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Radomira Lozeva, Andrew Stuchbery, Jürgen Gerl, Georgi Georgiev, Teodoros J. Mertzimekis

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Radomira Lozeva · Andrew Stuchbery · Jürgen Gerl · Georgi Georgiev · Teodoros J. Mertzimekis and the gSPEC collaboration

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Abstract Nuclear g factors are of the most accurate probes in modern nuclear physics investigations. Sensitive to the precise structure of the nuclear states, single-particle or collective nature is accessed directly by their measurement. At the border of nuclear existence, key regions of nuclei both neutron-rich and proton-rich are foreseen for studies. The investigations will cover shell structure, magicity, nucleon-nucleon interaction, collectivity, deformation, and shapes. With the new gSPEC project at the GSI/FAIR facility, such investigations are intended to scan various excited states of nuclei along the entire nuclear chart. Currently, the design of a new dedicated experimental apparatus is being performed, including magnetic system and detector R&D, together with feasibility studies of various scientific cases.

Keywords Nuclear moments · γ-ray Spectroscopy · Exotic nuclei

Radomira Lozeva
Centre de Sciences Nucléaires et de Sciences de la Matière, IN2P3/CNRS, Université Paris-Saclay, bats. 104 et 108, 91405 Orsay Campus, France E-mail: radomira.lozeva@csnsm.in2p3.fr

Andrew Stuchbery
Department of Nuclear Physics, Australian National University, Canberra, ACT 2601, Australia E-mail: andrew.stuchbery@anu.edu.au

Jürgen Gerl
GSI Helmholtzzentrum für Schwerionenforschung GmbH/FAIR Center, Planckstrasse 1, D-64291 Darmstadt, Germany E-mail: j.gerl@gsi.de

Georgi Georgiev
Department of Nuclear Physics, Australian National University, Canberra, ACT 2601, Australia Centre de Sciences Nuclaires et de Sciences de la Matire, IN2P3/CNRS, Université Paris-Saclay, bats. 104 et 108, 91405 Orsay Campus, France E-mail: georgi.georgiev@csnsm.in2p3.fr

Teodoros J. Mertzimekis
Department of Physics, University of Athens, Zografou Campus, 15784 Athens, Greece E-mail: tmertzi@phys.uoa.gr

gSPEC collaboration E-mail: gspec.fair@gmail.com

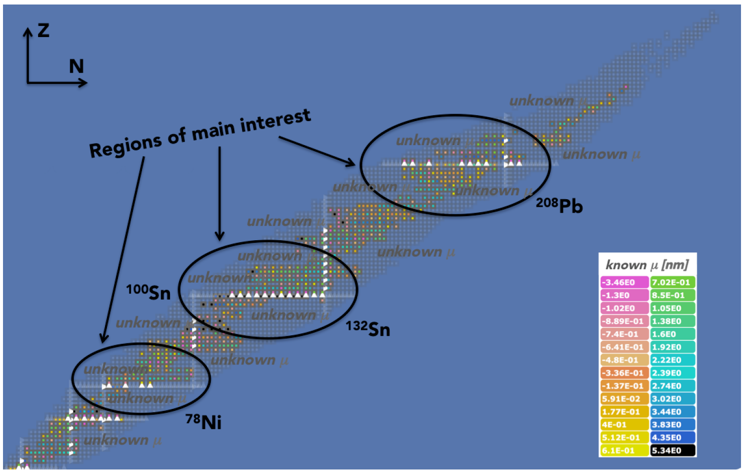

Fig. 1 Chart of nuclei along the β-stable isotopes with doubly-magic species in white [6]. The chart represents the aims of gSPEC (in black and in grey).

1 Introduction

Sensitive to the precise configuration of the nuclear states, nuclear magnetic moments are a fingerprint of their single-particle structure because the nucleon g factors depend strongly on their orbital and total angular momentum, and they are connected to the magnetic moments through the nuclear spin [1, 2]. Their investigations for exotic nuclei far-from-stability provide extremely valuable information on the orbital evolution and the development of collectivity. This is particularly important in the vicinity of doubly-magic nuclei, where moments can be the only measure of the unpaired-nucleon configuration of the emerging isomeric states [3–5]. Such information often comes from systematics or theoretical calculations and appears to be quite imprecise in barely explored regions. As in these investigations testing of shell structure and shell evolution is performed, new nuclear structure phenomena can be revealed as well.

