay fragments, the neutrons are not well separated in space and time. In particular, the recent measurement of the ^{26}O ground state [13] clearly demonstrates that the conventional invariant-mass method (which must detect all decay neutrons in coincidence with a heavy fragment) has a problem when distinguishing $2n$ events from either $1n$ hits or $1n$ double re-scattering (or a "cross-talk" effect) at $2n$-decay energies below 100 keV.

4.1. Method of detection of neutrons with very small decay energy

In view of the above-noted problem, a method proposed for future searches of $2n/4n$ radioactivity in Ref. [10] is likely to be free of the mentioned issues. The method is similar to the technique applied in the investigations of $2p$ precursors by tracking their decay products in flight [22–24].

The obtained angular correlation of just one proton (out of $2p$) and a heavy fragment was sufficient for a measurement of the low $2p$-decay energy with high precision [24]. Similarly, a detection of $2n/4n$ decays in flight by the tracking technique with the measured angular correlations between one neutron and a heavy fragment allows for precisely-derived low decay energies. A sketch of corresponding measurements is shown in Fig. 3. In such a case, the neutron detector must have a high granularity in transverse spatial coordinates and a reasonable $1n$-detection efficiency together with a relatively low efficiency of the $2n/4n$ detection. The first feature is needed to access the smallest correlation angles, and the latter two features allow to avoid the cross-talk problem in detecting multiple neutron decays.

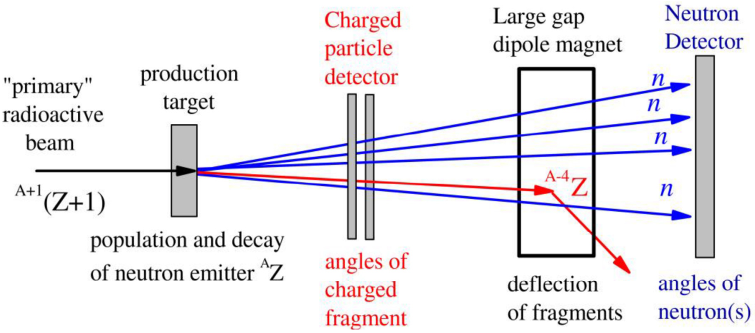

Fig. 3. The scheme of a setup for experimental studies of long-lived neutron emitters by tracking their decay products in flight. The high-resolution neutron and charged-particle detectors should provide the heavy-fragment–neutron correlations with high angular accuracy.

The Monte Carlo simulations of $2n$ decays of interest with the experimental setup sketched in Fig. 3 are shown in Fig. 4 (see details in [10]). Two cases are presented, the $2n$ decay of ^{26}O and the $4n$ decay of ^{28}O (the upper and lower panels in Fig. 4, respectively). Both parent nuclei are assumed to be unbound either by 20 keV (as predicted in Ref. [25] for ^{26}O) or 150 keV (the upper limit value measured in Ref. [12]). Both precursors decay to the ^{24}O ground state by $2n/4n$ emissions. The nuclei of interest are assumed to be populated in secondary reactions with radioactive beams, *e.g.*, in one-proton knock-out from ^{27,29}F projectiles at intermediate energies of $\sim 500\ A$ MeV. The simulated angular distributions of the decay products are shown in Fig. 4 and display very narrow peaks located at the smallest angles, down to 1 mrad. It was demonstrated for true $2p$ decays [22–24], that such characteristic correlation peaks are indeed formed which allow to identify the decay mechanism and to measure the decay energy provided all decay products are tracked with necessary accuracy.

