Final report

NN128172 NKFIH project

Title: β-decays in explosive nucleosynthesis scenarios

Cím: Béta-bomlások robbanásos elemkeletkezési folyamatokban

PI / vezető kutató: Gábor Gyula Kiss

The aim of the NN128072 grant was to provide solid ground for performing three experiments at RIKEN Nishina Center (Wako-shi, japan).

The modelling of stellar explosions and the calculation of the resulted abundance pattern require precise knowledge on the beta-decay rates of exotic, short-lived isotopes. However, such information is typically missing. To provide solid ground for nucleosynthesis calculations we measured the beta-decay of more than 100 isotopes, derived about 300 beta-decay parameters (half-lives, delayed one and two neutron emission probabilities), mostly for the first time ever.

The implementation of the project was hampered by many difficulties. Due to the coronavirus epidemic, entry restrictions were in effect in Japan between 01.02.2020 and 29.04.2023. Accordingly, we only had a limited opportunity to adjust the detector systems - which would have been required by the planned experimental work - and we had to rely on the work of our local partners during the setup of the experimental equipment. Most of the measurements of the project were thus carried out remotely. In order to do this, the researchers of the grant were deeply involved in the development and testing of the necessary codes and fast data transfer protocols. Furthermore, due to adaptation to the situation, other primary beams were available compared to the plans, and thus we had to slightly deviate from the submitted research plan. Finally, it should be mentioned that because of the above reasons more time was needed to achieve the goals of the project, so the term was extended by about 1.5 years.
As a result, we carried out four experiments (instead of the planned three) within the framework of the project and based on our achievements submitted two successful applications for beam time (one was planned). In more details:

- The aim of the NP1612-RIBF148 experiment (spokesperson: G. G. Kiss) was to measure the delayed neutron emission probabilities (P_n values) of the extreme neutron-rich rare earth isotopes to constrain the astrophysical models describing the formation of the rare earth abundance peak. We started the experiment in November 2018, at which time we could only measure one of the two beam settings. The second setting was measured by remote control in the spring of 2022.
- Due to the increase of the first-forbidden transition contribution to the beta-decays, the half-lives in the A~195 region are significantly reduced leading to a faster progression of r-process and this effect shifts the position of the third peak toward higher masses. The aim of the NP1712-RIBF159 measurement (spokesperson: S. Nishimura) was to measure the key decay rates. The measurement was completed remotely in the spring of 2022.
- The NP1712-RIBF158 experiment was not carried out due to the lack of ^{70}Zn primary beam. Instead we studied the beta-decay of extreme proton-rich isotopes (NP1111-RIBF93 experiment, spokesperson: A. Algora) and their nuclear shapes and structure was examined. Furthermore, the Gamow-Teller and spin-dipole transitions including their giant resonances

were studied for the first time on ^{8}He, ^{11}Li, ^{14}Be, ^{22,24}O using charge-exchange (p,n) reactions in the framework of the NP1412-SAMURAI30 experiment (spokesperson: L. Stuhl).

- Two beam time applications were accepted by the Program Advisory Committee of RIKEN Nishina Center.

In the following paragraphs the obtained results, sorted into 4 groups, will be introduced in details.

1. Delayed neutron emission probability measurements:

   The path of the astrophysical r-process (synthesizing about half of the stable isotopes above iron) located about 5-20 neutrons away from the valley of stability, the nuclei lying on its path decay most probably with β-delayed neutron emission. It is well known that the β-delayed neutron emission smooths the abundance pattern, alters the decay path toward the valley of stability and according to this, changes the position of the r-process abundance peaks. Unfortunately, at present theoretical models are not able to predict correctly the neutron emission probabilities which would be essential for precise abundance calculations.

