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FUTURE RISING EXPERIMENTS AT RELATIVISTIC ENERGIES *

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The proposed experiments for the first RISING (Rare ISotope INvestigations at GSI) campaign will exploit secondary unstable beams at relativistic energies in the range from 100 MeV/u to 400 MeV/u. The RISING spectrometer will be employed for relativistic Coulomb excitation and for high-resolution γ-spectroscopy experiments after secondary nucleon removal reactions and secondary fragmentation. New experimental methods for spectroscopy at relativistic energies will be investigated in order to measure nuclear structure observables beside the directly accessible level energies and quadrupole deformations. The future experiments will focus on: Shell structure of unstable doubly magic nuclei and their vicinity, symmetries along the $N = Z$ line and mixed symmetry states, shapes and shape coexistence, collective modes and E1 strength distribution.

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1. Introduction

The SIS/FRS facility provides secondary beams of unstable rare isotopes after fragmentation reactions or secondary fission of relativistic heavy ions with sufficient intensity for in-beam γ-spectroscopy measurements. The proposed experiments for the first RISING (Rare ISotope INvestigations at GSI) campaign exploit these unique beams at relativistic energies in the range from 100 MeV/u to 400 MeV/u. Comparing with other fragmentation facilities the majority of the experiments depend on fragmentation products from heavy primary beams or the high secondary beam energy and are predestined for GSI. The RISING spectrometer is employed not only for relativistic Coulomb excitation but also for high-resolution γ-spectroscopy experiments after secondary nucleon removal reactions and secondary fragmentation. The latter may lead to rather high angular momentum states. Several experiments will focus on new methods and techniques in order to obtain important nuclear structure observables beside the level energies and quadrupole deformations. As special application they may allow g-factor measurements for short lived states, systematic studies of the spin alignment/polarisation and to determine life times of short lived states and spectroscopic factors.

The proposed γ-ray spectroscopy of nuclei from exotic beams will be performed after in-flight isotope separation. The exotic beams will be produced by fragmentation of a heavy stable primary beam or fission of a ^{238}U beam on a ^{9}Be or ^{208}Pb target in front of the fragment separator FRS. A maximal beam intensity from the SIS synchrotron of 10^{10}/s for medium heavy beams and 10^{9}/s for ^{238}U is expected. The secondary beam intensities take advantage of the primary target thickness of $\approx$ 1–4 g/cm^2 and the high cross section, for fragmentation reactions and fission given *e.g.* by the EPAX parameterisation [1] and measured data for the fission processes [2]. Experimental details related to the RISING spectrometer and its ancillary detectors [3] are presented by the contributions of Bednarczyk [4] and Lozeva [5] to this conference.

2. RISING physics program

The motivations to explore nuclear structure of exotic nuclei focus on the following subjects:

(i) shell structure of unstable doubly magic nuclei and their vicinity;

(ii) symmetries along the $N = Z$ line and mixed symmetry states;

(iii) shapes and shape coexistence;

(iv) collective modes and E1 strength distribution.

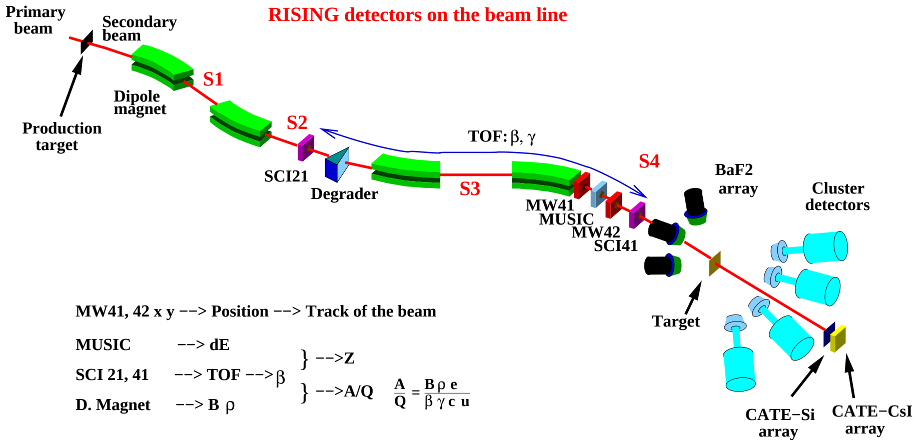

Fig. 1. Schematic layout of the RISING set-up at the FRS. The beam diagnostic and tracking elements consist of two multiwire detectors MW41, MW42, an ionisation chamber MUSIC and two scintillation detectors SC21, SC41. The γ-rays are measured with BaF2-HECTOR and Ge-Cluster detectors. The ions emerging from the reaction target are identified with the CATE array.

