The "Beta-Delayed Neutrons at RIKEN" Project (BRIKEN): Conquering the Most Exotic Beta-Delayed Neutron-Emitters

Among the main missions of modern radioactive isotope facilities is the exploration of properties of yet unknown isotopes on the neutron-rich side of the chart of nuclides. However, going more neutron-rich also means that the neutron separation energy decreases until it reaches the dripline at $S_n = 0$ MeV. If the neutron separation energy gets lower than the β-decay energy window (Q_β value), a new decay mechanism can occur: the emission of neutrons after β-decay. These "β-delayed neutron" (βn) emitters play a crucial role in nuclear structure, nuclear astrophysics, and for nuclear reactor applications.

For neutron-rich nuclei far from stability, β-delayed neutron emission becomes the dominant decay process. The neutron emission probability (P_n value) helps to verify the modeled β-strength distribution and the level structure of the daughter nucleus. Also the β-decay half-life of the parent nucleus can be determined via β-delayed neutron emission.

Explosive astrophysical scenarios in neutron-rich environments like the "rapid neutron-capture" (r) process are responsible for the creation of about half of the stable isotopes beyond iron. In core collapse supernova explosions or the merging of neutron stars with a neutron star or a Black Hole, neutron densities in excess of $>>10^{20}$ cm^{-3} can be reached, and ignite the r-process nucleosynthesis for a few seconds. Fast subsequent neutron captures and β-decays create very neutron-rich, heavy isotopes, most of which have not yet been discovered. When the temperature and neutron density drop rapidly due to the rapid expansion of the r-process rich material, the so-called "freeze-out" allows the neutron-rich material to decay back to stability via long β-decay chains.

βn-emitters in these decay chains can influence the neutron budget in the late-time evolution of the r-process in two ways: the emission of neutrons leads to a transfer of material into β-decay chains with lower mass number, and the emitted neutron can be thermalized and recaptured by the decaying material. Thus an accurate knowledge of the neutron-branching ratio and half-lives of as many βn-emitters as possible is a crucial prerequisite for improving theoretical models to achieve a better understanding of r-process nucleosynthesis models.

In fission reactors the longer response time of βn allows keeping the system in a controlled subcritical state. Although their number (delayed neutrons per fission event) is only in the order of 1% of the total neutron yield, they have a long enough effective lifetime to insert or withdraw rods containing neutron absorbing materials to control the reactor.

Out of the 2,451 isotopes listed in the latest Atomic Mass Evaluation (AME2016) [1], 621 are β-delayed neutron emitters. However, for only 298 of them (48%) a measurement of the one-neutron branching ratio (P_{1n} value) exists (Figure 1). For β-delayed multiple-neutron emitters, this ratio drops to less than 8%, and so far only one β-delayed four-neutron emitter (β4n) has been measured, ^{17}B.

There are two main reasons for the low number of measurements:

- The communities were so far focused on "easy" to reach nuclei, thus light nuclei with $A < 30$, and fission fragments around $A = 90$ and $A = 135$.
- The production rate for more neutron-rich isotopes at current radioactive beam facilities falls approximately by one order of magnitude per mass unit.

Setups using moderated proportional neutron counters, such as ^{3}He- or BF$_3$-filled tubes, are the most efficient way to detect β-delayed neutrons. Previous setups have reached (one-) neutron detection efficiencies of up to 60% (see Figure 2). To further increase the

	Identified (Qbxn>0)	Measured (06/2017)		Measured
	# of isotopes	# of isotopes	Fraction	mass region
β1n	621	298	48.0%	^{8}He-^{216}Tl
β2n	300	23	7.7%	^{11}Li-^{136}Sb
β3n	138	4	2.9%	^{11}Li-^{31}Na
β4n	58	1	1.7%	^{17}B

Figure 1. *Number of identified βn-emitters with $Q_{\beta xn} > 0$ keV (within the uncertainties, from AME2016) and number of isotopes where the neutron-branching ratio has been measured (Status: June 2016, isomeric states not included).*

