Proceedings of the 12th Asia Pacific Physics Conference
JPS Conf. Proc. **1**, 013046 (2014)

Status of the EURICA Project After One Year at RIKEN

Pär-Anders Söderström[1], Shunji Nishimura[1], Hidetada Baba[1], Frank Browne[1,2], Rie Daido[3], Pieter Doornenbal[1], Yifan Fang[3], Guillaume Gey[1,4], Tadaaki Isobe[1], Hyo-Soon Jung[5,6], Zhihuan Li[7], Giuseppe Lorusso[1], Daniel Lubos[1,8], Kevin Mochner[1,9], Zena Patel[1,10], Simon Rice[1,10], Hiroyoshi Sakurai[1,11], Laura Sinclair[1,12], Toshiyuki Sumikama[13], Jan Taprogge[1,14,15], Zsolt Vajta[1,16], Hiroshi Watanabe[1,17], Jin Wu[1,7], Zhengyu Xu[11], Ayumi Yagi[3], Rin Yokoyama[18], Kenta Yoshinaga[19], Giovanna Benzoni[20], Andrey Blazhev[9], Plamen Boutachkov[21], Alison Bruce[2], Roman Gernhäuser[8], Eiji Ideguchi[3], Andrea Jungclaus[15], Gi Dong Kim[22], Yong-Kyun Kim[22,23], Ivan Kojouharov[21], Nikolaus Kurz[21], Young Kwan Kwon[22], Marek Lewitowicz[24], Zhong Liu[25], Radomira Lozeva[26], Chang-Bum Moon[27], Megumi Niikura[11], Atsuko Odahara[3], Zsolt Podolyák[10], Patrick Regan[10,28], Oliver Roberts[2], Gary Simpson[4], Henning Schaffner[21], Christopher Townsley[10], Robert Wadsworth[12]

[1]*RIKEN Nishina Center, Saitama 351-0198, Japan*
[2]*University of Brighton, Brighton BN2 4JG, United Kingdom*
[3]*Osaka University, 560-0043 Osaka, Japan*
[4]*Université Joseph Fourier Grenoble 1, 38026 Grenoble Cedex LPSC, France*
[5]*Chung-Ang University, Seoul 156-756, Republic of Korea*
[6]*Universty of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Peking University, Beijing 100871, China*
[8]*Technische Universität München, D-85748 Garching, Germany*
[9]*University of Cologne, D-50937 Cologne, Germany*
[10]*University of Surrey, Guildford, GU2 7XH, UK*
[11]*University of Tokyo, Tokyo 113-0033, Japan*
[12]*University of York, Heslington, York YO10 5DD, UK*
[13]*Tohoku University, Miyagi 980-8578, Japan*
[14]*Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[15]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[16]*MTA Atomki, P.O. Box 51, Debrecen, H-4001, Hungary*
[17]*Beihang University, Beijing, China*
[18]*Center for Nuclear Study, University of Tokyo, Saitama 351-0198, Japan*
[19]*Tokyo University of Science, Chiba 278-8510, Japan*
[20]*INFN Milano, I-20133 Milano, Italy*
[21]*GSI, 64291 Darmstadt, Germany*
[22]*Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Republic of Korea*
[23]*Hanyang University, Seoul 133-791, Republic of Korea*
[24]*GANIL, F-14076 Caen Cedex 5, France*
[25]*University of Edinburgh, Edinburgh EH9 3JZ, UK*
[26]*IPHC, CNRS-IN2P3, 67037 Strasbourg, France*
[27]*Hoseo University, Chungnam 336-795, Republic of Korea*
[28]*National Physical Laboratory, Teddington, UK*

E-mail: pasoder@ribf.riken.jp

(Received July 8, 2013)

The EURICA array has currently been in operation at RIKEN Nishina Center for one year. During this time several physics campaigns have been performed. In this paper we report about the current status of the detector setup and the first year of experimental campaigns.

KEYWORDS: EURICA, γ-ray spectroscopy, β decay, nuclear isomers, HPGe array, $LaBr_3$ array

1. Introduction to EURICA and WAS3ABi

The Radioactive Isotope Beam Factory (RIBF) is an in-flight fragmentation facility with an intensity for radioactive isotope production unmatched by any other current facility. Together with BigRIPS and the ZeroDegree Spectrometer [1] for particle identification, the structure of a large number of exotic nuclei produced at RIBF have been studied with both fast [2] and stopped [3] beams. To fully exploit the spectroscopy possibilities at RIBF, the EURICA (Euroball-RIKEN Cluster Array) project was proposed in July 2011. EURICA is currently used for measuring γ rays from several hundred nuclei far from stability, following isomer- and β-decay. The combination of the most intense radioactive ion-beam facility with one of the highest efficiency γ-ray spectrometers is indeed a unique opportunity for the worldwide nuclear physics community.