2.1. Shell structure

Spectroscopic data on the single particle structure of unstable doubly magic nuclei and their nearest neighbours are pivotal for theoretical description of the effective interactions in large-scale shell-model calculations. The proposed studies along the $N = Z$ line, passing doubly magic nuclei ^{56}Ni and ^{100}Sn, provide an excellent probe for single-particle shell structure, proton–neutron interaction and the role of correlations, normally not treated in mean field approaches. For example, the $B(\mathrm{E}2,2^+_1 \rightarrow 0^+)$ values in semi-magic Sn nuclei provide a sensitive test for changing (sub)shell structure, the E2 polarisability and the shape response of the magic core. For several reasons conventional techniques, employing (HI,xn) reactions, are very difficult or even impossible and Coulomb excitation measurements with unstable beams are the most promising way to obtain the interesting $B(\mathrm{E}2,2^+_1 \rightarrow 0^+)$ values.

The development of new shell structure at $N \gg Z$ as studied in light and medium-heavy neutron-rich nuclei around $N = 8, 20, 28$ [6–8] is generally ascribed to the weakening of the surface slope of the neutron potential due to the large neutron excess. As a consequence the familiar Woods–Saxon shape of the potential for nuclei close to stability is expected to change towards a harmonic oscillator type. This goes along with a reduction of the spin–orbit splitting, which is proportional to the potential slope, for orbitals probing in their radial extension the surface region and thus harmonic oscillator magic numbers are expected to be reinforced [9]. Moreover, ^{78}Ni and ^{132}Sn are located close to the astrophysical rapid neutron capture process path and indirect evidence for an altered shell structure and shell quenching of magic gaps at $N = 82$ and $N = 126$ is derived from r-process network calculations [10].

Alternatively, the existing experimental evidence of changing shell structure along the $N = 8$, 20 and 28 isotonic sequences can be explained in terms of the monopole part of the nucleon–nucleon residual interaction. Schematically this is due to the $(\sigma\sigma)(\tau\tau)$ part of the interaction, which is binding and strongest in the $S = 0$ (spin-flip) and $T = 0$ (proton–neutron) channel of the two-body interaction. This causes large monopole shifts of neutron single-particle orbits due to their missing $S = 0$ proton partners at large neutron excess, and thus generates new shell gaps. The effect was first discussed for the sd shell [11, 12] and for the pf shell [12, 14]; see also contribution by Otsuka [13] to this conference.

To date the investigations concentrate on the region of neutron-rich Ca, Ni and Sn isotopes about the most significant matrix elements, the spectroscopic factors and the magnetic moments, which are sensitive indicators of their structure. It is known experimentally that the neutron $\nu f_{5/2}$ orbit from ^{57}Ni towards ^{49}Ca undergoes a large monopole shift due to the reduced binding with increasing removal of the proton $\pi f_{7/2}$ $S = 0$ spin–orbit partners [14]. Beyond $N = 28$ this opens a gap between the $\nu p_{3/2}, p_{1/2}$ and $\nu f_{5/2}$ orbits, which might be subject to change depending on the $2p_{1/2}$ position, as this also forms a $S = 0$ pair with $\pi 1f_{7/2}$ but with less radial overlap. In the Ca isotopes beyond $N = 28$ a possible (sub)shell closure at $N = 32, 34$ seems to develop in $E(2_1^+)$. It has been pointed out recently that the Cr isotopes show a maximum in $E(2_1^+)$ at $N = 32$. On the other hand within the $N = 34$ isotones $E(2_1^+)$ is increasing from Fe to Cr in contrast to the expected trend towards midshell, which supports a $N = 34$ closure [15]. Besides masses, which due to short half lives are difficult to measure, obviously B(E2) values are missing for a proof of the concept. A study of the $N = 30$–34 isotones of Cr would reveal such a change in shell structure and was started in one of the first RISING experiments; see contribution of Bürger to this conference [16].