   In the framework of the NP1612-RIBF148 proposal the beta-delayed neutron emission probabilities of 28 exotic neutron-rich isotopes of Pm, Sm, Eu, and Gd were measured for the first time and furthermore, the existing beta-decay half-life database was significantly increased toward more neutron-rich isotopes. As an example, figure 1 shows the obtained t1/2 values of samarium isotopes and the Pn values of Eu nuclei compared to theoretical predictions. The new data did not only constrain the theoretical predictions of half-lives and beta-delayed neutron emission probabilities but also allowed probing the formation mechanisms of the rare-earth peak. The newly introduced variance-based sensitivity analysis method offered a valuable insight into the influence of important nuclear physics inputs on the calculated abundance patterns (**G.G. Kiss** *et al*., Astrophys. J. **936** (2022) 107, **Á. Vitéz-Sveiczer** *et al*., Acta Phys, Pol. B Proc. Suppl. **16** (2023) 4-A8).

   The analysis of the data measured remotely is still in progress, we expect 4 new t1/2 and 14 new Pn values from this setting.

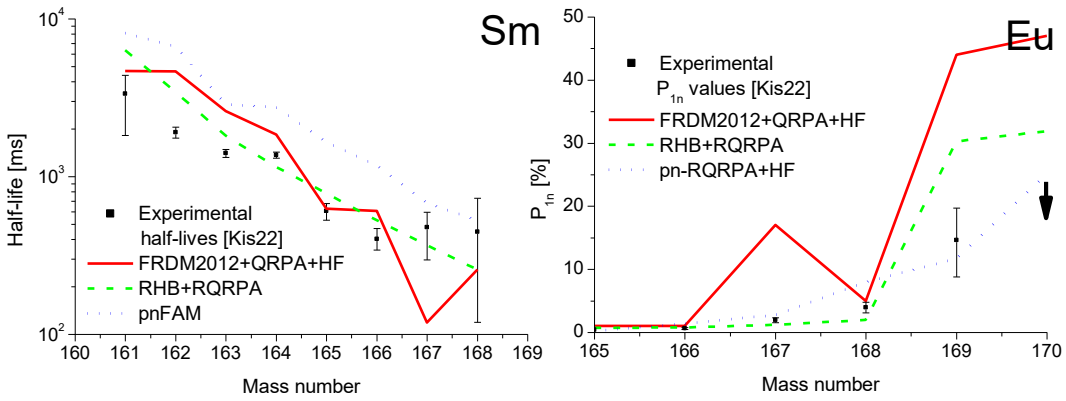

Figure 1: Recently measured half-lives of $^{161-168}$Sm isotopes compared to theoretical predictions (left) and experimental emission probabilities of $^{165-170}$Eu isotopes together with the calculated values (right).

In order to provide more precise nuclear physics data for the astrophysical simulations a new proposal, aiming the study of the beta strength function of Pm-Gd isotopes was submitted to the Program Advisory Committee of RIKEN Nishina Center. The PAC approved the beam time request and the NP2212-RIBF217 experiment (spokesperson: G. G. Kiss) will be carried out during the autumn of 2024.

We built a neutron detector similar to the one developed for the NP1612-RIBF148 experiment in the LNGS deep underground laboratory, where the measurement of the ^{13}C(α,n) reaction

cross section is in progress in the framework of the LUNA collaboration (**L. Csedreki** *et al.,* Nucl. Instr. Meth. **994** (2021) 165081).

The aim of the NP1612-RIBF159 proposal was to measure beta-decay parameters in the N=126 region. The first draft of the data, discussing the new isomers found in the region, was submitted to Phys. Rev. Lett. on the 29th of January 2024 (T.T. Yeung *et al*., Phys. Rev. Lett, submitted).

At the request of the editorial board of the European physical journal, we prepared a review manuscript on the new data available on the structure and decay mode of the heavy neutron rich nuclei (**G. G. Kiss** and Zs. Podolyák, Eur. Phys. J. – accepted for publication).

1.a. Furthermore, as the members of the BRIKEN collaboration we jointly performed two other experiments after the NP1612-RIBF148 measurement in the vicinity of ^{78}Ni and ^{130}Sn. In these experiments more than 60 P_n values were derived, often for the first time. In the case of the delayed two neutron emission probabilities (P_{2n} values), we doubled the size of the available database. The new data provides a strict constrain on the theoretical models and were used as inputs for astrophysical calculations (R. Yokoyama *et al*., Phys. Rev. C **100** (2019) 031302(R), O. Hall *et al*., Phys. Lett. B **816** (2021) 136266, V. H. Phong *et al*., Phys. Rev. Lett. **129** (2022) 172701 and R. Yokoyama *et al*., Phys. Rev. C **108** (2023) 064307).

