g-RISING

g-factor measurements on spin-aligned isomeric beams using the RISING cluster detectors.

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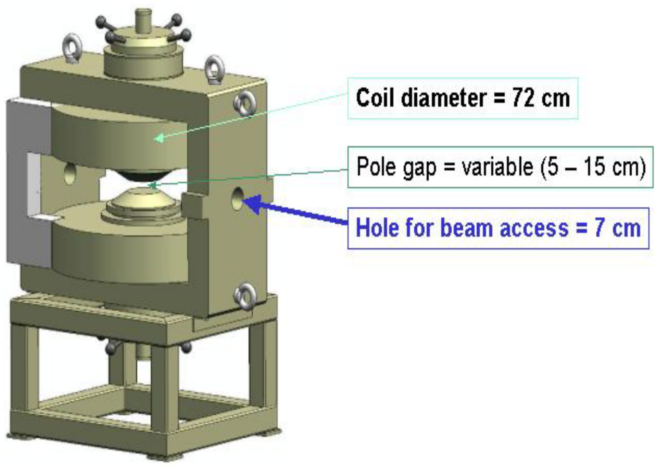
SUMMARY OF ACCEPTED BEAMTIME for g-RISING

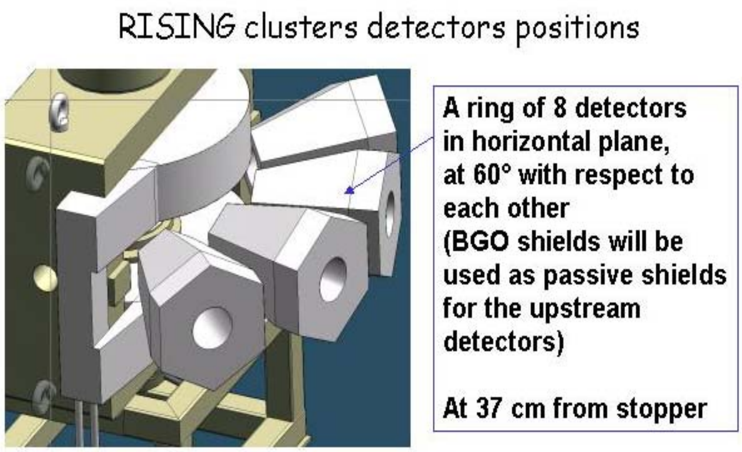
as part of the 'stopped beams' RISING campaign at GSI.

The experiments can be devided in two groups: experiments using isomers produced by projectile fragmentation (proposals 1.1 and 1.2) and experiments using isomers produced by relativistic fission of a ^{238}U beam (proposals 2.1 and 2.2).

The experiments are all performed with the same TDPAD experimental set-up, as described in the introductory section. This set-up is placed in the S4 vault, behind the FRS fragment separator at GSI. It consists of a magnet providing fields up to 1.1 T inducing a Larmor precession of the spin-aligned implanted isomeric fragment beam. This spin-precession is observed via the anisotropy in the γ-decay using 8 RISING Cluster detectors placed in the horizontal plane around the magnet in a close-packed geometry, as shown in the figures below.

Proposal Nr.	Spokespersons	Fragments	Beam, Energy	Target	shifts
1.1	D. Balabanski M. Hass	96Pd, 94Pd, 98Cd	112Sn,600 MeV/u	^{9}Be, 4 g/cm^{2}	24
1.2	A. Maj, J. Gerl	196Po	238U, 750 MeV/u	^{9}Be,1.6 g/cm^{2}	15
2.1 2.2	G. Neyens, G. Simpson	133Sb,135Te, 128,129,130Sn	238U, 750 MeV/u	^{9}Be, 1 g/cm^{2}	27





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Abstract. The aim of this proposal is to study the detailed structure of nuclei far from stability, from the very proton rich to the very neutron rich side of the valley of stability, by determining the magnetic moments of isomeric levels. We present below six sub-proposals, relating to various regions and different aspects of far-from-stability studies. One novel feature is to measure for the first time spin-alignment in isomeric fragments produced by ^{238}U fission at relativistic energies and to use this spin-alignment for the measurement of the g-factor of isomeric states in neutron rich nuclei that are not accessible by other methods (around ^{132}Sn and ^{100}Zr). As a second goal, we aim to investigate the single particle structure near ^{100}Sn, by measuring the g-factor of isomeric states produced and spin-aligned in the fragmentation of a ^{112}Sn beam. Finally, we suggest investigating isomeric states in the very neutron-deficient Pb-region using U-fragmentation. This region is no longer accessible via in-beam fusion-evaporation work.
The proof of principle for such measurements in different reactions and mass regions, is a first step towards a study of g-factors (and later also quadrupole moments; see Letter of Intent at the end) of very exotic isomers, using the intense isomeric beams that will become available at the super-FRS in the future FAIR facility.

Before discussing each of the 4 accepted proposals individually, we first present some general aspects that are related to all the proposals, such as general motivations, the experimental set-up and methodology and the experimental feasibility and limitations.

GENERAL ASPECTS OF G-FACTOR STUDIES AT THE FRS

Motivation for g-factor measurements.

Static nuclear moments (magnetic dipole and electric quadrupole moment) present critical tests for the nuclear wave functions obtained within theoretical models, since only one state is involved in the calculation of the expectation values of these observables. The magnetic moment, μ, being the product of the nuclear g-factor and the spin I, is a very sensitive probe of the single-particle structure of nuclear states. High-spin isomers in the region of doubly-magic nuclei often have a rather pure single particle configuration, for which the g-factor is a very good observable to determine the valence nucleon configuration. Measurements of nuclear g-factors can also serve as stringent tests of spin and parity assignments [1], especially in far-from-stability regions where such assignments are often based on systematics and theoretical predictions. The measurement of the spectroscopic quadrupole moment, Q, is of particular and complimentary interest since it directly probes the deformation aspect of the investigated level.

The proposed g-factor studies focus on two types of nuclei in the nuclear chart: nuclei along shell closures (Z=50 and Z=82) and near doubly magic nuclei on one hand and in the mid-shell region around A~100 on the other hand. Near the Z=50 shell closure, we aim at investigating the structure of isomeric states which consist of rather pure particle and/or hole configurations with respect to the doubly-magic proton-rich ^{100}Sn and the doubly-magic neutron rich ^{132}Sn cores. The relevant single particle orbits are shown in Fig. 1. Study of the g-factors of isomers in these regions will help to pin down the suggested configurations and spin assignments, as well as to study the properties of the M1 operator and it's suggested quenching at two extremes of isospin, from ^{100}Sn to ^{132}Sn.

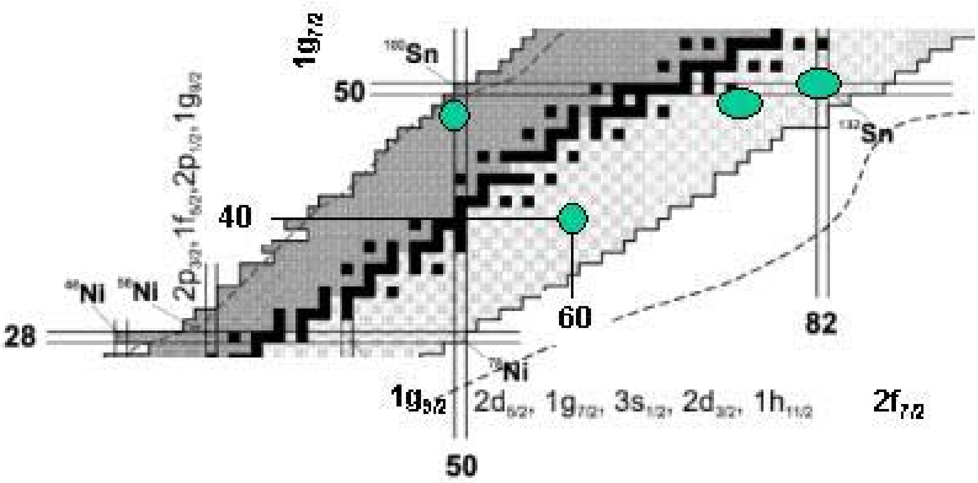

Figure 1: Part of the nuclear chart, with three of the regions in which we plan to perform g-factor measurements on microsecond isomers. The involved proton and neutron orbits of the valence particles are shown for protons between Z=28 and Z=50 and for neutrons between N=50 and N=82. The fourth region is along the Z=82 shell closure and N~114.

Nuclei along the Z=82 proton shell closure exhibit a variety of nuclear structures at low excitation energy. In the neutron mid-shell region, a transition from 'normal' shell model type structures towards more 'collective' states seems to set in. We plan to investigate the g-factors in this region to probe that onset of collectivity in the isomeric wave functions.

In the mass A ~ 100 neutron rich region (Fig. 1), where both protons and neutrons are between the doubly-magic regions, a strong onset and rapid change of deformation has been observed as a function of N and Z. We intend to investigate the g-factors of the isomeric states in this region, which should help to assign more firmly the suggested valence configuration. Later, quadrupole moment measurements will be carried out to investigate the deformation at higher excitation energy.

Motivation for measuring spin-alignment.

A spin-aligned ensemble of isomers is required to study the isomeric nuclear moments via their anisotropic γ-decay. The method to measure a g-factor (or a spectroscopic quadrupole moment) of an isomer is based on measuring the perturbation of the γ-anisotropy due to externally applied magnetic (or electric) interactions, after implantation of the spin-oriented isomeric beam into a suitable stopper (crystal or foil). This TDPAD method (Time Differential Perturbed Angular Distribution) has been used extensively in the last decades for measuring static moments of isomeric states produced and spin-aligned in in-beam fusion-evaporation reactions (see e.g. Tables of Nuclear Moments [2] for an overview).
However, to investigate neutron rich isomers, with lifetimes in the range of 10^{-7} – 10^{-4} s, the projectile fragmentation and projectile fission reactions are the most suitable (often the only available) methods for producing, spin-orienting and selecting the isomers in a fast way. *Within the proposed campaign we intent to use both mechanisms in order to populate the isomers of interest.*

So far, only a few TDPAD measurements have been done on isomers produced in reactions at intermediate and relativistic energies of the primary beam [3,4,5]. The major difference with the in-beam experiments is that the isomers are first mass separated in-flight using dipole magnets. During the separation process, the reaction-induced spin-orientation needs to be maintained until the moment of implantation. The hyperfine interaction between the nuclear and random-oriented electron spin can cause a loss of orientation during the flight through vacuum. To avoid the hyperfine interaction, we have two possibilities: either the isomer is produced without electrons (fully stripped fragments), or the isomeric beam is selected in a noble-gas-like charge state (as demonstrated in [6] for fusion-evaporation products). Because of the high primary beam energies used in fragmentation reactions, most fragments can be produced fully stripped, and therefore such beams have been used till now. **Further, care has to be taken that no electrons are picked-up during the separation and ion-identification process (when passing degraders and beam-tracking detectors).**
In a first experiment, Schmidt-Ott demonstrated that considerable alignment (~ 30%) is observed in the ^{43m}Sc isomeric ensemble selected with the FRS at GSI and produced in the fragmentation of a relativistic ^{46}Ti beam (500 MeV/u) [3]. Later on, g-factors of isomers produced at intermediate energies of the primary beam (60 – 100 MeV/u) were measured at GANIL for nuclei in the region around ^{68}Ni [4,5]. After a significant improvement of the experimental technique, the observed alignment was increased there from less than 2% to 15%. The mechanism leading to the spin-orientation in the projectile fragmentation has by now been qualitatively explained and is reasonably well understood [7,8].
Experiments with fully stripped fragments were limited to nuclei up to mass number $A_{max} \approx$ 80 using intermediate energies as provided at e.g. GANIL, RIKEN and MSU. That is because the probability to pick-up electrons increases with Z for a particular beam energy, and it decreases with the beam energy for a given Z.