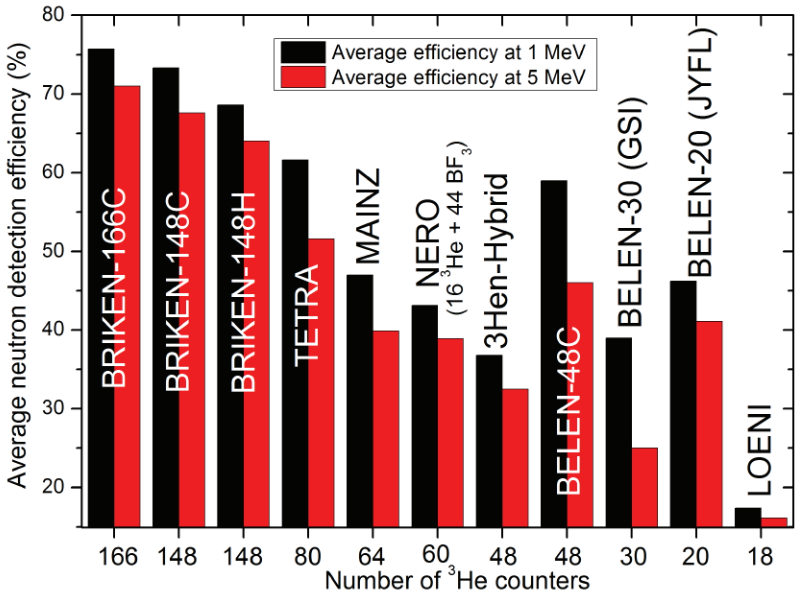

Figure 2. *Comparison of neutron detection efficiencies of various neutron detectors with the BRIKEN setups at average neutron energies of 1 MeV (black columns) and 5 MeV (red columns). The "C" or "H" at the end of the name indicates the "compact" or "hybrid" modes. Note that the value for NERO includes 44 BF3 counters. Figure adapted from Ref. [11].*

detection efficiency despite the drastically increased prize for ^{3}He, the merging of tubes from existing neutron detectors is the most cost-effective solution.

The BRIKEN project was initiated in 2012, after the successful campaigns of the BELEN collaboration at GSI Darmstadt, Germany [2] with the BELEN-30 detector, and at the IGISOL facility in Jyväskylä, Finland with the BELEN-20 and BELEN-48 detectors [3–5]. For the detection of ion and beta particles the state-of-the-art "Advanced Implantation Detection Array" (AIDA) was used, which was developed by the University of Edinburgh, University of Liverpool, STFC Daresbury Laboratory, and STFC Rutherford Appleton Laboratory [6, 7].

The "Beta-delayed neutrons at RIKEN" project was born with the goal to design the world's most efficient neutron detector array and set it up at the presently most powerful facility to produce neutron-rich isotopes. By 2013 the size of the collaboration had doubled, and the setup with the originally 52 ^{3}He tubes provided by UPC Barcelona, IFIC Valencia, and GSI Darmstadt (from the BELEN detector), had almost quadrupled to up to 179 available ^{3}He tubes. The additional tubes were provided by Oak Ridge National Laboratory (81 counters from 3Hen) [8, 9], JINR Dubna (20 counters from VASSILISSA) [10], and RIKEN (26 counters). In addition, γ-ray detection capabilities were implemented by the addition of two large-volume HPGe clover detectors from Oak Ridge National Laboratory.

Between 2013 and 2016 an extensive conceptual design study was carried out for two versions of the BRIKEN array: a "hybrid mode" including the two clover detectors (BRIKEN-148H) and a high-efficiency "compact mode" (BRIKEN-148C and BRIKEN-166C) [11]. The hybrid setup can be easily transformed into a compact design with 166 counters, which increases the average detection efficiency for single neutrons up to 1 MeV from 68.6% to 75.7% (BRIKEN-166C).

For very neutron-rich nuclei with a large βn-energy window, a strong dependence of the detector efficiency on the neutron energy might hamper the respective measurement of the neutron branching ratios. Thus special care was taken in these simulations to design a neutron detector that has a relatively constant and high neutron detection efficiency up to 1 MeV with small variations up to 5 MeV (Figures 2 and 3).

A comparison of the design efficiencies for the hybrid and compact versions of the BRIKEN array and other existing neutron detectors for β-delayed neutron experiments is shown in Figure 2.