At the end of 2011 and beginning of 2012 the EURICA array was assembled at RIKEN from twelve Euroball IV high-purity germanium (HPGe) cluster detectors [4]. Each EURICA cluster consists of seven tapered, hexagonal HPGe crystals, with one central crystal and the remaining six crystals placed in a surrounding ring. The 84 crystals are arranged into a spherical shape consisting of three rings at 51°, 90°and 129° relative to the beam axis at a nominal distance of 22 cm from the center. In March 2012 a successful commissioning of EURICA was carried out to verify performance for energy and lifetime measurements of isomeric states, and β-delayed γ-ray spectroscopy [5]. For further details about the EURICA array, see Refs. [3,5].

Another fundamental component of the setup is the silicon detector array WAS3ABi (Wide-range Active Silicon Strip Stopper Array for β and ion detection), developed and constructed at RIKEN in collaboration with Technische Universität München and Institute for Basic Science. In a typical experiment, up to 100 high-energy radioactive isotopes are implanted into WAS3ABi every second. WAS3ABi consists of eight $40 \times 60 \times 1$ mm^3 double-sided silicon strip detectors, each with 40 horisontal and 60 vertical strips. The resulting 1×1 mm^2 pixelation enables us to do a spatial correlation between the implanted ion and detection of β-decay electrons, so the β-decay half-lives and Q-values can be measured. Details about WAS3ABi can be found in Ref. [3].

2. LaBr$_3$:Ce Detectors for Fast Timing

To increase the scope of the EURICA plus WAS3ABi setup for nuclear spectroscopy, the HPGe detectors have been complemented with an array of LaBr$_3$:Ce(5%) (LaBr$_3$) scintillators for γ-ray detection. This gives us the opportunity to use fast-timing techniques to measure life times of excited states down to sub-nanosecond level. The LaBr$_3$ is a relatively new kind of scintillator [6] which combines excellent timing properties with a good energy resolution and efficiency. There are two standard methods to use fast γ-ray scintillator detectors for timing measurements. One method uses $\beta\gamma\gamma$ coincidences between a thin β scintillator and the LaBr$_3$ detector, and a HPGe detector for precise selection of the desired γ-ray cascade [7]. The other method uses $\gamma\gamma\gamma$ coincidences where one HPGe detector is used to select the decay branch and two LaBr$_3$ detectors are used for relative timing [8].

The cylindrical $1.5'' \varnothing \times 2''$ LaBr$_3$ crystals currently installed in the EURICA setup are from the FATIMA array within the DESPEC project [9,10]. The detectors are arranged into three clusters with six detectors in each cluster, see illustration in Fig. 1. The time resolution of these crystals is 250 ps full-width at half-maximum (FWHM) and the energy resolution is 3.2–3.5% FWHM at 662 keV γ-ray energy. The distance between the center of the EURICA array and the surface of the LaBr$_3$ crystals is nominally 20 cm, but can be adjusted according to the individual experimental needs. All LaBr$_3$ clusters are mounted in the 90° ring of the EURICA support structure. A typical efficiency curve of the LaBr$_3$ setup is shown in Fig. 1. For $\beta\gamma\gamma$ coincidences, it is possible to sandwich the WAS3ABi silicon detectors between two $65 \times 45 \times 2$ mm^3 BC-418 plastic scintillators.