In this proposal we address mass $A \approx 100$ - 200 nuclei. The proposed experiments can be done at present only at GSI, because the energy of the primary beam at other facilities is not high enough. Further, the fragmentation of a relativistic ^{238}U beam, available only at GSI, offers the unique possibility to study isomers in neutron rich nuclei approaching ^{132}Sn and ^{78}Ni. In a pioneering proposal, the presence of spin-alignment in fragments produced by a relativistic ^{238}U fission reaction will be demonstrated for the first time.

TDPAD @ FRS+RISING: set-up, methodology and its limitations

The set-up. The isomeric g-factors will be measured using the Time Differential Perturbed Angular Distribution (TDPAD) method. The equipment needed to apply this method on a spin-aligned ensemble of isomeric states is shown on Fig. 2:

(1) a foil or crystal providing a perturbation-free environment (bcc or fcc type materials are mostly used) for the implanted isomers. For future, next-step, measurements of quadrupole moments, crystals with appropriate Electric-Field-Gradients are needed.

(2) a magnet providing a high homogeneous field over a large area and with a large gap between the poles (a Bruker BE 25v will be used, offering field values up to 1.1 T for a 10 cm pole gap and with a homogeneity of 5.10^{-4} over an area of 5x5 cm^2).

(3) a particle identification detector, providing a start signal for the observation of the isomeric γ-decay as function of time, using a delayed-gamma - ion coincidence method. A plastic scintillator placed upstream of the implantation crystal will be used for this.

(4) 8 Euroball Ge Cluster detectors from RISING (we consider to use their BGO shield as a passive shielding for the low-energy X-rays and Bremsstrahlung from scattering beam particles upstream). A cluster detector consists of seven close-packed tapered hexagonal Ge crystals housed in a common cryostat, each crystal having a relative efficiency of 60 % and an energy resolution of ~ 2 keV at 1333 keV [9]. The Cluster detectors have an advantage as compared to large-volume single-crystal Ge detectors, namely that due to the fact that each crystal in the cluster can act as a separate detector, the effective efficiency of the set-up is larger (taking into account that some crystals are blinded for several μs by the low-energy gamma-flash). In addition, the cluster detectors allow the use of the add-back mode for high-energetic γ rays, which increases the photo-peak efficiency.

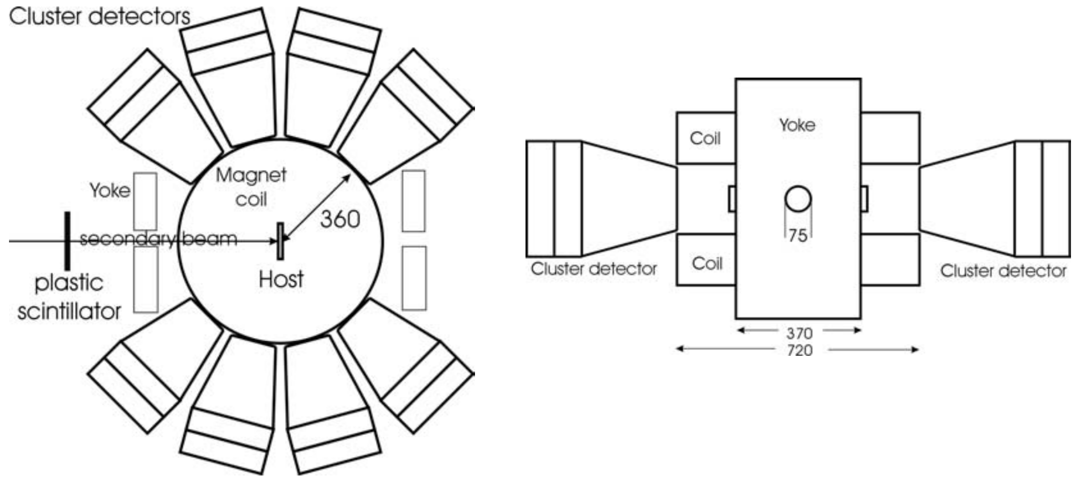

Figure 2: Schematic layout of the TDPAD set-up for measuring isomeric g-factors (left a view from above, right a view along the beam direction). Detectors are at 36 cm from the stopper, and at relative angles of 60 degrees to each other. The total γ-efficiency is estimated at 4%. Not using the BGO-shields would lead to a relative gain in efficiency of just a few percent.

Note that the selected fragment beam needs to pass the 75 mm hole of the magnet yoke. This means that the **final focus slits need to be closed accordingly, which is taken**

into account in the simulated rates. Further, we consider to place a collimator + shield between the slits and the magnet yoke, to avoid scattered beam particles from hitting the magnet yoke and thus giving rise to background gamma radiation.

The methodology. The static magnetic field induces a Larmor precession of the nuclear spins with a frequency $\omega_L = -gB\mu_N/\hbar$ that depends on the isomeric g-factor and on the applied field strength B. The ensemble of implanted isomers is spin-aligned and the alignment symmetry axis is along the fragment beam direction (because the FRS is a zero-degree fragment separator). The Larmor precession of the spin-aligned isomers can be observed as a time-dependent change in the intensity of the γ-radiation emitted by the aligned isomeric states, which is related to the angular distribution [10]:

$$N(t,\theta,\omega_L) = e^{-t/\tau}\, W(t,\theta,\omega_L).$$

The precession frequency is most efficiently detected in the plane perpendicular to the magnetic field direction, where the angular distribution reduces to a simple expression (ignoring the 4th order components):

$$W(t,\theta,\omega_L) = 1 + Q_2U_2\, A_2\, B_2\, P_2[\cos(\theta-\omega_L t)].$$

Here, A_2 is the radiation parameter of the γ-decay, B_2 the second-order orientation tensor (directly related to the amount of alignment in the isomeric ensemble [1]), U_2 the de-orientation due to previous γ-decay in the cascade, Q_2 a quality factor taking into account the detector opening angle and P_2 the Legendre Polynomial. The observed anisotropy $a_2 = Q_2U_2A_2B_2$ will determine the amplitude of the R(t) function.

By combining the intensity in two detectors, $R(t) = [N(\theta_1) - N(\theta_2)] / [N(\theta_1) + N(\theta_2)]$, this function no longer depends on the isomeric decay-time (provided a proper efficiency calibration has been done).
For detectors placed at exactly 90° with respect to each other, the highest amplitude is obtained for the R(t) function, which can then be written as (illustrated in Fig. 2a):

$$R(t) \approx \tfrac{3}{4}\, a_2 \cos(2\theta - 2\,\omega_L t)$$

If the detectors are not exactly at 90°, the amplitude of the R(t) function is reduced from its optimal value, as demonstrated in Figure 2b. Because the Cluster detectors consist each of 6 crystals and most of them are not exactly at 90º with respect to the vertically oriented magnetic field, we have also simulated how this influences the R(t) function. It does not change the observed frequency, but again the amplitude is reduced, as demonstrated in Fig. 2c.
In all cases a deviation of the detector position with about 25° from the optimal value, leads to less than 15% lower amplitude, which means a loss in sensitivity of less than 4%. We calculated that this reduces the accuracy on the g-factor with a similar amount (so less than 15% worse determination of the value as compared to optimal case).

The limitations. Few aspects need to be considered about the isomeric states that are most suitable for performing a g-factor measurement using the TDPAD method:

(1) the isomers should be produced fully stripped and remain stripped until implantation
(2) the γ-decay occurs preferentially via a transition of pure multipolarity (if mixed, a larger or lower anisotropy parameter is possible).
(3) the γ-energy of at least one transition in the cascade is higher than 300 keV
(4) the isomeric lifetime is between 300 ns and a 30 μs.

If these conditions are not fulfilled the experiment will be more difficult, but not necessarily impossible.

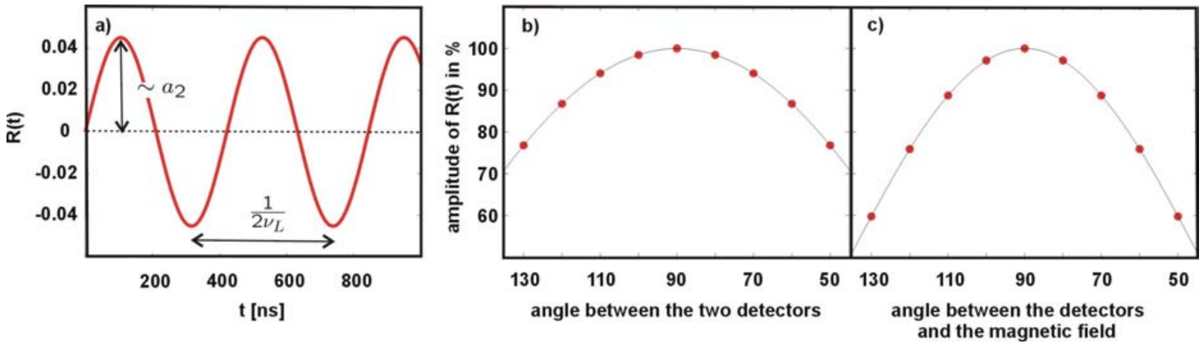

Figure 3: (a) A typical R(t) function with a_2 determined by the alignment in the selected fragment ensemble and ν_L depending on the isomer g factor and the applied field strength B.
(b) The R(t) amplitude decreases if the two detectors are not at 90° wrt each other.
(c) The R(t) amplitude decreases if the Ge-crystals are not exactly in the horizontal plane.

Another way to cancel out the lifetime curve, is to combine the intensity observed when the field is up or down. In this case, the R(t) function is obtained from N(up)-N(Down) divided by the sum, and this is less sensitive to small differences in the detector efficiencies. For this, the magnet power supply control will be integrated into the GSI data acquisition, allowing to change the polarity via remote control.

General aspects related to the feasibility and beam time request

Beam type and energy. The energy of the primary beam is chosen such that the fragments are produced fully stripped and remain fully stripped during the mass separation process. Simulations carried out with the LISE++ program [11] indicate that the rate as well as the probability to get the fragments fully stripped after the target, increases with the primary beam energy (higher transmission mainly). On the other hand, the cross-section for producing atomic γ-rays when degrading or stopping the fragment beam is also increasing with the beam energy [12], an effect which needs to be avoided as much as possible. This effect will be minimized by using a low-Z beam degrader and stopper (see further).