2 Physics objectives

gSPEC aims at studying g factors of isomeric states in three key regions of the nuclear chart such as Pb, Sn and Ni and their vicinity, including both neutron-rich and proton-rich nuclei (see Fig. 1). First main interests of the collaboration are centred at 1) the neutron-rich ^{208}Pb region, 2) proton-rich ^{100}Sn region and 3) neutron-rich ^{132}Sn region. At the GSI/FAIR facility [7] all these regions can be accessed by employing heavy-ion fission or fragmentation reactions of primary beams and it is the only facility providing access for measurements to all of them.

Moreover, the regions beyond ^{208}Pb and below ^{100}Sn have never been explored with nuclear moment investigations of this type, especially on isomeric states. In the region around ^{132}Sn, such data is scarce. Thanks to the high-beam intensities we expect to reach extremely neutron-rich nuclei (e.g. $N/Z>$1.5) in this region. Therefore, except precise nuclear structure, their study gives unique opportunity to develop knowledge about proton-neutron interaction near astrophysical pathways including the r-process (^{208}Pb, ^{132}Sn) and rp-process (^{100}Sn). Furthermore, when using a technique sensitive to only particular excited nuclear states with certain lifetimes, gSPEC becomes unique in aiming to probe these fundamental nuclear properties. At the same time investigations using the method of measuring exited states is completely complementary to other e.g. laser methods typically used to ground or very long-lived states.

Among the important questions to study e.g. in the $A\sim$100 region, especially around ^{100}Sn, is the onset of very rapid deformation, expected when varying both N and Z [8,9]. For the $N=Z$ nuclei information about excited states is extremely scarce. Nuclear isospin and spin-aligned coupling may replace the normal coupling scheme [10] and only moments can probe the real configuration to compare with theory. Except the relevant single-particle structure and spin assignments, the investigation of pairing below ^{100}Sn, core-polarization effects, as well as the intrinsic properties of the M1 operator [1–3] and its suggested quenching at the two extremes of isospin from ^{100}Sn to ^{132}Sn [10–12] are all with high relevance in future investigations. For the very-neutron-rich nuclei beyond ^{132}Sn, details on the nuclear wave function composition come exclusively from shell-model theory. Also, the robustness of one of the most well-pronounced shell gaps at N=82 and Z=50 is questioned [11] and by self-consistent theory suggested to change when approaching the neutron drip line [12]. Heavier nuclei along Z=82 exhibit variety of nuclear shapes [13] all at low excitation energy [14,15]. Theoretically, it is expected that this deformation increases with the nucleon increase and forms an island of deformation in the heavy nuclei around ^{208}Pb [16]. Therefore, except on the formation of shapes, by measuring single-particle contribution of states in nuclei around ^{208}Pb, one obtains information about the evolution of shell orbitals, seniority mixing, the need of three-body forces in the nuclear interaction, especially where up to now lack of experimental data resulted in inaccurate or false explanations of nuclear phenomena [17].

3 Methodology

Pioneering works on g-factor measurements during the g-RISING campaigns at GSI [18–23] paved the way for the new gSPEC investigations at FAIR allowing 1) spin-aligned isomeric beams to be maintained in-flight and used for nuclear moment measurements; 2) heavy-ions of $A\sim$200 to be sufficiently fully stripped to allow no loss of orientation, which is a necessity for such investigations and is generally obtained in the nuclear reaction; 3) nuclear states of different isotopes to be accessed and their wave-function content measured simultaneously, depending on the momentum selections using both fission and fragmentation reactions to produce the heavy-ion cocktail beams [18,20,21]. First, it is planned to employ the highly-productive TDPAD technique by implanting the nuclei in a host placed in static magnetic field and measuring the anisotropy in the angular distribution of γ-rays with HpGe detectors. It is a vast experimental challenge to access very exotic neutron-rich and proton-rich nuclei for a first time, with the highly-improved