2.2. Spectroscopic factors in ^{132}Sn

The spin–orbit splitting plays the crucial role in determining the binding and structure of nuclei. Depending on the relative orientation of the spin and the orbital angular momentum, the energy of the associated nuclear state is shifted up or down. According to certain model predictions [9], the energy splitting of the spin–orbit partners should decrease or even vanish far from stability for very neutron-rich isotopes. Recently energy differences between pairs of high-j proton single-particle states and the spectroscopic factors of these states were measured following Sn(α,t) reactions for all seven stable even Sn isotopes [17]. A possible explanation of the changing energy separation is a decreasing overall spin–orbit splitting, proposed by [9]. Experiments with radioactive ion beams measuring spectroscopic factors in the vicinity of ^{132}Sn are, therefore, especially intriguing.

The determination of the spectroscopic factors in $A-1$ nucleus at the $N=82$ shell closure will provide detailed information on the mixing of single particle states with more complicated configurations. The mixing is expected to occur mainly with configurations containing a low-lying surface vibrational mode [18]. Estimates of absolute one-particle removal cross sections for knock-out reactions indicate considerable cross sections of the order of a few mb/sr. The evolution of the single-particle levels, of which only a few are known, could be studied with knock out reactions by detecting the gamma rays deexciting the states in nuclei around the $Z=50$ proton closed shell and the $N=82$ neutron shell. The spectroscopic factors for ^{132}Sn obtained through Hartree–Fock calculations with SGII effective interaction, including the coupling to collective phonons, underline the doubly magic character of the ^{132}Sn.

A direct way to measure the ground state structure of ^{132}Sn, employing the RISING setup, is to determine the spectroscopic factors for the removal of a neutron. The observation of the decay of the $7/2^-$ level in the gamma spectrum of ^{131}Sn should directly probe the occupancy of the $2f_{7/2}$ orbit. The neutron closed shell configuration $(h_{11/2})^{12}$ would give spectroscopic factors of $12/(2j+1)$ for the $11/2^-$ and 0 for the $7/2^-$ states. The experimental determination of the single particle character of the $5/2^+$ state above the $\nu d_{3/2}$ ground state, should shed some light on the relatively low value of the $\nu d_{5/2}-\nu d_{3/2}$ spin orbit splitting.

2.3. Magnetic moments

Nuclei near closed shells are characterised by specific single particle components in the wave functions, which changes into collective structures when departing from shell closures. In comparison to the stable even-A Te isotopes $^{120-130}$Te, which are collective of vibrational nature, the structure of the unstable neutron-rich isotopes $^{132-136}$Te is strongly influenced by the $N=82$ shell closure and the two protons outside the magic $Z=50$ shell. This feature becomes evident already from their 2_1^+ excitation energies. For the stable ^{134,136}Xe nuclei g-factors were recently determined for the 2_1^+ and 4_1^+ states clearly exhibiting single proton excitations with dominant $\pi 1g_{7/2}$

configuration [19]. Large and positive g-factors of both states in ^{136}Xe and of the 4_1^+ state in ^{134}Xe unambiguously shows the dominant proton nature whereas the smaller $g(2_1^+)$ value in ^{132}Xe implies additional neutron hole configurations.

At present, for *ps* lifetimes of nuclear states only the technique of transient magnetic fields (TF) provides the necessary field strengths of several kTesla, to observe spin precessions with the method of perturbed γ-angular correlations (PAC). The TF are hyperfine fields, which are experienced in fast moving ions during their passage through ferromagnetic materials [20]. TF are described by empirical parameterisations [20] at intermediate ion velocities, $v \ll Zv_0$ (in units of the Bohr velocity v_0), whereby the field strength generally increases with velocity reaching a maximum at $v = Zv_0$ for single-electron ions with its maximum fraction at the $1s$ electron Bohr velocity. Hence, the largest TF are expected for H-like ions implying velocities of relativistic heavy ions available at GSI.