Target. The target thickness is optimised to have a maximum rate for the fully stripped fragments. The type of target is optimised as to have the highest possible isomeric ratio produced.

Stopper foil. The isomers will be stopped in a host placed between the magnet poles (after they passed the 7.5 cm diameter hole of the yoke). The host material should be efficient in maintaining the spin-orientation. Poly- or single crystal materials with a cubic lattice structure should be used. The stopper will be placed in air.
In general, the use of a stopper with as low as possible Z, has several advantages:

- the thickness can be high (the attenuation of γ-rays decreases with decreasing Z)
- the thickness of the second Al-degrader is then consequently lower
- this results in less electron pick-up, thus a higher residual alignment
- this results also in less production of atomic photons, both in the degrader as well as in the stopper.

We suggest to use a **stopper composed out of two layers**, glued to each other: a **first layer of plastic to reduce the beam energy** (plastic has a very low Z, thus limiting γ-absorption and inducing a limited photon flash). In the second layer, as thin as possible, all fragments of interest should be stopped. This material is chosen to provide a perturbation free environment for TDPAD. To tune the beam for stopping into the center of the stopper foil, we will place a veto-detector behind the stopper and adjust the 2nd Al degrader accordingly.

The implantation surface of the stopper foils needs to be at least 8x8 cm^2 in order to cover the beam spot from the FRS (which is reduced to 7x7 cm^2 in order to pass the hole in the magnet yoke).

<u>FRS – Thickness of the 1st and 2nd Al degraders.</u> The FRS spectrometer, equipped with standard detection, allows the selection of the fully stripped fragments [13]. A scheme of the FRS, including all ancillary particle detectors, degraders is shown in Fig. 4.
Note that *the Nb stripper foils*, which are often used to strip an electron from H-like or He-like charge states, are maybe not useful in our case. Fragments that leave the target in a one-electron state, lose their orientation in about 1 ns. So, if a stripper foil then makes such fragments fully stripped again, these fragments will not be oriented and contribute as random background radiation in our γ-spectra.
The ***1st Al degrader*** is used to purify the secondary fragment beam using the standard energy-loss versus TOF techniques. The appropriate thickness is about 20% of the range of the fragments. With such a thickness, the selection and straggling are optimal.
The selection procedure should be such that fully stripped fragments that where produced at the target (and not in a stripper downstream) reach the implantation foil. This means that the thickness of all materials in the beam line needs to known in order to verify this. They are given in Table 1.
Isomers reaching the final focus of the FRS are decelerated by means of the 2nd Al degrader before traversing a plastic scintillator which provides the “start” signal and ion identification for the R(t) detection of the ion-correlated delayed γ-decay. The **thickness of this *2nd Al-degrader* is reduced (to reduce the γ-flash and minimize electron pick-up) by using a plastic energy degrader glued to the stopper foil** such that the selected fragments end in the stopper foil.

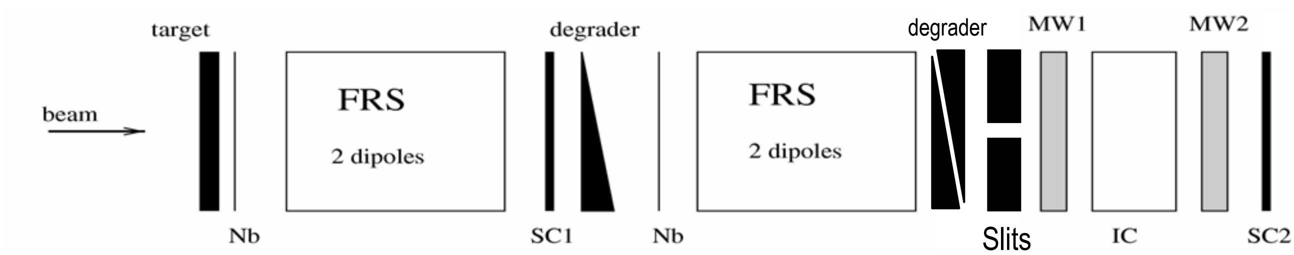

Fig. 4. Schematic diagram of the FRS and beam-line detectors. The Nb stripper foils will probably not be used in our experiment, because they would produce stripped non-oriented fragments. Scintillator SC2 will provide our start signal for the R(t) detection. A correlation between the γ–rays and the ions in SC1 will allow the simultaneous selection of ions in different parts of the longitudinal momentum distribution. During beam tuning, we will place a position sensitive Si-detector in front of the magnet, in order to make sure that the selected beam does not hit the magnet yoke.

<u>Alignment of the fragments</u> The longitudinal momentum acceptance of the FRS is 3.1%. In order to select an aligned ensemble of fragments, it is necessary to select only a part of the full fragment momentum distribution (typically < 1% and preferentially in the wing of the momentum distribution, as demonstrated in Fig. 5). Simulations of the spin-alignment with increasing beam energy and number of removed nucleons from the projectile show that the alignment follows a similar trend at relativistic energies (and this was confirmed in a 500 MeV/u ^{46}Ti fragmentation on a ^{9}Be target at GSI [3]).
The FRS should be tuned such that the wing of the longitudinal distribution is selected after the wedge degrader (or the full distribution if possible) and a correlating between the observed isomer γ-decay in S4 and the ion passing the scintillator in S2 will be used to select off-line (and on-line) the ensemble with highest alignment.

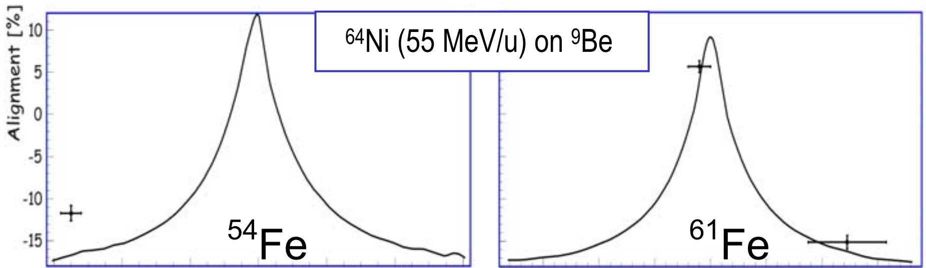

Figure 5: Observed and calculated spin-alignment in the fragmentation of a ^{64}Ni beam onto a ^{9}Be target for isomers in ^{61}Fe(9/2$^+$) and ^{54}Fe(10$^+$). At relativistic beam energies, the alignment is calculated (and observed) to be a factor of 2 higher.

Table 1: thickness of all materials in the FRS beam line, needed when calculating the final rates and especially to estimate the probability for electron pick-up.

object	**material**	**thickness (mg/cm^2)**
target	^{9}Be	1000 mg/cm^2
Scint21	$H_{11}C_{10}$	309.6
S2-wedge	Al	~ 2400 - 6000 (adapt)
MW41	Ti	90
exit window	Ti	90
beam line entry window	Ti	45
beam line exit window	Ti	45
Music	$Ar_{90}C_2H_8$	100
Music Kaptor	H_8C_8	14
MW42	Ti	90
Scint41	$H_{11}C_{10}$	51.6
Degrader	Al	≤ 8000-9000 (adapt)
Air gap	air	~ 1 m (~ 100 mg/cm^2)
Stopper	Cu	< 6 mm

The selected fragment rates are simulated using LISE++, and in some cases MOCADI calculations, specifying the chosen 1st Al degrader thickness, beam and target, and with appropriate slit settings. The probability for electron pick-up has been calculated after the 2nd Al degrader, and the thickness of this one is limited to have as little as possible electron pick-up. It was verified that the load in S2 does not exceed 10^6 pps, such that we can make the necessary correlations between the delayed γ-rays and the ions passing the S2 scintillator.

Beam time requests: they are based on the calculated rates, assuming 0.5% detection efficiency for 1 Cluster detector at the closest possible position with respect to the stopper foil. The estimated isomeric ratio and alignment are specified in each proposal. For many of the suggested isomers a ratio of about 10-20% has been observed [14].
To estimate the beam time, we need to know how many delayed γ-rays need to be observed to obtain a reasonable R(t) function. Based on our experimental data for the ^{61}Fe isomer ($T_{1/2}$ = 250(10)ns, I^{π}=9/2$^+$) [5], we have plotted the R(t) functions taking respectively 2.10^4, 2.10^5 and the total of 8.10^5 observed ion-correlated gamma rays in the R(t) function. This results in typical R(t) function qualities as given in Fig.6a-c, showing that even with as little as 2.10^4 observed delayed γ-rays, the g-factor of the isomer can be deduced to an accuracy of 5%, while it improves to an accuracy of 1% with 10 times more detected γ-rays.

The alignment expected from high-energy projectile fragmentation (~ 30%) or from projectile fission (to be found out, but if similar as in spontaneous fission we can expect ~ 20-30%) are both higher than the one observed in the intermediate energy fragmentation (~ 15%) at GANIL, **and therefore we will make the beam time request assuming a minimum of 10^4 gamma's needs to be observed in the ion-gamma correlation spectra.**
This should lead to a result that is accurate enough to confirm or reject the configurations adopted for certain isomers, while for studies where details on the M1 operator are aimed after, a minimum of 10^5 gamma's will be required.

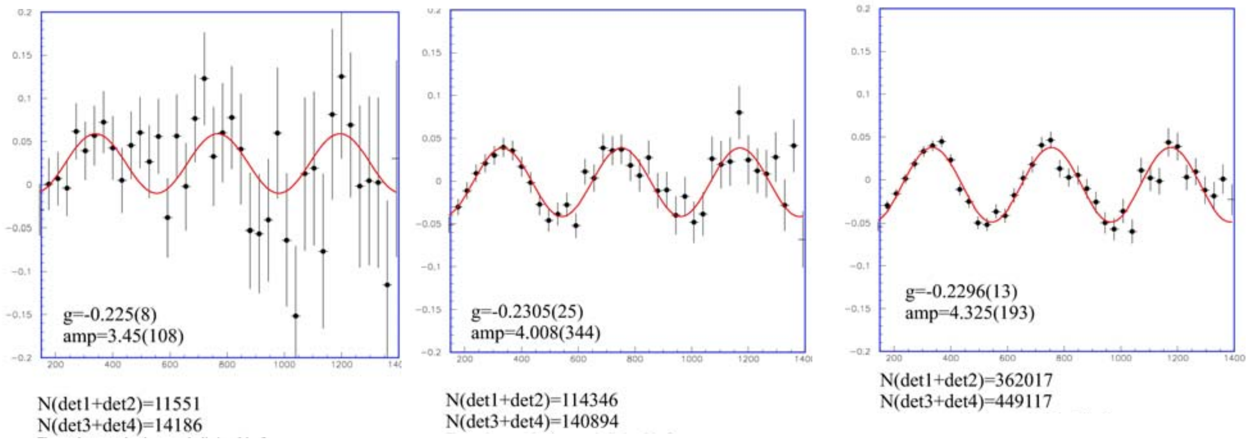

Figure 6: The R(t) function for the ^{61m}Fe(Cu), measured at LISE-GANIL, taking respectively $2.5.10^4$ delayed gamma's (a), $2.5.10^5$ delayed gamma's (b) and the total amount of 8.10^5 observed delayed gamma's (c). The deduced g-factors and amplitudes, with their respective accuracies, are given in each case. With $1.5.10^4$ observed γ-rays in a Cluster, it is thus possible to deduce the g-factor to a precision of better than 5%.