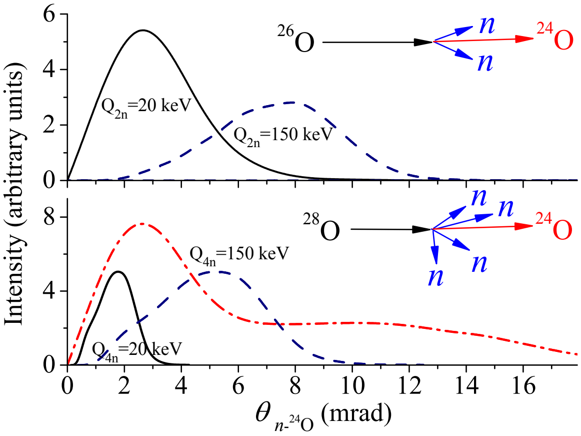

Fig. 4. The angular correlations between the heavy fragment and one of the neutrons simulated in Ref. [10] for decays of ^{26,28}O with the decay energies of 20 keV (solid curves) and 150 keV (dashed curves). Upper panel: the spectra for the true $2n$ decay of ^{26}O; Lower panel: the spectra for the true $4n$ decay of ^{28}O. The dash-dotted curve refers to a sequential $2n$–$2n$ decay of ^{28}O via the ^{26}O g.s. with $4n$- and $2n$-decay energies of 300 keV and 20 keV, respectively.

From the upper panel in Fig. 4, one may conclude that $2n$ decay energies as low as few keV can be reached provided the experimental setup has an angular resolution lower than 1 mrad. The true $4n$ decay presented in the lower panel of Fig. 4 is characterized by a single peak, which corresponds to uniform sharing of the decay energy among all neutrons. The correlation pattern is sensitive to the decay mechanism, as the sequential $2n$–$2n$ decay via the ^{26}O g.s. provides a two-peak correlation distribution. Similarly, for the simulated $4n$ decay, the necessary angular resolution of the neutron detectors should be ≤ 1 mrad as well. Existing detectors, such as the present large-area neutron detectors at RIKEN, GSI and MSU, provide an angular resolution of ≈ 10 mrad, thus, new developments are needed.

A compact neutron detector NEURAD ("NEUtron RADioactivity") is in research-and-development work at the Super-FRS NUSTAR Collaboration of the FAIR project (Darmstadt, Germany). The NEURAD is aimed for registration of neutrons from decays-in-flight with extremely low energies of isotopes beyond the neutron drip line and uses the above-discussed angular correlation technique.

This relatively compact ($30 \times 30 \times 50$ cm^3) detector built of scintillation fibers with small cross area (*e.g.* of 0.2×0.2 cm^2) can provide the necessary angular resolution already at 10–20 m distances from the decay point, see Fig. 5. Its dynamical range is limited to small decay energies

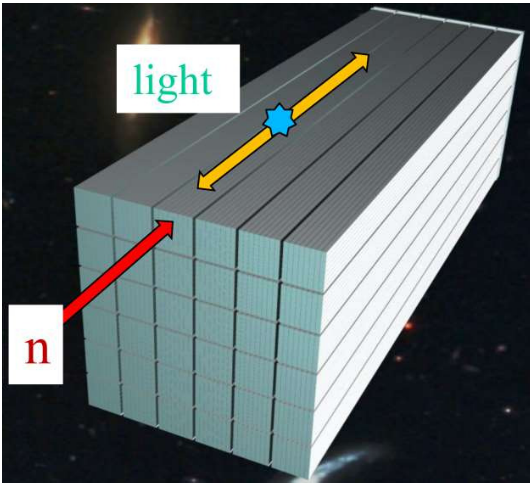

Fig. 5. Sketch of a high-resolution neutron detector consisted of scintillating fibers of spaghetti type. Recoil protons scattered by intermediate-energy incident neutrons produce a light flash mostly in one fiber which is read-out from both sides. Then transverse coordinates of the neutron interaction are derived from the fired fiber position, and a longitudinal neutron-hit coordinate comes from a time difference of the readouts.

only, that makes no competition to large-energy-range invariant-mass detectors like the "NeuLAND" [26]. The NEURAD detector is devoted to future neutron-radioactivity experiments proposed by the GAWP (GSI–ACCULINNA–Warsaw–Petersburg) initiative to the Super-FRS Collaboration as a part of its future physics program [15].