The presently most powerful facility for the production of neutron-rich isotopes is located at RIKEN Nishina Center in Wako, Japan. At the "Radioactive Ion Beam Factory" (RIBF) a ^{238}U beam with 345 MeV per nucleon is impinging on a production target, and the neutron-rich fragments are filtered out by the BigRIPS fragment separator and the Zero-Degree Spectrometer, and are then stopped in the stack of six double-sided silicon-strip detectors (DSSSDs, wafer size 8 × 8 cm^2) in the implantation detector AIDA, which serves as an ion and beta counter. AIDA is surrounded by the respective BRIKEN neutron/gamma detector array.

The BRIKEN project relies fully on digital electronics systems. The GASIFIC triggerless DAQ—developed by IFIC Valencia for the BELEN detector [5]—has been upgraded, and a set of software tools for data analysis have been developed.

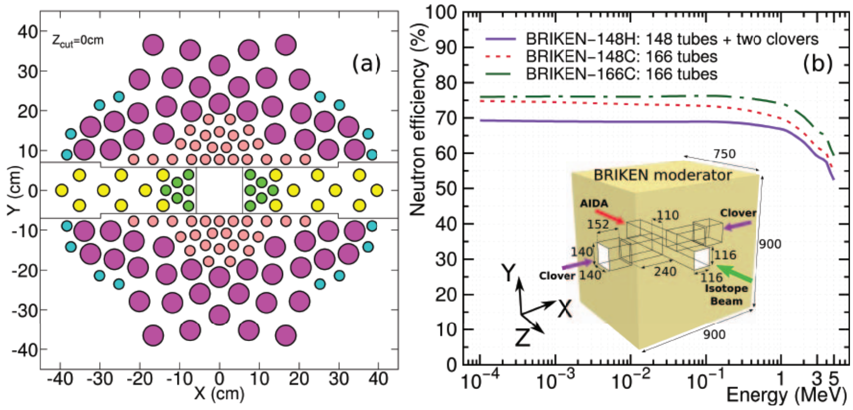

Figure 3. *(Left) Design of the BRIKEN array in the hybrid mode with 148 counters and compact design with up to 166 counters. (Right) Comparison of neutron detection efficiencies of all three modes.*

The setup has been installed and commissioned in 2016. For the first phase of the BRIKEN campaign in 2016/17 the hybrid setup with 140 counters and two clovers was used, with a detection efficiency that closely resembles the one given for BRIKEN-148H in Figure 2.

Two experimental proposals have very successfully been carried out in the first campaign, focusing on βn-emitters around and beyond the shell closures at N = 50 and N = 82. In addition, the preparatory phase of another proposal aiming the measurement of β-decay properties at the N = 104 mid-shell closure was completed.

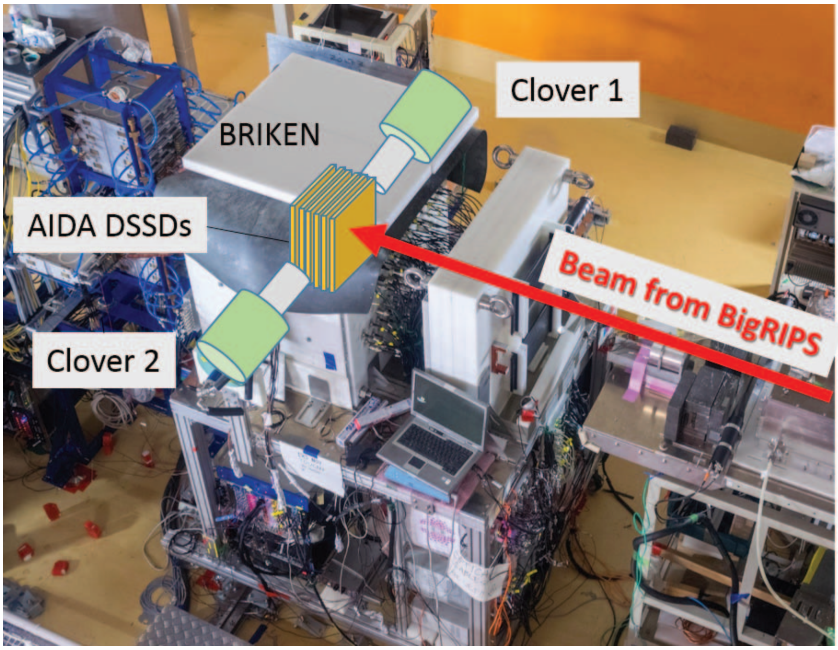

Figure 4. *BRIKEN hybrid setup with schematic positions of the AIDA detectors and the two HPGe clovers.*