To obtain 1.5 10^4 correlated γ-decays in one Cluster detector (so 3.10^4 in a pair), it means a total of about 3.10^6 isomers need to be implanted. Assuming an isomeric ratio of 10%, this means 3.10^7 ions need to be implanted (but this is assuming only 1 gamma decay and 1 detector pair). Considering that R(t) functions from 4 independent detector pairs can be used, it means we need **at least 1.10^7 ions implanted** (and less if more γ-rays are available for analysis in the isomeric decay). With an implantation rate of 1000/s of the isotope of interest, this means 3 hours of beam time (and 30 hours to get the statistics from Fig. 6b). For a fragment rate of 100/s, it means 30 hours of beam time to obtain a statistics as in Fig. 6a. Therefore, we consider that **100 ions/s is the minimum rate required to make an experiment with guaranteed success on the g-factor. For the alignment measurement, an ion rate of 200 pps is desirable to obtain an accuracy of better than 1%.** The particular conditions for each case (isomeric ratio, alignment, amount of observed anisotropy, …) will then determine how many isomers can be measured during one experiment and which statistics can be obtained.
In each of the suggested proposals, several isomers occur in the region of interest. Depending on the FRS settings and the used reaction, one of more of them can be selected simultaneously for investigation.

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INDIVIDUAL PROPOSALS

Hereafter, we will describe the physics motivation, feasibility and beam time request for each of the experiments. We can distinguish two types of proposals:

(1) based on the principle of projectile fragmentation, for which the spin-orientation has been proven to be of the order of 20-30% at relativistic energies. Two proposals, addressing different regions in the nuclear chart, are presented (^{100}Sn region, ^{196}Pb region).
   1.1. g-factors of isomeric states around ^{100}Sn (D.L. Balabanski, M. Hass)
   1.2. g-factor of the 11^- isomer in ^{196}Po (A. Maj, J. Gerl)

(2) based on the principle of ^{238}U fission, for which a proof of principle should show the presence of spin-alignment. Once established, it will be used for g-factor studies in the neutron rich region around ^{132}Sn. Two proposals are presented.
   2.1 spin-alignment of relativistic ^{238}U fission fragments around ^{132}Sn (G. Neyens)
   2.2 g-factors of relativistic ^{238}U fission fragment isomers around ^{132}Sn (G. Simpson)

We also added at the end a "Letter of Intent", related to the study of quadrupole moments. An excellent candidate to make a proof of principle for such studies on isomeric relativistic fragment beams is the 8^+ isomer in ^{96}Pd, for which the physics motivation is closely related to that of proposal 1.1. Obviously, once successful, several other proposals here have the intension to extend the work to study quadrupole moments, which are in general much more sensitive to the collective nature of the isomeric states.

Proposal 1.1

g-factors of isomeric states near the doubly magic N=Z nucleus ^{100}Sn.

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Abstract: We intend to measure the g factors of isomeric states in the vicinity of the doubly-magic ^{100}Sn, in order to verify their wave functions as predicted in large-scale shell model calculations. The isomeric states of interest: ^{94}Pd and, if possible, ^{98}Cd will be produced in projectile-fragmentation reactions at relativistic energies, utilizing a ^{112}Sn beam with energy of about 600 MeV/u. These experiments can serve as a stepping stone towards g-factor measurements for more exotic cases, as well as for subsequent quadrupole moment determinations (see the Letter of Intent for measurement of the quadrupole moment of the 8^+ isomer in ^{96}Pd).

Motiviation. The evolution of the shell structure towards exotic nuclei is a major topic of modern experimental and theoretical studies in nuclear physics. One of the main regions where such studies are carried out nowadays is around the doubly-magic $N = Z$ nucleus ^{100}Sn. Doubly-magic nuclei are benchmarks within the chart of the isotopes. They and their near neighbourhoods serve as constraints for the shell-model parameter sets, as demonstrated in some recent experiments on ^{98}Cd [1] and ^{94,95,96}Ag [2–6]. The study of the properties of isomeric states provides a sensitive probe for quantities such as single-particle energies, residual interactions, core excitation and shell gaps which are key ingredients for the nuclear shell model. Recently large-scale shell model calculations (LSSM) have proven that excitations of the ^{100}Sn core are essential to reproduce the isomerism and the experimental E2 strengths [1,6]. While for E2 properties and the eventual evolution of deformation the $g_{9/2}^{-1}d_{5/2}$ stretched ΔI=2 particle-hole *(ph)* excitation plays a key role [1], the magnetic and spin-response observables are most sensitive to $g_{9/2}^{-1}g_{7/2}$ spin-flip *ph* excitations, as is known from the study of Gamow-Teller ß$^+$/EC-decay [7]. Thus in the (*0g,1d,2s*) model space the $0\hbar\omega$ parts of E2 and M1 core polarization, as expressed in effective charges and g factors are accessible to shell model predictions.

Aim. Here we propose to measure magnetic moments in the vicinity of the $N = Z = 50$ shells. The states of interest, the 14^+ isomer in ^{94}Pd (E_{ex} = 4886 keV, $T_{1/2}$ = 0.53(1) µs) [3,5], and the (8^+) isomer in ^{98}Cd (E_{ex} = 2428 keV, $T_{1/2}$ = 170(+60/–40) ns) [1,8,9], can be populated in projectile-fragmentation reactions at relativistic energies. Both isomers are decaying via *E2* cascades of γ rays, with high enough energy to allow a TDPAD measurement (Fig. 1).
The (8^+) isomer in ^{98}Cd and 14^+ isomer in ^{94}Pd provide a test ground for the basic ingredients of shell model calculations in the vicinity of ^{100}Sn. Already for ^{96}Pd it has been

shown that the measured value for the g factor deviates from the model description [10] which leads to the necessity to introduce an effective M1 operator. Further measurements towards the doubly-magic ^{100}Sn are needed to investigate this effect and determine the amount of quenching.

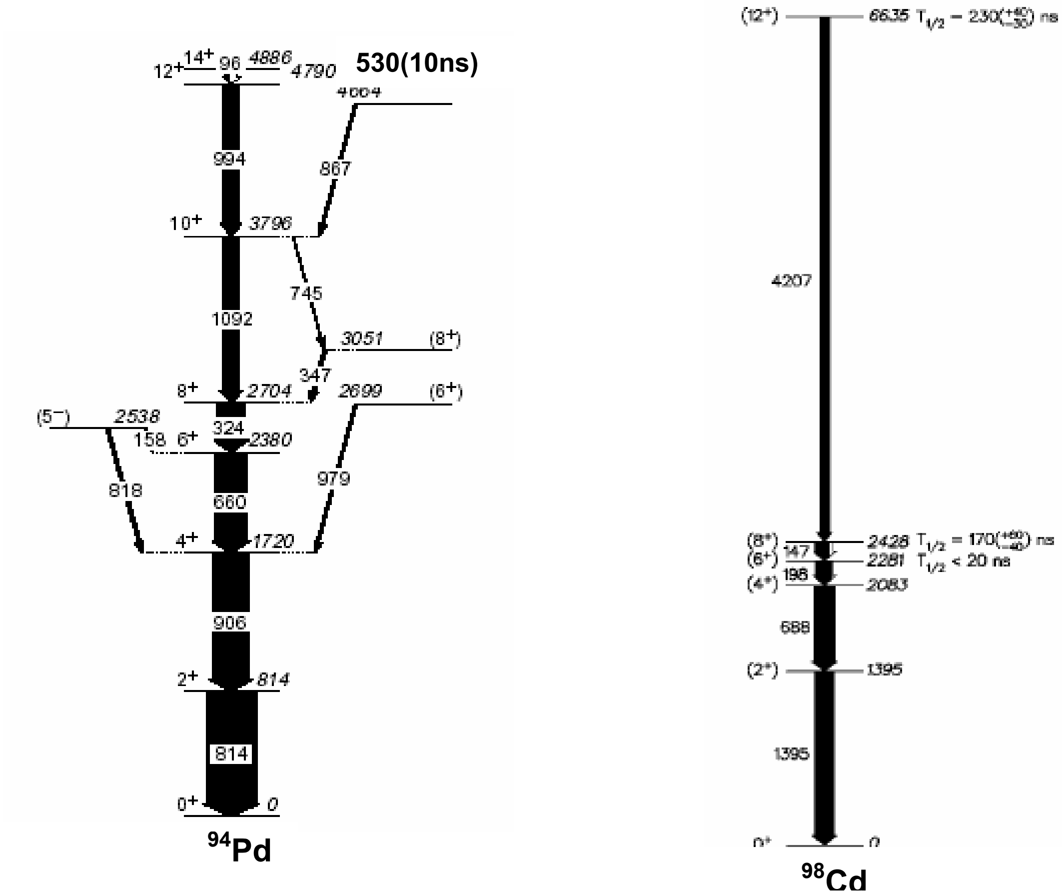

Figure 1: Decay schemes of the isomers of interest in 94Pd and 98Cd.

We need to note already here that a measurement of the g factor in ^{94}Pd can be done at GSI utilizing the beams available at present, while an order of magnitude improvement on beam intensity and/or detector efficiency, needs to be obtained in order to reach ^{98}Cd. The 14^+ isomer in ^{94}Pd has been shown to belong to the same class of spin-gap isomers [11] that have recently been studied in ^{98}Cd [1] and in ^{94,95,96}Ag [2-4,6] .
The suggested configuration for the 14^+ isomer in ^{94}Pd is $(\pi g_{9/2})^{-4}(\nu g_{9/2})^{-2}$ [5] and for the 8^+ isomer in ^{98}Cd it is $(\pi g_{9/2})^{-2}$ [1]. A g-factor measurement will give evidence to these configurations. The empirical g-factors for the ^{94}Pd isomer are estimated to be $g_{emp}(14+)$ =+0.45 or +0.57, depending on whether the protons are coupling to a 6^+ or an 8^+ configuration. LSSM calculations have shown [6] that ^{100}Sn core excitations are needed to describe isomerism in this region, which should influence the effective M1 operator. A 6^+ coupling involves seniority v=4 components, which can contribute only in the diagonal terms to the M1 matrix elements due to a seniority selection rule. The high-rate 8^+ isomer in ^{96}Pd ($T_{1/2}$ = 2.2 μs) could be used to test quickly the experimental set-up and to calibrate the applied magnetic field strength using the known g-factor for this $(\pi g_{9/2})^{-2}$ configuration, g= 1.371(7) [10]. For the ^{98}Cd isomer we expect a similar value as for this isomer in ^{96}Pd, as they are suggested to have the same configuration.
We note that in a next proposal, we plan to suggest a determination of the quadrupole moment of the 8^+ isomer in ^{96}Pd, where a break down of the seniority scheme has recently been observed and this measurement is needed as a normalisation (see the Letter of Intent for this experiment). The experiment can be done by applying the same

TDPAD technique on isomers stopping in a non-cubic crystal with an appropriate electric field gradient. It will be done under the same conditions (beam energy, FRS settings, etc.) as the g-factor measurement of the same isomer which is proposed here and these data will be used to determine the amplitude of the TDPAD curve for the quadrupole moment measurement.