4.2. Lifetime measurement methods

Two prospective methods to measure a lifetime of neutron radioactivity are presented in Refs. [9, 13]. Both methods rely on the production and decay of the precursor nucleus in flight. The first technique is based on measurements of the relative velocity between the neutron and the fragment, and it was recently applied for the first time in the decay of the precursors ^{26}O into the fragments ^{24}O and two neutrons [11]. When the decay of ^{26}O occurred inside the same target where it was produced, the fragments ^{24}O were systematically slower then the decay neutrons due to energy loss in the target. Monte Carlo simulations of such an effect have shown that it is sensitive to half-lives measured between 1 and 100 ps [9]. The second technique is based on the transverse position measurements of the neutrons and heavy fragments resulted from the decay of their precursor in an external magnetic field [13]. Due to deflection of the precursors and heavy fragments in the magnetic field (*e.g.*, in a horizontal direction), the horizontal distribution of the neutrons depends on the precursor's lifetime and velocity as well as the magnetic field strength. Monte Carlo simulations show that this method is sensitive to half-lives in a range from 10 ps to 1 ns [9, 13].

5. Summary

Experimental advance in studies of nuclear structure towards the neutron drip line makes plausible discoveries of unobserved yet forms of radioactivity, $1n$, $2n$, and $4n$ decays. First theoretical studies show that the respective precursors should have very small decay energies, that requires developments of dedicated experimental methods and detectors.

REFERENCES

[1] V.I. Goldansky, *Nucl. Phys.* **19**, 482 (1960).

[2] V. Karnaukhov, G. Ter-Akopyan, V. Subbotin, L. Petrov, *J. Exp. Theor. Phys.* **45**, 1280 (1963) (in Russian).

[3] R. Barton *et al.*, *Canadian J. Phys.* **41**, 2007 (1963).

[4] K. Jackson *et al.*, *Phys. Lett.* **B33**, 281 (1970); J. Cerny *et al.*, *Phys. Lett.* **B33**, 284 (1970).

[5] M. Pfützner, L.V. Grigorenko, M. Karny, K. Riisager, *Rev. Mod. Phys.* **84**, 567 (2012).

[6] M. Pfützner *et al.*, *Eur. Phys. J.* **A14**, 279 (2002).

[7] J. Giovinazzo *et al.*, *Phys. Rev. Lett.* **89**, 102501 (2002).

[8] L.V. Grigorenko *et al.*, *Phys. Rev. Lett.* **85**, 22 (2000).

[9] M. Thoennessen, *Rep. Prog. Phys.* **67**, 1187 (2004).

[10] L.V. Grigorenko, I. Mukha, C. Scheidenberger, M.V. Zhukov, *Phys. Rev.* **C84**, 21303(R) (2011).

[11] Z. Kohley *et al.*, *Phys. Rev. Lett.* **110**, 152501 (2013).

[12] E. Lundenberg *et al.*, *Phys. Rev. Lett.* **108**, 142503 (2012).

[13] C. Caesar *et al.*, *Phys. Rev.* **C88**, 34313 (2013).

[14] L.V. Grigorenko, I. Mukha, M.V. Zhukov, *Phys. Rev. Lett.* **111**, 042501 (2013).

[15] Superconducting fragment separator (Super-FRS) facility, `http://www.fair-center.eu/en/for-users/experiments/nustar/experiments/super-frs.html`

[16] I. Mukha *et al.*, *Phys. Rev. Lett.* **95**, 022501 (2005).

[17] J. Cerny *et al.*, *Phys. Rev. Lett.* **103**, 152502 (2009).

[18] A. Kankainen *et al.*, *Phys. Rev. Lett.* **101**, 142503 (2008).

[19] I. Mukha *et al.*, *Nature (London)* **439**, 298 (2006).

[20] C.R. Hoffman *et al.*, *Phys. Rev. Lett.* **100**, 152502 (2008).

[21] M. Thoennessen *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A729**, 207 (2013).

[22] I. Mukha *et al.*, *Phys. Rev. Lett.* **99**, 182501 (2007).

[23] I. Mukha *et al.*, *Phys. Rev.* **C82**, 054315 (2010).

[24] I. Mukha *et al.*, *Phys. Rev.* **C85**, 044325 (2012).

[25] A. Volya, V. Zelevinsky, *Phys. Rev.* **C74**, 064314 (2006).

[26] Neutron ToF Spectrometer NeuLAND, `www.gsi.de/work/fairgsi/rare_isotope_beams/r3b/neuland.htm`