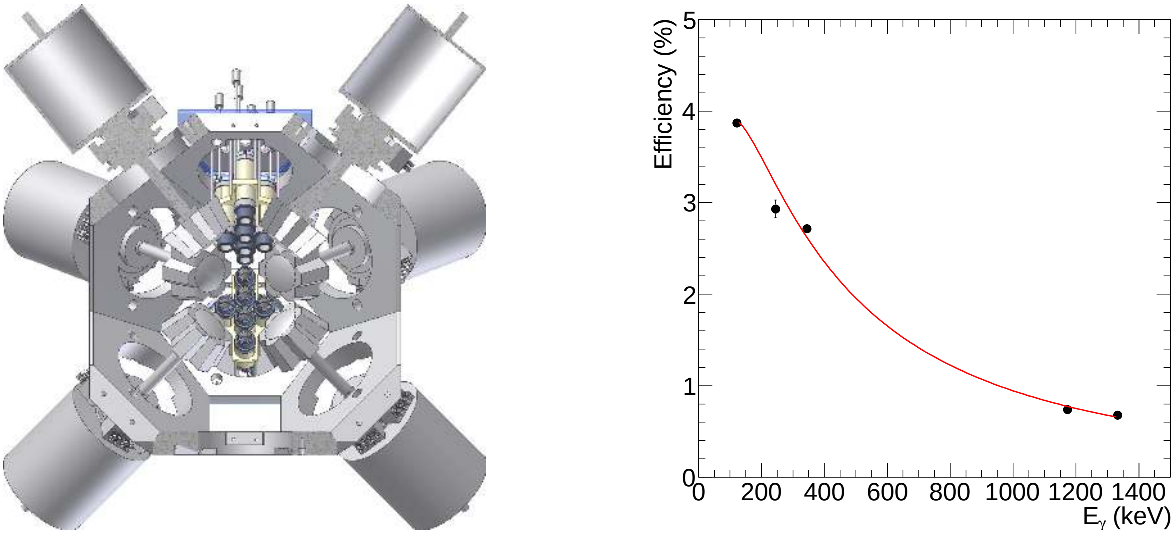

Fig. 1. Left: CAD drawing showing half of the EURICA frame, containing six of the HPGe clusters and two of the LaBr$_3$ clusters. Right: Efficiency curve of the full LaBr$_3$ array as used in the uranium-beam campaign of spring 2013. The efficinecy per cluster is just slightly lower than that of the HPGe clusters [5]. The low-energy and high-energy data points are obtained using a ^{152}Eu and using a ^{60}Co source, respectively. The red line is a model-dependent interpolation fitted to these data points.

3. Status of the Experiments

The first EURICA experimental campaign was successfully performed in June 2012. Since then, several experiments have been performed during three more campaigns. Many more are accepted by the RIKEN Program Advisory Committee, and the EURICA campaigns are planned to continue at least until December 2015. A summary of the nuclei produced during the first year is shown in Fig. 2.

On the proton-rich side of the nuclear chart EURICA has been used to study decays of known isomers in $N = Z$ nuclei, in order to provide detailed tests of the shell model, as well as to search for evidence of predicted isomers in $N \leq Z$ nuclei [11]. In the first experiment, the number of implanted ^{100}Sn, ^{98}In, ^{96}Cd and ^{94}Ag nuclei were about 200, 5000, 20000 and 50000, respectively. In a dedicated ^{100}Sn experiment another 2000 nuclei of this isotope were produced, which is a factor of ten larger than the recent flagship experiment with the RISING stopped beam setup at GSI, Germany [12].

The ^{78}Ni region has been the focus of several experiments. With $Z = 28$ and $N = 50$, ^{78}Ni is believed to be the most neutron-rich doubly magic nucleus. In total, half-lives of 37 isotopes, of which 12 were previously unknown, have been measured [13]. We also measured the decay of isomers with high statistics in the ^{78}Ni region. In Fig. 2, the isomeric decay spectrum of ^{76}Ni is shown. In the $2^+ \rightarrow 0^+$ peak, 1400 counts are observed which is a factor of 230 more than the previous experiment [14]. Here we can clearly see that the intensities of the four transitions are the same, resolving the discrepancy in [14] where the 355 keV transition was just 50% as strong as the others, and improve the precision in the half-life of the isomer from 590^{+180}_{-110} [14] to 543.9 ± 3.4 ns.

Several experiments have been performed for $105 \lesssim A \lesssim 130$. One preliminary result worth mentioning is the measurement of the lifetime of the 2^+ state in ^{104}Zr using the LaBr$_3$ detectors, proving the effectiveness of this set-up. From the β-delayed γ-rays in the middle of the region we have shown the persistence of triaxial deformation to larger N and the beginning of a shape transition into spherical nuclei [15]. South-west of the doubly magic ^{132}Sn more than 30 new half-lives, including ^{128}Pd and and ^{127}Rh, will both provide direct input for the astrophysical r-process nucleosynthesis calculations and new understanding of the nuclear structures [16]. Several isomers have also been