Feasibility. We propose to produce the isomers of interest by means of projectile fragmentation reactions at about **600 MeV/u of the ^{112}Sn** primary beam which impinges on a **^{9}Be target (4 g/cm^{2})** (earlier experiments at GSI have shown that the production of these nuclei with a ^{112}Sn beam is considerably higher than with a ^{124}Xe beam [12,13], and this was confirmed also by our simulations).
The reaction products will be slowed down to about 200 MeV/u, and implanted in a host material (a Cu foil). It is necessary that the isomers are stopped in the host with cubic lattice structure, in order to preserve the initial alignment of the isomeric ensemble. The energy of the secondary beam has been chosen to be high enough, in order to minimize the electron pick-up during the flight through the FRS. For the different calculations (^{94}Pd - ^{98}Cd) this is done using the 1st Al wedge degrader (at the middle focus of the FRS) with thickness of 2000 and 1800 mg/cm2. At the final focus a plastic degrader is glued to the Cu-stopper, such that the fragments are slowed down in a material with as low as possible Z to reduce the γ–flash. The probability for electron-pickup in the second Al degrader, placed upstream of the stopper, is calculated to be less than 1%.

The isomer in ^{94}Pd decays through a cascade of six stretched *E2* transitions with suitable energies to be detected by the RISING clusters (Fig. 1, Table 1). For ^{98}Cd the decay cascade involves four transitions. Thus, the high γ-ray multiplicity for both isomers will help to improve significantly on the detection efficiency, and allow the performance of high-quality measurements with an implantation rate of less than **100 ions/s**. Realistic simulations with GEANT4 of the R(t) function and its fast-Fourier transform (FFT) for the case of the 14^{+} isomer in ^{94}Pd are presented in Fig.2. They take into account the orientation of the isomeric ensemble, the isomeric decay, the γ-ray attenuation in the host and the efficiency of single Ge detectors (no add-back). A moderate magnetic field of 0.2 T and a g factor value of g = 0.6 have been used. Note that the expected g-factor value and the isomer lifetime allow several oscillation periods to be observed within a period $\Delta t = 3 \cdot T_{1/2}$. Since in this case all γ rays of interest have energies above 300 keV, the γ flash is not considered. The FFT demonstrates that in both cases a high signal-to-noise ratio can be obtained. Note that the rates are for the full opening of the FRS longitudinal momentum slits which is possible for this experiment because the load at S2 is $3 \cdot 10^{5}$ pps for the considered beam intensity of 10^{8} pps. In this way we can perform an off-line cut in the distribution and thus utilize the total statistics. In order to obtain a reasonable alignment we expect a reduction of useful rate to less than ½ of the calculated one. In case an order of magnitude higher more intense beam can be delivered, the slits will be closed.

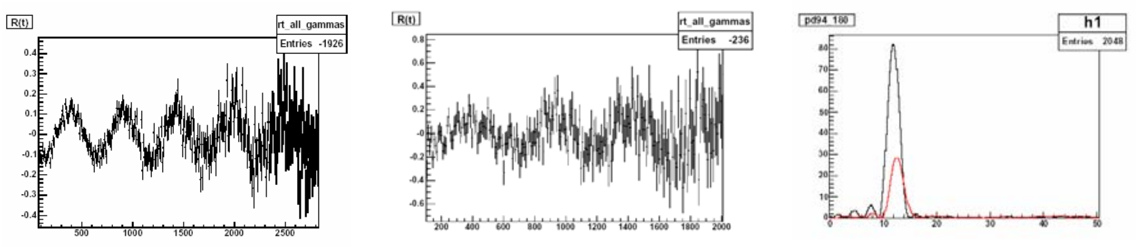

Figure 2: Simulated R(t) functions for the 14^{+} isomer in ^{94}Pd for beam intensity of 10^{8} (middle) and 10^{9} pps (left). On the right-hand side, a FFT of the R(t) function is shown.

With an intensity for the primary beam, **2·10^8 pps of ^{112}Sn**, we have estimated the production of isomers of interest (Table1). Note that it is possible to measure the g factor of the 14$^+$ isomer in ^{94}Pd with as less as 10^8 pps, because of the γ-ray multiplicity, the suitable γ-ray energies and the isomer lifetime.

Beam time request.
In order to measure the g factor of the ^{94}Pd isomer, we request 19 shifts. We also ask for 1shift to measure the Larmor frequency for the 8$^+$ isomer in ^{96}Pd, as a calibration measurement. For each isomer a separate beam tuning is needed, for which we ask in addition 4 shifts of beam time.
As this stage of the project, we ask for 24 shifts for g-factor measurements in projectile fragmentation in the vicinity of the doubly-magic ^{100}Sn.

If the **intensity of the ^{112}Sn primary beam is an order of magnitude higher, *i.e.* ~ 10^9 pps, and can be provided throughout the experiment,** a measurement of the g factor of the 8$^+$ isomer in ^{98}Cd becomes feasible. In such a case we will need 21 shifts for ^{98}Cd, 2 shifts of ^{94}Pd and 1 shift for ^{96}Pd. Including a beam tuning of 6 shifts (for the 3 settings), would then lead to a request of **30 shifts.**

In addition, in a separate Letter of Intent, we declare our wish within this campaign to measure the quadrupole moment of the 8$^+$ isomer in ^{96}Pd.

Table 1: Rates for isomers below ^{100}Sn produced in ^{112}Sn fragmentation. For all isomers, the suggested single particle configuration and its empirical g-factor are given (^{96}Pd is a measured value).

Isotope	I^π	$T_{1/2}$ (ns)	ref	Eγ(multi-polarity)	Estimated g-factor	suggested configuration	Ion Rate (pps)
^{94}Pd	14+	530(10)	3,4,5	994,1092 324,660, 906, 814	g=+0.568 g=+0.453 (all E2)	$\pi(g_{9/2})^4_{8+}\ \nu(g_{9/2})^2_{8+}$ $\pi(g_{9/2})^4_{6+}\ \nu(g_{9/2})^2_{8+}$	50
^{95}Ag	23/2+	>1μs, <16ms	2,3	428(E3), 1004,937	g=+0.304	$\pi(g_{9/2})\ \nu(g_{9/2})^2_{8+}$	
^{96}Pd	8+	2.2(3) μs	8,9 11	325,684, 1415 all E2	**μ_{exp}= 10.968(56)** g=1.371(7)	**$\pi(g_{9/2})^4_{8+}$**	6000
^{96}Ag	15+ or 13-	700(200)	4	470,668	g=0.89 g=0.75	$\pi(g_{9/2})\ \nu(g_{9/2})^2_{8+}$ $\pi(g_{9/2})^2_{8+}\ [\pi g_{9/2}\ \nu p_{1/2}]_{5-}$	
^{98}Cd	8+	$170(^{+60}/_{-40})$	1	147,198, 688,1395	g=+1.371 (all E2)	$\pi(g_{9/2})^2_{8+}$	5
	12+	230	1	4207 (E4)	g=+1.371 g=+0.933 g=+0.479	$\pi(g_{9/2})^4_{8+}$ $\pi(g_{9/2})^2_{8+}\nu(g_{9/2}^{-1}\ d_{5/2})_{4+}$ $\pi(g_{9/2})^2_{6+}\nu(g_{9/2}^{-1}\ d_{5/2})_{7+}$	5

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Proposal 1.2

g-factor of the 11$^-$ isomer in ^{196}Po

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NIPNE, Bucharest: M. Ionescu-Bujor
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UJ Kraków: R. Kulessa

Abstract: We intend to measure the g-factor of the 11$^-$ isomeric state with a half-life of 850 ns in the neutron deficient ^{196}Po, in order to explain the origin of the enhanced B(E3)-value for the transition depopulating the isomer. The isomeric state of interest will be produced in projectile-fragmentation reactions at relativistic energies, utilizing a ^{238}U beam with energy of about 750 MeV/u which will also provide the necessary spin-alignment.

Motivation. The polonium isotopes with Z=84 are excellent candidates to study the transition from single-particle to collective behavior in nuclei. Especially interesting in this aspect is ^{196}Po (N=84, N=112) as it seems to be a transitional nucleus between "shell-" nuclei for A>196 and "collective-" nuclei for A<196. Around A=196 in addition, strong phenomena of shape-coexistence are expected [Smi,Ber].

The structure of very light Po nuclei shows properties of collectively rotating shape. For example the intruder states in those nuclei can constitute band-heads for superdeformed bands (see [Smi,Lei,Nab96] and references therein).

Contrary, the structure of heavier Po-isotopes (A>196), as can be seen in Fig.1, is governed by the single-particle excitations. They have remarkably similar low-spin yrast state energy spacings with low lying 2$^+$, and closely spaced 6$^+$ and 8$^+$, making the 8$^+$ state being the isomer. The g-factors of the 8$^+$ isomeric states confirm their almost pure $\pi h_{9/2}^2$ structure. Similarly, the isomeric 11$^-$ states have been found in all Po-isomers, with almost constant excitation energy, and lifetime increasing with the decreasing neutron number. The g-factors for the measured isotopes from N=124 down to N=114 are all around $g\approx1.1$ (see [Maj90] and references therein), only slightly below the value obtained for the neutron magic nucleus ^{210}Po, thus, suggesting the same single-particle nature, $\pi h_{9/2} i_{13/2}$, for all 11$^-$ isomeric states in the Po-chain, down to N=114 (Fig. 2).

In almost all isotopes, the 11$^-$ isomer can decay to the 8$^+$ isomer via an E3 transition. With the initial and final configurations of $\pi[h_{9/2} i_{13/2}]_{11^-}$ and $\pi[h_{9/2}^2]_{8^+}$, respectively, such a transition corresponds in principle to an orbital change of $\pi i_{13/2} \rightarrow$

$\pi h_{9/2}$, and consequently may lead to a spin-flip transition that is expected to be slow, with B(E3)-value of few W.u. Indeed, this is the case for all Po isotopes with A≥200 (see Fig.3). However, the B(E3)-value for $11^- \rightarrow 8^+$ transition in ^{198}Po (25 W.u.) was found [Maj86] to be much increased as compared to the heavier Po isotopes. Even a larger value of 27 W.u. was found for such a transition in ^{196}Po [Alb]. In addition, in this nucleus stronger changes in the level spacings are visible, as seen in Fig.1, what suggests stronger onset of deformation or of collectivity, as discussed in [You] and references therein.