1.b. Furthermore, we discovered new isomers (V. H. Phong *et al*., Phys. Rev. C **100** (2019) 011302) in the vicinity of ^{130}Cd.

2. <u>Beta-decay of extreme proton-rich isotopes: an insight into nuclear shapes:</u>

Nuclear shapes play an important role in our understanding of nuclear structure. Since its first introduction to explain collective phenomena, the shape concept has become an important tool. However, experimentally it's difficult to determine the shape of a nucleus. Recently it was showed that – in particular cases – the beta-strength distribution for transitions to states in the daughter nucleus depends on the shape assumed for the ground state of the decaying isotope. In the framework of this project we used this approach to derive the shape of neutron-rich isotopes such as ^{70}Kr and ^{186}Hg.

The aim of the NP1112-RIBF93 proposal was to study the beta-decay of the neutron-deficient ^{70,71}Kr isotopes which are lying on the path of the astrophysical rp-process. Fifteen γ-rays associated with the β-decay of 70Kr → 70Br have been identified for the first time, defining ten populated states below E_{exc}=3300 keV. The half-life of ^{70}Kr was derived with increased precision and the β-delayed proton emission probability has been also determined (**Á. Vitéz-Sveiczer** *et al*., Acta Phys. Pol. B **51** (2020) 587).

Using the experimental data, the Gamow-Teller strength distribution was derived and compared to predictions calculated assuming different shapes for the ground state of the decaying ^{70}Kr isotope (**Á. Vitéz-Sveiczer** *et al*., Phys. Lett. B **830** (2022) 137123). The decay scheme of ^{70}Kr isotope and the Gamow-Teller strength distribution are shown on the left and right hand side of figure 2, respectively.

Moreover, an increase in the beta-strength to the yrast 1+ state in comparison with the heaviest Z=N+2 system studied so far was observed that may indicate increased np correlations in the T=0 channel. The beta-decay strength deduced from the results was interpreted in terms of the proton-neutron quasiparticle random-phase approximation (QRPA) and also with a schematic model that includes isoscalar and isovector pairing in addition to quadrupole deformation. The application of this last model indicated an approximate realization of pseudo-SU(4) symmetry in this system (P. Van Isacker *et al.,* Symmetry 15 (2023) 2001).

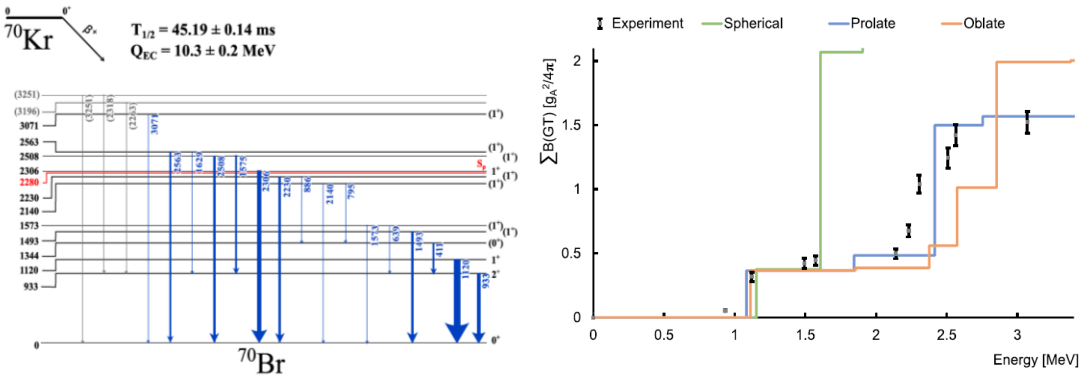

Figure 2.: Partial level-scheme of ^{70}Br derived from the beta-decay of ^{70}Kr (left). Experimental Gamow-Teller strength distribution [B(GT)] compared to calculations assuming spherical (green), prolate (blue) and oblate (orange) shapes for ^{70}Kr(right).