The technique proposed for future RISING g-factor measurements is projectile Coulomb excitation in combination with TF in ferromagnetic Gadolinium. The target, consisting of approximately $50\,\mathrm{mg/cm^2}$ of ^{208}Pb and $50\,\mathrm{mg/cm^2}$ of Gd, serves for excitation in Pb and Gd and spin precession in the Gd layer. After fragmentation reactions of stable ^{136}Xe and ^{164}Dy beams, the secondary ^{132,134,136}Te and ^{138}Xe ions will be focused onto the double-layered target polarised by an external field of 0.08 Tesla. The mean energy of the excited ions in Gd corresponds to a velocity of $v_{\mathrm{ion}} \simeq 60v_0$, implying a H-like ion fraction of $q_{1s} \simeq 0.5$. For the TF strength in these conditions one calculates a very high field strength of $B_{\mathrm{TF}} \simeq 23\,\mathrm{kTesla}$ and effective interaction times of $t_{\mathrm{eff}} \approx 0.3$ps and 0.2 ps for excitation in Pb or Gd, respectively. Main advantage of the relativistic energy will be a huge precession angle of *e.g.* $\theta_{\mathrm{exp}}(2^+) \approx 240$ mrad assuming a positive g-factor in ^{134}Te of $g(2^+) = +0.8$. Its observation is based on a pronounced anisotropy of the angular correlation of the $(2^+ \rightarrow 0^+)$ γ-rays of ^{134}Te in the rest frame of the emitting nuclei. As the Te ions recoil out into vacuum, the anisotropy of the correlation will be attenuated by the strong hyperfine fields of $1s$ electrons in the dominant H-like ions, expressed by attenuation coefficients. The spin precession is observed via the rotation of the anisotropic angular correlation of γ-rays emitted from the excited states. The deexcitation γ-rays are measured with the RISING Ge-detectors — at fixed polar angles θ_γ, in and close to the reaction plane — in coincidence with the scattered ions, registered in the position sensitive Si detector array CATE [5]. In such a geometry previous TF measurements were successfully carried out at lower beam energies of 15 MeV/u [21] which will be extended now to higher energies.

2.4. Symmetries

Recently spectroscopy at high spin of even–even $T = 1 (T_z = \pm 1)$ mirror nuclei with $A = 50$ [22] and $A = 46$ [23] has been achieved, by identifying gamma decays in the most proton-rich $(N = Z - 2)$ isobars. The Coulomb Energy Differences CED between these $T = 1$ mirror states showed that a very detailed understanding of the spatial correlations of pairs of particles can be gained. In these cases, it was also found necessary to include "one-body" effects in order to understand the CED. One such effect [22] is the Coulomb energy associated with nucleon orbitals of different radii, the occupation of which evolve as a function of spin, resulting in a contribution to the CED. These $A = 46$ and $A = 50$ even–even mirror nuclei described above represent the largest value of total isospin T, for which isobaric analogue states have been studied at high spin.

For mirror nuclei with larger values of isospin $(T \leq 3/2)$ no detailed spectroscopic studies in medium-mass nuclei have been undertaken. The large proton excess for the proton-rich members of these isobaric multiplets may be expected to have an increasingly significant effect on the one-body part of the measured Coulomb energy. This includes the bulk Coulomb effect associated with the differences in radii of specific orbitals as well as the more subtle effect of the Coulomb distortion of the specific nucleon wave functions (the Thomas–Ehrman shift). The mirror pair ^{53}Ni/^{53}Mn is of particular interest, as these nuclei have a very simple $(f_{7/2})^{-3}$ structure — neutron holes in ^{53}Ni and proton holes in ^{53}Mn. This allows for a comparison of the $(f_{7/2})^{-3}$ proton and neutron multiplets, and the CED between these will give new information on the Coulomb two-body matrix elements in the upper $f_{7/2}$ shell — a vital ingredient for the shell model calculations that can only be derived from experimental data.

Therefore, in one of the first RISING experiments even Z, $T_z = -3/2$ nuclei in the $f_{7/2}$-shell were produced after secondary fragmentation reactions and a spectroscopic study of the energy levels up to 3–4 MeV excitation energy was started. The fragmentation reaction may populate low-spin non-yrast structures that are only weakly populated in the fusion–evaporation technique, allowing a more complete study of the Coulomb effects. For details of the status of the analysis of this experiment see contribution by Hammond [25] to this conference.