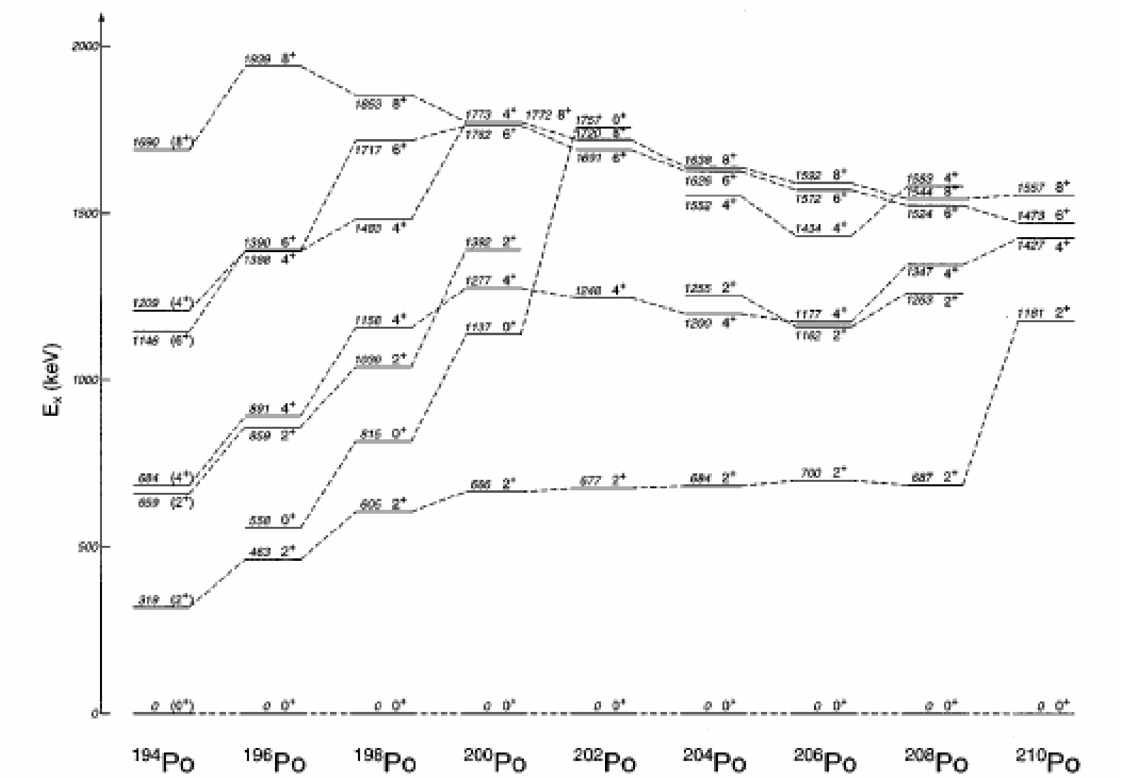

Fig.1. Energy systematics of low-lying, positive-parity states in even-A Po isotopes (from [You])

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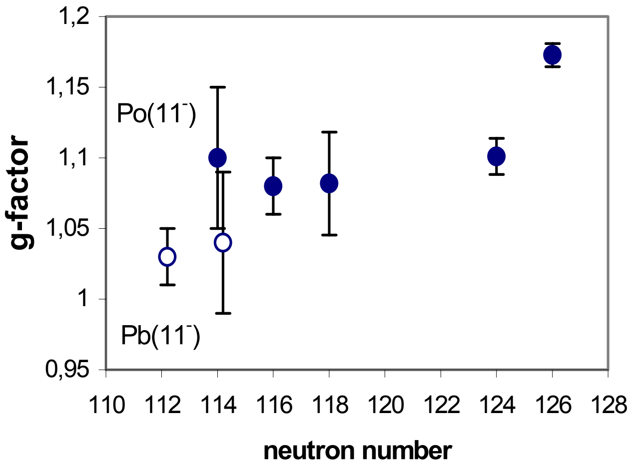

Figure 2: Experimental g-factors of $(\pi h_{9/2} i_{13/2})11^-$ isomers in Po [Maj90] and their intruder partners in the Pb isotones [Vyv04b].

This unexpected behavior of the B(E3)-value can be explained by two different scenarios. One interpretation, originally proposed in [Maj86], was that this is the result of the octupole collectivity setting in for A<200. In such a scenario the 11^- state is not pure $\pi h_{9/2} i_{13/2}$ but has a component of $|8^+ \otimes 3^-\rangle$, i.e. admixtures of the coupling of 8^+ state to the 3^- octupole vibrational phonon, which microscopically consists of the particle-hole excitations with ΔI=3 (mostly $\nu i_{13/2}$-particle and $f_{7/2}$-hole excitations from the nearby filled $f_{7/2}$ neutron shell). In [Maj86] it was estimated that the squared amplitude of such an admixture is around 0.33(12). On the other hand, the g-factor result for ^{198}Po [Maj90], g=+1.10(5), gave the upper limit for such an admixture to be 0.28, what could within the error bars support such an interpretation.

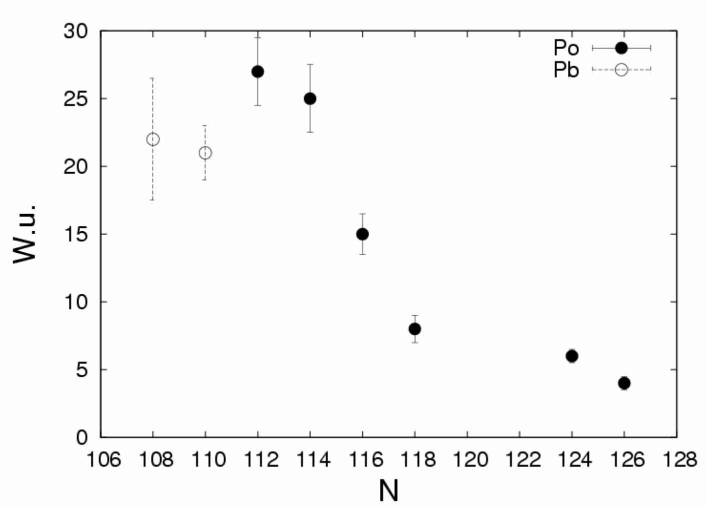

Figure 3: Experimental B(E3)-values for the $11^- \rightarrow 8^+$ transitions in Po and Pb isotopes [Maj86,Alb,Dra].

The alternative scenario for the enhanced B(E3)-value is the effect of an oblate deformation. The 11^- and 8^+ states become oblate when neutrons are removed, what causes that the 11^- state should not be interpreted within spherical shell-model orbitals but rather in the Nilsson approach. In this approach, the Nilsson configuration for the 11^- state is $13/2^+[606] \otimes 9/2^-[505]$, while 8^+ would be $7/2^-[514] \otimes 9/2^-[505]$. This provided a basis for a "natural" strong E3 transition between these states, as explained in [Dra]. In fact, the observation of B(E3)-values of ≈21 W.u (Fig. 3) for light Pb-isotopes [Dra] was consistent with an oblate deformation of β_2 = -0.18. This deformation is in agreement with that deduced from the measured quadrupole moments of the 11^- isomers [Vyv04a]. Such a scenario would affect the g-factor and reduce its value as it was observed and discussed recently for these deformed intruder 11^- isomers in the Pb-isotopes [Vyv04b and references therein] (see Fig. 2).

The question arises whether similar deformation effects play a role also for the ^{198}Po and ^{196}Po, and can be responsible for the enhanced E3 transition? The measured g-factor for ^{198}Po, having larger value than of corresponding Pb-isotone, rather seem to contradict such an assumption. However, the large error of the experimental g-factor cannot exclude such a possibility. Moreover, the g-factor for the more clear case, ^{196}Po, is not known. Therefore, the precise knowledge of g-factor value for ^{198}Po and, especially, for the ^{196}Po, is needed to suggest, which of these 2 scenarios, if any, is more likely be responsible for the unusually strong E3 transitions.

Aim. The aim of the proposed experiment is to answer the interesting question, whether the enhanced E3 transition depopulating the 11^- isomer in light Po-isotopes is due to the octupole instability, or due to the onset of oblate deformation. For that, we propose to perform a precise measurement of the g-factor for the 11^- state in the ^{196}Po (and remeasurement of the known g-factor for ^{198}Po with higher precision would be desired as well, but due to the specific decay properties of this isomer very difficult in recoil fragmentation). The isomeric state of interest, with the half-life of 850(90) ns, will be produced in a projectile-fragmentation reaction at relativistic energies, utilizing a ^{238}U beam with energy of about 750 MeV/u, which will also provide the necessary spin-alignment. It was found in the previous FRS experiments [Gla] that the isomeric states in all the region of interest are populated strongly in such a reaction. The 11^- state decays to 8^+ state via 552 keV E3 transition, and the decay proceeds further via E2 transitions of 549 keV, 499 keV, 428 keV and 463 keV (see Fig.4, left panel). In ^{198}Po (Fig.4, right panel) the 11^- isomer has a lifetime of only 200 ns (g=+1.10(5)) is fed by the decay of the longer-lived 12^+ isomer (750 ns, g= -0.155(3)). Further, it decays to the 8^+ isomer (29 ns, g=+0.91) by a 712 keV E3 transition that is very little converted.

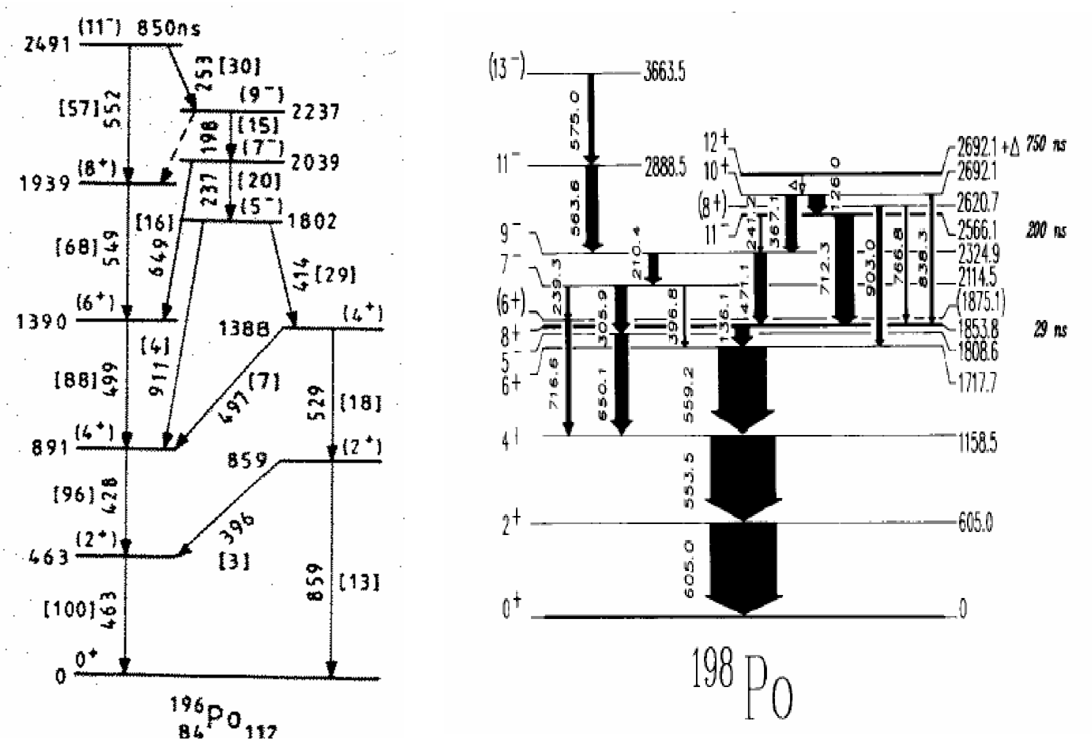

Figure 4: Level schemes of ^{196}Po [Alb] and ^{198}Po [Maj90).