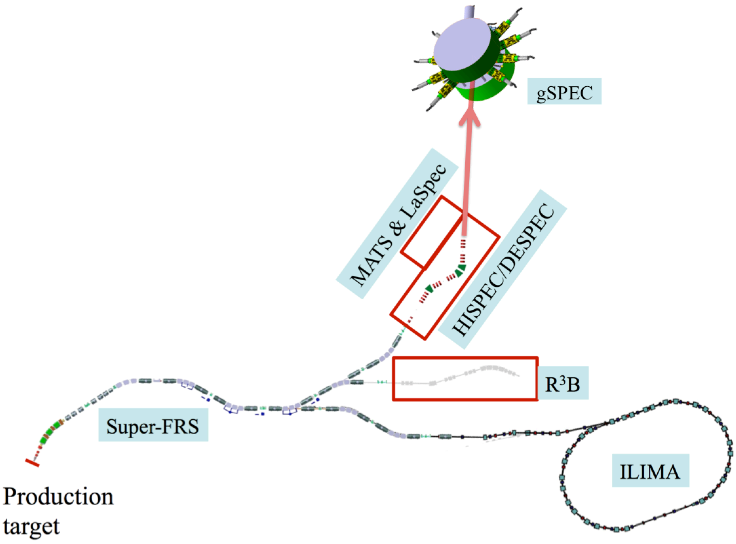

Fig. 2 gSPEC at the Super FRS spectroscopy lines of FAIR [7].

beam quality and intensity, and in much better experimental conditions at FAIR. Within the collaboration, two other techniques such as TDRIG and TF are also suggested to be employed for gSPEC with some modifications of the standard experimental setup. This will allow applying these techniques to excited states with ps lifetimes and extending gSPEC beyond the TDPAD method, generally working well for excited states with lifetimes in the ns-μs range. For the last, certain ion/host combinations may need to be excluded, due relaxation effects limiting the sensitivity range. As it can be seen in Fig. 2, this spectroscopy is planned in one or multiple focal planes of the Super-FRS at FAIR (or in some cases FRS at GSI).

4 R&D and ongoing works

Simulations of various detector combinations and feasibility studies are currently ongoing for gSPEC. In addition, magnet design study, HpGe detectors, and ancillary detectors are being designed, prepared and tested. The full R&D on the project will be the subject of a dedicated publication. Here, we give the main components: 1) The magnetic design is currently discussed with industrial suppliers and aims at building a system with a sufficiently high field ($B > 2$T) to suit the above-mentioned methods, have a good homogeneity (better than 5x10^{-3} T) and allow reasonably large beam distributions to be implanted into the system. The last is a specificity of GSI/FAIR and from our simulations of realistic cases it turns out that collimation of the beam is mandatory. Further work in investigating angular distributions depending on the ion implantation position is ongoing to choose the appropriate collimation. 2) Simulations on the HpGe detector configurations are also taking place. Furthermore, their best arrangement, efficiency, angular resolution and position are among the factors being optimized. 3) R&D on ancillary detectors is also ongoing. Similarly to g-RISING, these detectors need to be with optimized configuration, positioning, and usage in a high magnetic field. 4) Investigations on the employment of another type of methods/setups using e.g. secondary reactions (to access e.g. states with shorter lifetimes and/or reaction to obtain high-degree of alignment of a secondary-ion product [3,13,24]), multiple setups in e.g. more than one focal plane, are all being carried out. Some of these applications include the usage of additional tracking detectors, other than standard tracking detectors at FRS/Super FRS. Such modifications are considered as ancillary for the main experimental setup, however possible as they allow an extension of the standard applicability of gSPEC.

5 Perspectives

Further work on simulations, detector R&D and tests are foreseen together with the commissioning of the system. LoI of the collaboration and TDR are also in preparation. Feasibility simulations in the main regions of interest allow concentrating to several physics cases for e.g. commissioning the system with the FRS/GSI. With the further increase of the primary-beam intensities (e.g. of the order of 3 orders of magnitude for ^{238}U) next Day-1 experiments can be conducted with Super FRS at FAIR. Reports of these achievements are planned in forthcoming publications of the gSPEC collaboration.

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