Spectacular shape effects are observed in the $A = 70$–80 mass region with extremely large oblate deformation for $N = Z = 36$ changing to a large prolate deformation for $N = Z = 38, 42$. Therefore, the light Se- to Zr-isotopes are amongst the best candidates for investigations of the origin and development of nuclear shapes and shape coexistence. Moreover, in the $N = Z$ odd–odd nucleus ^{70}Br [24] indication exist that the Coulomb distortion of the nucleon wave functions may be important as the dripline is approached. The CED between the $T = 1$ states and those in the neighbouring analogue nucleus ^{70}Se shows anomalous behaviour which has been interpreted in terms of the Thomas–Ehrman shift.

A proposed spectroscopic RISING investigation of excited states in the $T_z = -1/2$ nucleus ^{69}Br should reveal information on one of the accessible, heaviest mirror nucleus. Due to the location at the proton drip line or even beyond, extended proton distributions may become apparent from the break down of the mirror symmetry. The differences in proton radii should manifest themselves through differences in the behaviour of CEDs. A recent investigation of the Coulomb energy differences in ^{70}Br,^{70}Se has shown a similar effect possibly attributed to a decrease of the nuclear two-body residual interaction due to the different radial distributions of the wave functions for neutrons and loosely bound protons [24]. In case of ^{69}Br due to the very low binding energy major differences are expected with respect to the strongly bound ^{69}Se in the excitation energy of the low lying states.

The rapid-proton capture process (rp process), first proposed by Wallace and Woosley [26], proceeds via a sequence of proton capture and beta decays near and along the proton drip line. The path of the rp process is determined by the stability of the nuclei involved. Different predictions of the exact position of the proton drip line are related to possible termination points of the rp process. The odd-Z isotopes of ^{65}As and ^{69}Br are considered as possible termination points because the half-lives of their proton capture targets ^{64}Ge and ^{68}Se are supposed to be longer than the time scale of the explosion that provides the proton flux. With respect to ^{69}Br, a first evidence for the existence was reported [27]. However, follow-up experiments did not succeed to observe ^{69}Br. In particular, experiments at GANIL [28] and NSCL [29] could not attribute an event to ^{69}Br. The latter experiment indicates that ^{69}Br was not stable or had a very short half-life in the range below 24 ns. To overcome difficulties due to the flight path limit in a fragment separator, the RISING study of ^{69}Br will investigate the prompt gamma decay produced in a secondary fragmentation reaction.

2.5. Collective excitations

Collective excitations such as the giant dipole resonance (GDR), built from superpositions of single-particle excitations are necessarily influenced by the nuclear shell structure. In exotic nuclei like $^{68-78}$Ni the proton–neutron asymmetry may give rise to differing shell structure. Theoretical calculations predict a significant change in the GDR strength distribution as one progresses towards the doubly magic ^{78}Ni [30, 31]. The excitation function of the isovector GDR mode is expected to fragment substantially, favouring a redistribution of the strength towards lower excitation energies (Pygmy resonance). Measurements of the GDR strength function provide access to the isospin dependent part of the in-medium nucleon–nucleon interaction and on dipole type vibrations of the excess neutrons. The predicted low-energy shift of the GDR strength was confirmed in neutron-rich oxygen isotopes by the LAND group at GSI by means of virtual photon absorption measurements [32]. A RISING GDR experiment in ^{68}Ni will apply a complementary method, virtual photon scattering, which relies on real projectile γ-ray emission following the virtual excitation. In order to observe discrete γ-transitions with high resolution and γ-decay from the GDR, the RISING array will be augmented the HECTOR array [33], 8 large volume BaF2 scintillator detectors positioned at very backward angles. With the scintillators the highest energy transitions up to $\approx 30\,\text{MeV}$ can be measured efficiently.