<u>Feasibility.</u> The experimental set-up is described and basic assumptions for the rate estimate are given in the cover proposal *GENERAL ASPECTS OF g-FACTOR STUDIES AT THE FRS.* From previous experience we know that the usable intensity of the primary ^{238}U beam at 750 MeV/u is limited by the load of all the isotopes in their different charge states reaching the mid-section S2 of the FRS. Calculations predict an optimal yield of ^{196}Po by employing a 1.6 g/cm^2 Be production target with a Nb stripper foil and a S2 degrader leading to an energy of 300 MeV/u at the S4 catcher. For 10^8/s primary ^{238}U ions and appropriate S1 and S2 slit settings the load at S2 is 10^6/s and 10^4/s at S4, which is the maximum intensity feasible without degradation of the resolution of the beam tracking and identification detectors. With this setting $2x10^2$/s fully stripped ^{196}Po ions are calculated to reach the catcher. The beam spot size is about 2.5 cm FWHM. Extrapolating from previous FRS experiments [Sch, Pfü] an isomeric ratio of 5% for populating the 11^- isomers results in $2x10^4$ correlated decays within 50 hours to obtain the required accuracy as shown in fig. 5.

<u>Beam time request</u> Assuming that this experiment can be performed together with another g-factor proposal using a ^{238}U beam the set-up time of the FRS will be shared. Therefore only 6 shifts of initial set-up time is required, followed by 9 shifts for ^{196}Po production and R(t) measurement in order to obtain a precision of better than 1% in the g-factor. **Therefore, in total we ask for 15 shifts of beam time.**

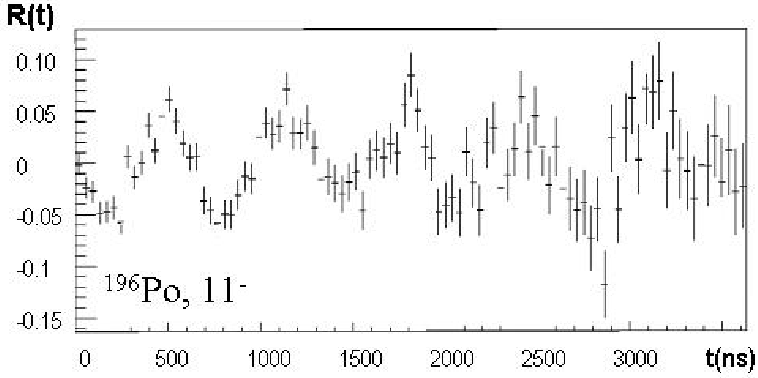

Figure 5: Simulation of the R(t) function for the 11^- isomeric decay in ^{196}Po, assuming a total of 330000 γ-rays observed in one detector pair. Taking into account that 4 γ-decays can be used for the analysis, and that 4 pairs of detectors are available, this corresponds to a total of about 2.10^4 isomeric γ-decays needed.

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Proposal 2.1:
Spin-alignment of isomeric states in relativistic fission fragments around ^{132}Sn.

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Abstract: This proposal aims at investigating the reaction-induced spin-alignment of fission fragments from the relativistic fission of a ^{238}U beam onto a ^{9}Be target and subsequently recoil-separated with the FRS fragment separator. The alignment will be measured for different selections in the fragment longitudinal momentum distribution and for different isomers selected in a single FRS setting. The observed alignment is a pre-requisit to allow nuclear moments measurements on isomeric states in neutron-rich nuclei produced by projectile fission. The TDPAD method will be used, which provides at the same time the isomeric g-factor from the frequency and the produced spin-alignment and/or multipolarity of the transitions from the amplitude of the observed R(t) pattern.

Motivation. Projectile fission allows the study of very neutron-rich isomers, not or hardly accessible by other production methods. Thanks to the spin-alignment that comes inherently with the fission reaction process [1], the nuclear moments of isomeric states in fission fragments can be investigated using perturbed angular distribution or correlation methods. Such experiments on microsecond isomers are however impossible in in-beam experiments or in spontaneous fission experiments, because of the very low peak/total intensity in the long-lived decay as compared to the spontaneous γ–decay intensity. Therefore, such studies have to be performed at fragment separators, provided that the reaction-induced spin-alignment is maintained during the recoil-separation process.
That is the case in relativistic fission reactions, because the fragments have such a high momentum that they come out of the target fully-stripped. Relativistic fission of a high-energy ^{238}U beam is possible only at GSI, and therefore the FRS fragment separator offers the worldwide unique possibility to study moments of neutron rich isomers in fission fragments. Such microsecond isomers are by almost no other method accessible for moments measurements.
The spin-alignment of fragments produced in spontaneous fission and from neutron-induced fission reactions is found to be high. Anisotropies a_2 = 15-30% have been observed ($a_2 = A_2B_2$, this means alignments of the order of 30-60%) [1,2,3]. The γ–emission occurs preferentially in the fission direction, which means that the spin of the fragments is aligned in a plane perpendicular to the fission direction (being the symmetry

axis of alignment). For comparison, a spin-alignment of 35% was observed at the FRS in the projectile-fragmentation reaction $^{36}Ti+^{9}Be$ at 500 AMeV [4].

In order to observe the spin-alignment of the fission products, a particular ensemble needs to be selected out of all produced fission fragments (namely fragments emitted in a certain direction with respect to the fission axis). This occurs automatically in the case of recoil-fragment separation, where the fission products with a particular momentum correspond to fission products emitted at a particular angle with respect to the primary beam in the projectile rest-frame (as illustrated in Fig. 1 below) and thus with a well-defined longitudinal momentum in the laboratory frame.

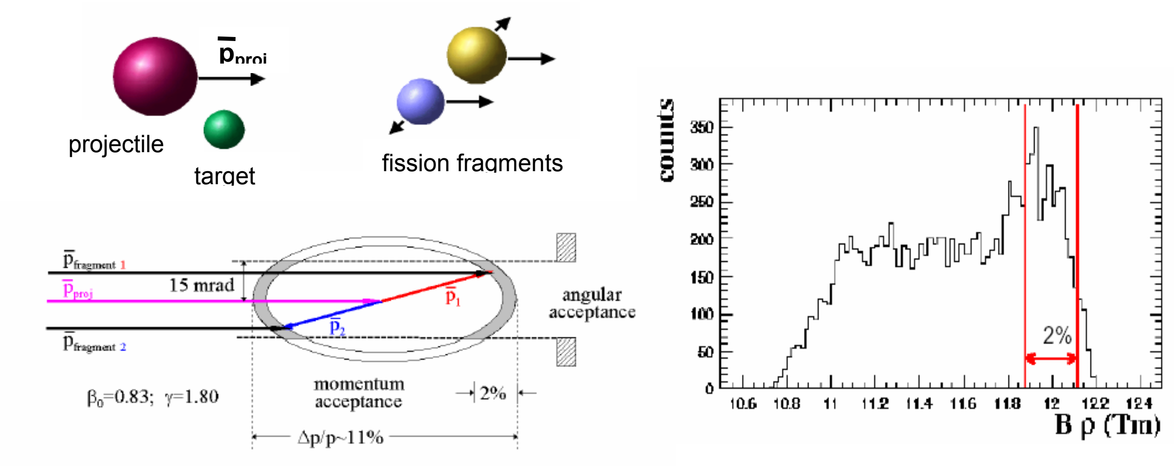

Figure 1: In a projectile fission reaction at relativistic energies (E> 500 MeV/u), the two fission fragments are relatively cold and emitted back-to-back in the projectile reference frame (left). Only part of the momentum distribution of the fragments in the laboratory frame can be accepted by the FRS (filled areas), which is shown in the MOCADI simulation at the right for ^{130}Sn fragments selected with the full 2% acceptance of the fragment separator (figures from the Ph.D. thesis of M. Mineva).

Because the longitudinal momentum distribution of the fission fragments is simulated to be of the order of 11%, compared to only 2% accepted by the FRS fragment separator, the selected fragment beam should always contain an aligned ensemble [7]. However, in the outer wing of the momentum distribution, the alignment is likely to be higher. A model to describe the expected amount of alignment as a function of the fragment momentum will be developed, based on the quasi-statistical model described by Wilhelmy et al. [1].

Aim. We intend to use the TDPAD technique to obtain information on the spin-alignment. The amplitude of the observed R(t) function is proportional to the spin-alignment and the A_2 parameter of the γ–rays in the isomeric cascade. If the multi-polarities and spins in the γ-decay of the isomer are known, the alignment of the ensemble can be deduced. Therefore, isomers with a rather well understood decay scheme are preferably used for this study. Once sufficient alignment is established, the obtained R(t) function will automatically yield the information about the g-factors of selected isomeric states, from the measured oscillation frequency (see introduction section).

We suggest to investigate the isomers in ^{135}Te (Z=52, N=83) and ^{133}Sb (Z=51, N=82). These isomers have recently been produced at the FRS in the relativistic fission of a 750 MeV/u ^{238}U beam on a ^{9}Be target [5-7]. Their decay schemes are given in Fig. 2. The spin/parities and the single particle structure of both isomers are assigned tentatively. A consistent fit of the measured R(t) functions of the γ-transitions in their decay will provide information on the spin-alignment, allow to confirm/reject the suggested E2-multipolarity of the transitions and give the isomeric g-factor. They have suitable lifetimes, decay properties and production rates, in order to allow a TDPAD measurement.

The isomer in ^{135}Te is suggested to have a spin/parity J^{π} = (19/2$^-$) [9] and $T_{1/2}$ = 0.51(2) μs [5,7]. It decays via an E2 cascade in which E_{γ} = 325, 1180 keV are well-suited to perform an R(t) measurement in optimal conditions. A value for the magnetic moment μ= (-)3.8(4)μ_n is reported in the book of abstracts of a Hyperfine Interactions Conference [10], but never published. The (19/2$^-$) isomeric state in ^{135}Te, having two valence protons and one valence neutron outside the core, has most likely a $[\pi(0g_{7/2})^2{}_{6+}\ \nu(1f_{7/2})]_{19/2-}$ configuration, which would imply a positive g-factor g~+0.4. Our measured g-factor (with sign) will allow to confirm or reject this suggested configuration. The magnetic moments of the $[\pi(0g_{7/2})^2]6^+$ isomers in ^{132}Te and ^{134}Te (both with a half life around 150 ns) have been measured as +4.74(54)μ_N and +5.08(15) μ_N respectively [10] by recoil implantation into a Cu backing. These might be used as test cases (although their lifetime is rather short).