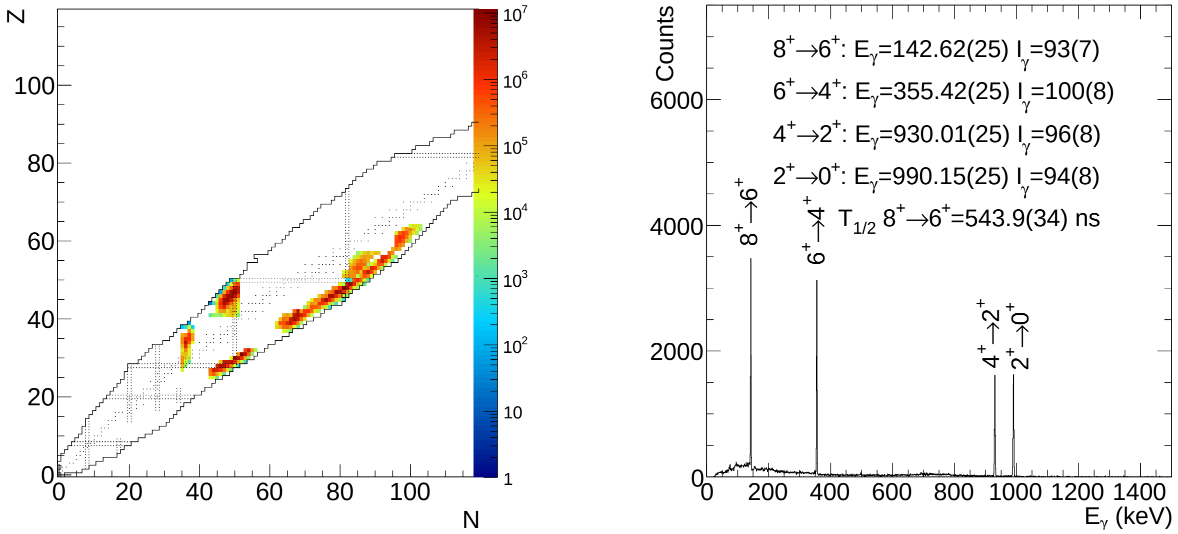

Fig. 2. Left: Approximate distribution of nuclei detected in the first year of experimental campaigns shown in a part of the nuclear chart with element number Z and neutron number N. The dots show the stable isotopes and the dotted lines the magic numbers in the nuclear shell model. Black lines show the current frontier of nuclei that have been discovered. Most of the nuclei close to this limit have no experimental information about their properties. For nuclei with $\gtrsim$ 100 counts, half-lives can be measured in WAS3ABi and for nuclei with $\gtrsim$ 1000 counts γ-ray spectroscopy in EURICA is possible. Right: Isomer-decay spectrum of ^{76}Ni including γ-ray energy, E_γ, and relative intensity, I_γ.

measured, for example in ^{126,128}Pd [17].

Beyond ^{132}Sn, isomers in ^{136}Sn and ^{138}Sn with life-times down to ~ 50 ns have been discovered [18]. This discovery both shows the capability of EURICA to measure short isomeric life-times, and that the closed shell at $Z = 50$ stays intact at least up to $N = 88$. North-east of ^{132}Sn the phase transition between single-particle and collective modes have been studied from ^{138}Sb to ^{158}Nd. The low-lying level structure of the ground-state rotational bands can be studied from the isomeric decay cascades as well as the β-delayed γ-rays.

References

[1] T. Kubo, et al.: Prog. Theor. Exp. Phys. (2012) 03C003.
[2] P. Doornenbal: Prog. Theor. Exp. Phys. (2012) 03C004.
[3] S. Nishimura: Prog. Theor. Exp. Phys. (2012) 03C006.
[4] J. Eberth, et al.: Nucl. Instrum. Meth. **A369** (1996) 135.
[5] P.-A. Söderström, et al.: Nucl. Instrum. Meth. B, in print.
[6] E. V. D. van Loef, et al.: Appl. Phys. Lett. **79** (2001) 1573.
[7] D.L. Smith, et al.: Phys. Rev. C **77** (2008) 014309.
[8] N. Mărginean, et al.: Eur. Phys. J. **A46** (2010) 329.
[9] P. H. Regan, Appl. Radiat. Isot. **70** (2012) 1125.
[10] O. Roberts, et al.: EPJ Web Conf. (Heavy Ion Accelerator Symposium, Canberra), submitted.
[11] P. Boutachkov, et al.: RIKEN Acc. Prog. Rep., submitted.
[12] C. Hinke, et al.: Nature **486** (2012) 341.
[13] Z. Xu, et al.: These proceedings.
[14] C. Mazzocchi, et al.: Phys. Lett. **B622** (2005) 45.
[15] P.-A. Söderström, et al.: Phys. Rev. C **88** (2013) 024301.
[16] G. Lorusso, et al.: RIKEN Acc. Prog. Rep., submitted.
[17] H. Watanabe, et al.: Phys. Rev. Lett, **111** (2013) 152501.
[18] G. S. Simpson, et al.: Phys. Rev. Lett, submitted.