3. Summary

As part of an extended physics program the first Coulomb excitation and secondary fragmentation experiments [16, 25] were successfully performed with the RISING spectrometer, a new instrument for high-resolution γ-ray spectroscopy experiments employing beams of short-lived isotopes at 100–400 MeV/u energy from the SIS/FRS facility at GSI. The experimental set-up comprises heavy-ion tracking detectors for incoming beam nuclei impinging on a secondary target, the CATE detector for outgoing heavy ions, the EUROBALL Ge-Cluster detector and the BaF2-HECTOR detector arrays for γ-ray detection. In the near future the remaining part of the relativistic RISING experiments will be performed hopefully contributing to a better understanding of several open nuclear structure problems.

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REFERENCES

[1] EPAX Version 2, K. Sümmerer, B. Blank, *Phys. Rev.* **C61**, 034607 (2000).

[2] W. Schwab *et al.*, *Eur. Phys. J.* **A2**, 179 (1998); J. Benlliure *et al.*, *Eur. Phys. J.* **A2**, 193 (1998).

[3] H.J. Wollersheim *et al.*, accepted for publication in *Nucl. Instrum. Methods Phys. Res. A*.

[4] P. Bednarczyk *et al.*, *Acta Phys. Pol. B* **36**, 1235 (2005), these proceedings.

[5] R. Lozeva *et al.*, *Acta Phys. Pol. B* **36**, 1245 (2005), these proceedings.
[6] A. Navin *et al.*, *Phys. Rev. Lett.* **85**, 266 (2000).
[7] N. Orr *et al.*, *Phys. Lett.* **B258**, 29 (1991).
[8] O. Sorlin *et al.*, *Phys. Rev.* **C47**, 2941 (1997).
[9] J. Dobaczewski *et al.*, *Phys. Rev. Lett.* **72**, 981 (1994).
[10] B. Pfeiffer, K.-L. Kratz, F.-K. Thielemann, *Z. Phys.* **A357**, 235 (1997).
[11] T. Otsuka *et al.*, *Phys. Rev. Lett.* **87**, 082502 (2001).
[12] T. Otsuka *et al.*, *Eur. Phys. J.* **A13**, 69 (2002).
[13] T. Otsuka *et al.*, *Acta Phys. Pol. B* **36**, 1213 (2005), these proceedings.
[14] H. Grawe, *Acta Phys. Pol. B* **34**, 2267 (2003).
[15] J.I. Prisciandaro *et al.*, *Phys. Lett.* **B510**, 17 (2001).
[16] A. Bürger *et al.*, *Acta Phys. Pol. B* **36**, 1249 (2005), these proceedings.
[17] J. Schiffer *et al.*, *Phys. Rev. Lett.* **92**, 162501 (2004).
[18] F. Barranco, G. Colo‘, private communication.
[19] G. Jakob *et al.*, *Phys. Rev.* **C65**, 024316 (2002).
[20] K.-H. Speidel *et al.*, *Prog. Part. Nucl. Phys.* **49**, 91 (2002).
[21] U. Grabowy *et al.*, *Z. Phys.* **A359**, 377 (1997).
[22] S.M. Lenzi *et al.*, *Phys. Rev. Lett.* **87**, 122501 (2001).
[23] P.E. Garrett *et al.*, *Phys. Rev. Lett.* **87**, 132502 (2001).
[24] G. de Angelis *et al.*, *Eur. J. Phys.* **A12**, 51 (2001).
[25] G. Hammond *et al.*, *Acta Phys. Pol. B* **36**, 1253 (2005), these proceedings.
[26] R.K. Wallace, S.E. Woosley, *Astrophys. J. Suppl.* **45**, 389 (1981).
[27] M.F. Mohar *et al.*, *Phys. Rev. Lett.* **66**, 1571 (1991).
[28] B. Blank *et al.*, *Phys. Rev. Lett.* **74**, 4611 (1995).
[29] R. Pfaff *et al.*, *Phys. Rev.* **C53**, 1753 (1996).
[30] G. Giambrone *et al.*, *Nucl. Phys.* **A726**, 3 (2003).
[31] D. Vretenar *et al.*, *Nucl. Phys.* **A692**, 496 (2001).
[32] A. Leistenschneider *et al.*, *Phys. Rev. Lett.* **86**, 5442 (2001).
[33] A. Maj *et al.*, *Nucl. Phys.* **A571**, 185 (1994).