We currently finished the analysis of the beta decay data of ^{71}Kr. The manuscript discussing the results will be submitted soon to Physical Review Letters (**A. Algora** *et al.*, in preparation).

After the measurements carried out in the region of ^{70}Kr, we submitted a beam time application to conduct a similar experiment in the ^{100}Sn range. The PAC approved the NP2112-RIBF210 experiments (spokesperson: A. Algora).

Moreover, the Gamow-Teller strength distribution of the decay of ^{186}Hg → ^{186}Au has been determined for the first time using the total absorption gamma spectroscopy technique and has been compared with theoretical QRPA calculations using the SLy4 Skyrme force. The measured Gamow-Teller strength distribution and the half-life are described by mixing oblate and prolate configurations independently in the parent and daughter nuclei (**A. Algora** et al., Phys. Lett. B **819** (2021) 136438).

Further experiments, aiming the study of the shapes and structure of proton-rich isotopes, were also carried out by the researchers of the NN128072 NKFIH grant. Here a brief summary on these results are given.

2.a. The decay schemes and absolute Fermi and Gamow-Teller transition strengths have been determined for ^{60,62}Ge nuclei. The beta-delayed proton-emission branching ratio was determined for ^{60}Ge for the first time. The ground state–to–ground state feeding for the decay of ^{62}Ge was determined and eight new gamma lines have been added to the de-excitation of levels populated in the ^{62}Ga daughter [S. E. A. Orrigo *et al.*, Phys. Rev. C **103** (2021) 014324].

2.b. Furthermore we studied the structure of the N = Z = 36 nucleus ^{72}Kr by inelastic scattering. The data were analyzed in terms of a two-band mixing model which showed clear evidence for an oblate-prolate shape coexistence, explained by a shape change from an oblate ground state to a prolate deformed yrast band from the first 2+ state (K. Wimmer *et al.*, Eur. Phys. J. **56** (2020) 159).

3. <u>Nuclear structure studies carried out using the SAMURAI spectrometer</u>:
Until recently, only the spin-isospin collectivity in stable isotopes was investigated and there is no available data for nuclei with large isospin asymmetry factors, where (N − Z) / A > 0.25. However, (p, n) reactions at intermediate beam energies (E/A >100 MeV) and small scattering angles can excite Gamow-Teller (GT) states up to high excitation energies in the final nucleus,

without Q-value limitation and this fact offers a tool to study isovector response of light nuclei near the neutron drip line. Therefore, the Gamow-Teller and spin-dipole transitions on ^{8}He, ^{11}Li, ^{14}Be, ^{22,24}O were studied for the first time in the framework of the NP1412-SAMURAI30 (spokesperson: L. Stuhl) experiment. To perform the measurement a new low energy neutron spectrometer, called PANDORA, had to be developed (**L. Stuhl** *et al*., Nucl. Instr. Meth. **463** (2020) 189). The analysis of the data collected in the NP1412-SAMURAI30 experiment is still in progress.

Furthermore, we jointly performed other experiments aiming the study of the nuclear structure of isotopes located close to the islands of inversion.

3.a. Exclusive cross sections and momentum distributions have been measured for quasifree one-neutron knockout reactions from a ^{54}Ca beam. The significantly larger cross section to the p3/2 state compared to the f5/2 state observed in the excitation of ^{53}Ca provides a direct evidence for the arising of a new shell closure in neutron-rich calcium isotopes (S. Chen *et al*., Phys. Rev. Lett. **123** (2019) 142501).

3.b. The low-lying states in ^{51,53}K populated from the ^{52,54}Ca(p,2p) reactions at ∼250MeV/nucleon were studied. The 1/2+1→3/2+1 transitions of ^{51,53}K were measured for the first time and the spins-parities were assigned based on the measured cross sections and parallel momentum distributions (Y. L. Sun *et al*., Phys. Lett. B **802** (2020) 135215).