The first experiment produced and implanted a world record number of 7,500 doubly magic ^{78}Ni nuclei (Z = 28, N = 50), about three orders of magnitude more than in a previous experiment at NSCL [12]. In the region between ^{75}Co and ^{96}Br in total about 30 β1n- or β2n-branching ratios were measured, many of them for the first time, as well as 20 β-decay half-lives.

The second experiment focused on the region around the N = 82 shell closure, which is of particular interest for astrophysics. The solar abundance curve shows an abundance peak at A ≈ 130, which is directly connected to neutron-rich βn-emitters at N = 82 produced by the r-process. About 30 new neutron-branching ratios were measured in a region at or very close to the r-process path predicted by some astrophysical models, including some of the heaviest β-delayed multiple neutron emitter.

The third experiment is focused on deformed βn-emitters, which are critical for understanding the formation of the rare-earth abundance peak at A ≈ 160 during the r-process. Presently there is a large gap between ^{150}La (Z = 57) and ^{210}Hg (Z = 80) with no measured neutron-branching ratios. The preparatory phase of this experiment was completed in June 2017 by verifying the production cross-sections. Although only a small fraction of this experimental program was carried out, already 10 P_{1n} values and β-decay half-lives were measured for the first time.

The BRIKEN collaboration (Figure 5) has carried out the second phase of measurements in fall 2017. The previous statistics for the A = 80 region could be tripled, and many new beta-delayed neutron emitters in the A = 100–125 region could be added. For this phase, an adaption of the hybrid setup was used to increase the gamma-detection efficiency of the

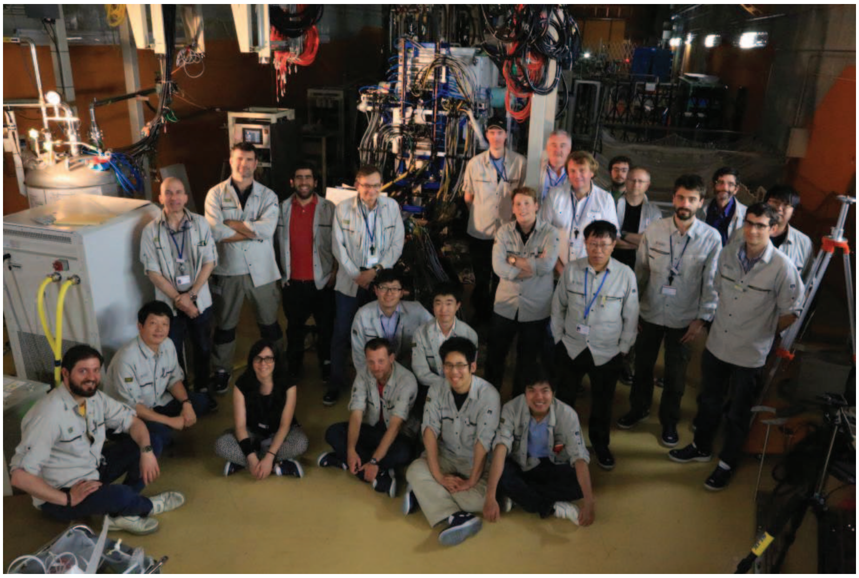

Figure 5. *(Part of the) BRIKEN collaboration after the experimental campaign in spring 2017.*

two clover detectors. In the first phase each clover was 68 mm away from the implantation area. In the new design this distance was reduced to 38 mm, which allowed doubling the efficiency and reaching a value that is roughly half of that of the EURICA array.

After these successful first experiments, the BRIKEN collaboration is planning to continue their measurements until at least 2019. With this setup, the largest investigation of β-delayed neutron emitters so far is being carried out, measuring well over a hundred β1n-, β2n-, and β3n-emitters, and in the future also β4n-emitters, in the mass region between A = 10 and 210, many of them for the first time. This effort will help to better understand β-delayed neutron emission, the dominant decay mechanism of neutron-rich nuclei.

Acknowledgments

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