3.c. Detailed spectroscopy of the neutron-unbound nucleus ^{28}F has been performed for the first time following proton/neutron removal from ^{29}Ne/^{29}F beams. The reconstructed ^{27}F+n momentum distribution following neutron removal from ^{29}F indicates that it arises mainly from the 1p3/2 neutron intruder configuration. This demonstrates that the island of inversion around N=20 includes ^{28}F, and probably ^{29}F, and suggests that ^{28}O is not doubly magic (A. Revel *et al*., Phys. Rev. Lett. **124** (2020) 152502).

3.d. Low-lying excited states in the N = 32 isotope ^{50}Ar were investigated by in-beam γ-ray spectroscopy following proton- and neutron-knockout, multinucleon removal, and proton inelastic scattering. The energies of the two previously reported transitions have been confirmed, and five additional states are presented for the first time, including a candidate for a 3− state. Theoretical proton- and neutron-knockout cross sections suggest that two of the new transitions correspond to 2+ states, while the previously proposed 4+ state could also correspond to a 2+ state [M. L. Cortés *et al*., Phys. Rev. C **102** (2020) 064320].

3.e. Besides the known isomeric state in ^{59}Ti, two isomeric states in ^{61}Ti were observed for the first time. Based on the measured lifetimes, transition multipolarities as well as tentative spins and parities were assigned. Large-scale shell model calculations based on the modified LNPS interaction show that both ^{59}Ti and ^{61}Ti belong to the Island of Inversion at N=40 with ground state configurations dominated by particle-hole excitations to the g9/2and d5/2orbits (K. Wimmer *et al*., Phys. Lett. B **792** (2019) 16)

3.f. New data on isomeric states in the vicinity of the N = 40 island of inversion have been obtained. The decay scheme of the isomeric state in ^{60}V to the ground state and a very low-lying state at only 4 keV have been established using γ-γ coincidence analysis (K. Wimmer *et al*., Physical Review C **104** (2021) 014304).

4. Other results:

The heavy stable proton-rich isotopes are thought to be synthesized during the explosion of a type IA and/or Type II supernovae. Modeling this nucleosynthesis scenario requires knowledge on the cross sections of the relevant γ-induced reactions. Usually the activation technique is used to measure the inverse reactions and from this data the photodisintegration rates are derived using the detailed balance theorem. The uncertainty of the half-lives of the reaction products influences the precision of the measurements sensitively.

In the framework of the NN128072 NKFIH grant we measured precisely the half-life of ^{65}Ga, ^{95}Ru, ^{95}Tc, ^{95m}Tc, ^{125}Cs and ^{125}Xe using gamma spectroscopy. The proclaimed new half-life values are much more (often by more than an order of magnitude) precise than the ones available from literature (**Gy. Gyürky** *et al*., Appl. Rad. and Isotopes **148** (2019) 87, **T. N. Szegedi** *et al*., Nucl. Phys. A **986** (2019) 213 and **T. N. Szegedi** *et al*., Eur. Phys. J. **56** (2020) 182).

Furthermore, to constrain the cosmological lithium problem, the cross sections of the ^{7}Be(n,p0/1)^{7}Li, ^{7}Be(n,^{4}He)^{4}He reactions were determined using the Trojan Horse Method at RIKEN Nishina Center. The new experimental data were used as inputs for Big-Bang Nucleosynthesis calculations which resulted in the decrement of the primordial ^{7}Li abundance by about one-tenth or 2 standard deviations (S. Hayakawa et al., Astrophys. J. Lett. **915** (2021) L13].

Summary

As the result of the NN128072 NKIH grant we published 9 D1, 16 Q1 papers (and further three papers are under review). The members had 9 talks at international conferences / schools. Furthermore, students for the University of Debrecen and ELTE were deeply involved into the project. Two students (T.N. Szegedi and S. Kovács) showed their analysis at the National scientific student association conference (TDK) and won first prizes in Nuclear Physics session. Based on the data derived in the framework of the NN128072 NKFIH grant a PhD has already been completed (T.N. Szegedi) and another three are in progress (Á. Vitéz-Sveiczer, D. Körtefái and S. Kovács).