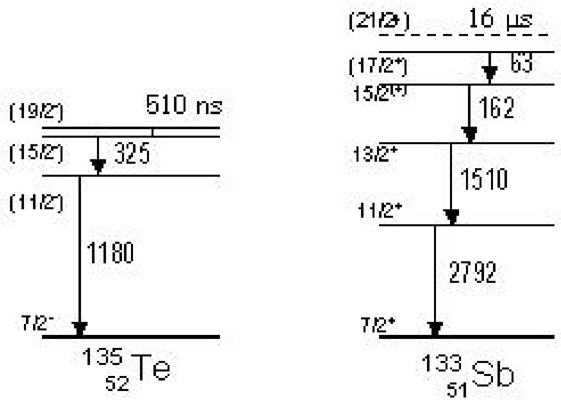

Figure 2:Partial level schemes of ^{135}Te and ^{133}Sb, with microsecond isomers.

For ^{133}Sb two isomers have been reported [11] with half-lives of 3 and 16 μs and spins J≥13/2 in ^{133}Sb (see Fig. 2). Recently, more extensive studies [12,13] confirmed the existence of the 16 μs isomer and assigned to it a spin and parity of J^{π}=21/2$^+$. Shell model calculations suggest that this isomer is a member of the multiplet build on a neutron core-excited state coupled to the odd $\pi g_{7/2}$ proton, with major configuration $\pi g_{7/2}(\nu h_{11/2}^{-1} f_{7/2})$ [13]. The 21/2$^+$ member of this multiplet is suggested to be isomeric, due to the fact that the 19/2$^+$ lies above it and this state has to decay to the 17/2$^+$ via a low-energy E2 transition. The measurement of the g-factor should be able to confirm this suggested configuration. The 3 μs isomeric state, could not be seen in the later experiments, and thus its existence will have to be confirmed in our own experiments before a determination of its g-factor can be contemplated.

Feasibility. A primary beam of **^{238}U at 750 MeV/u, 2.10^8 pps** minimal intensity will be used. Relativistic fission can be induced by the peripheral nuclear interaction (such as on a ^{9}Be target) or by dissociation in the coulomb field of a heavy target (such as ^{208}Pb). In experiments at the FRS, the isomeric ratio for more than 10 isomers in the region of ^{132}Sn produced by fission on a ^{208}Pb and a ^{9}Be target (both 1.0 g/cm^2) were compared [7]. It was observed that in the reaction on Be, the isomeric ratio was systematically higher (around 15-20%) than for the reaction on Pb (less than 10%). Therefore, we plan to use a **^{9}Be (1g/cm^2) target**.

Typically about 1% of the produced fission fragments reaches the focal plane [4,6]. Simulations made with the MOCADI program show that the full longitudinal momentum distribution of fission fragments is around 11% [6], while the acceptance of the FRS is 3% only. This means that we always select part of the full momentum distribution, and should thus obtain a spin-aligned ensemble. By correlating the γ-decays in S4 with the longitudinal momentum of the fragments in S2, the ensemble providing highest orientation can be selected off-line (and on-line). If the energy of the fragments before implantation

is reduced to about 150 MeV/u, then about 70% of the fragments remain fully stripped. That is sufficient to allow maintaining the major part of the produced orientation.
The ^{134m}Te has been investigated in Cu [14]. An anisotropy of 50% was observed in a field of 7000 Gauss. We suggest to place a **5N Cu foil** (surface 8x8 cm^2) **sandwiched with a plastic degrader (total thickness about 8 mm)** between the magnet poles (in air). The thickness of Cu/plastic is adapted such that at most 20% of a 300 keV γ-ray is absorbed.
For the case of a 750 MeV/u ^{238}U beam impinging onto a ^{9}Be target of 1 g/cm^2, the appropriate thickness of the 1st Al degrader (20% of the range of the fragments) corresponds to about 2.4 g/cm^2. The calculated rates for the FRS **optimised on two settings** are given in Table 1, including those of proposal 2.2. The Sn, Sb and Te isomers have been investigated before in the projectile fission of a ^{238}U beam and about 8.10^{-7} ^{130}Sn ions were observed per beam particle [5]. This corresponds to 160 pps of ^{130}Sn for a ^{238}U beam intensity of 2.10^8 pps (in good agreement with our simulated numbers in Table 1).

Table 1: μs-isomers around ^{132}Sn, suitable for a TDPAD investigation of the g-factor and spin-orientation (including those of proposal 2.2, as some of these are produced also in the FRS-settings for ^{135}Te or ^{133}Sb). The setting fragments are ^{135}Te and ^{130}Sn respectively, for a 2.10^8 pps ^{238}U beam at 750 MeV/u.

Isotope	**I**	**$T_{1/2}$ (μs)**	**Eγ(multi-polarity)**	**estimated g-factor**	**Suggested configuration**	**ref**	**Rate (pps)**
^{135}Te	(19/2-)	0.51	325(E2), 1180(E2)	(-)0.40(4) from abstract	$\pi(g_{7/2})^2_{6+}\ \nu(f_{7/2})$	[8]	55
^{134}Te	6+	0.163	295(E2) 1279(E2)	+0.846(25)	$[\pi(0g_{7/2})^2]6^+$	[12]	100
^{133}Sb	(21/2+)	16	163 (M1) 1510(M1)	+0.12	$\pi g_{7/2}\nu(h_{11/2}^{-1}f_{7/2})$	[13]	160
^{128}Sn	10+	3.4	327(E1)	~ -0.24 from $^{116-118}$Sn	$\nu(h_{11/2}^{-4})$	[8]	70
^{129}Sn	19/2+	3.7	382(E1) 1136(E2)	-0.15	$\nu(h_{11/2}^{-1} \otimes 5^-)$	[15]	115
^{130}Sn	10+	1.61	391(E1)	~ -0.24	$\nu(h_{11/2}^{-2})$		140
^{132}Sn	8+	2.03	300,375, 4041 (E2)	-0.25	$\nu(h_{11/2}^{-1}f_{7/2})$	[16]	48

<u>Beam time request</u> We aim to measure for the first time spin-alignment in projectile fission at relativistic energies, as well as the g-factor of these isomeric states near ^{132}Sn. This will be demonstrated by measuring the anisotropy of the γ-decays in the isomeric states specified in Table 1. All isomers have μs half lives, which makes them very suitable for a proof of principle.
In Fig. 3 a simulated R(t) curve is given for the case of ^{135m}Te (worst one from lifetime and production point). The simulation includes the realistic set-up for 1 pair of detectors and for 1 analysed isomeric γ-decay. A total of 2.10^7 ions are considered, which is obtained in 4 days for the given ^{135m}Te rate.
The amplitude of the measured R(t) function will allow to deduce the amount of spin-alignment maintained after implantation in the Cu-foil to an absolute accuracy of at least 1.5%, while the frequency of the oscillation yields the g-factor of the isomeric state to an accuracy of at least 3%. The accuracies should be better for the longer lived and better produced isotopes.

By measuring a cocktail of isomers (as shown from the simulations, this is possible), we will automatically obtain the alignment from fragments selected in different parts of their momentum distribution. This will allow to study the spin-alignment as a function of the selected momentum window (first aim of this proposal), while automatically we will also obtain the isomeric g-factors from the oscillation period. For the estimated g-factors of the isomers in cocktail (1), and considering their rather short lifetime, a magnetic field of about 0.7 Tesla (or less) is preferably used (Fig. 3). For the g-factors in cocktail (2) being around 0.15-0.25 and the isomers all having longer lifetimes, a similar magnetic field will be used.

Including about 4 days for making two beam tunings, and 5 days for measuring the R(t) for these two settings, results in a total of **9 days of beam time (= 27 shifts) for proposal 2.1 and 2.2.** It will allow measuring both the alignment and the g-factor of at least 4 isomers (and likely more) in the region around ^{132}Sn. Note that the tuning of the U-beam is not easy, and therefore we would also like to ask for 3 days of parasitic beam time before the start of a U-beam campaign, to prepare carefully the beam tuning and beam line detector calibrations (which are very important for performing on-line momentum selection to see the R(t)).

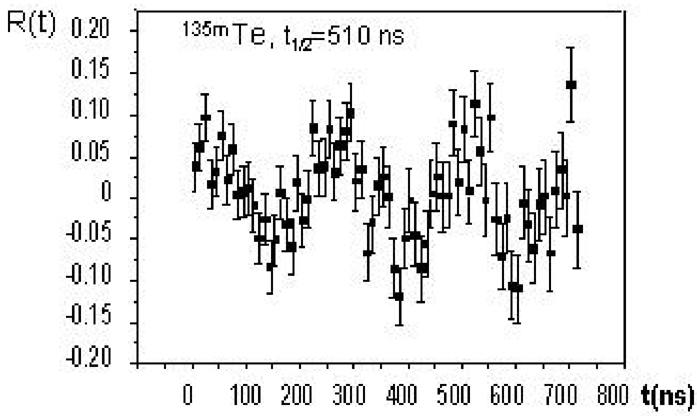

Figure 3: Simulated R(t) for the isomer in ^{135}Te, assuming a total of 2.10^7 ions implanted (4.10^4 γ's in the R(t)). The simulation is for a γ-ray energy of 325 keV, a single pair of cluster detectors at 60° with respect to each other and a magnetic field of 0.7 T. An isomeric ratio of 20%, an alignment of 28% and E2 transition are assumed.

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Proposal 2.2:
g-factors of 10^+ isomers in relativistic fission fragments around ^{132}Sn.

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Abstract: The g factors of 10^+ isomeric states in $^{128-130}Sn$ will be measured, in order to probe the first- and second order core polarization effects and the quenching of the M1 operator, in comparison to the same effects occurring in the 12^+ isomers in the neutron-deficient Pb-region. The isomeric states of interest will be produced in a relativistic fission reaction using a 750 MeV/u ^{238}U beam, which will also provide the necessary spin-alignment (see proposal 3). These experiments will serve as a first step towards g-factor measurements for more exotic cases using the more intense fission-fragment beams of the super-FRS, as well as for subsequent quadrupole moment determinations, that will allow to investigate the core polarization.

Motivation. The only doubly magic regions accessible for detailed spectroscopic studies on the neutron-rich side of the nuclear landscape, above ^{48}Ca, are the ^{132}Sn and ^{78}Ni regions, both very far from the valley of stability. Nuclei near double shell closures can be considered to have a simple structure, a number of particle and hole excitations with respect to an inert core. High-spin isomers in these nuclei have very often a rather pure single-particle configuration, making them ideal candidates to study details of the nuclear M1 and E2 properties. This has been extensively demonstrated by the study of moments of high-spin isomers in the region of the only other doubly-magic heavy nucleus: the stable ^{208}Pb (see e.g. [1] for a recent review).
Experimental data in the neutron rich region around ^{132}Sn can provide similar useful information for testing the basic ingredients of shell-model calculations, but now in a region far from stability, where different nuclear structure effects (such a shell quenching) are expected to occur [2]. By measuring the static moments one can determine effective interactions between nucleons, here in the neutron rich region around Z=50 and N=82. Currently no high-spin g factors are known near the ^{132}Sn region (up to +/- 2 protons), except for a few ground state moments and for some very long-lived (> minutes) isomeric states. Only for the 2^+ states systematic studies of g-factors have been performed up to ^{124}Sn, ^{116}Cd and ^{130}Te [3]. Shell-model calculations can reproduce most of the high-spin features of the nuclei in this region, but still some discrepancies remain. Measuring the g factors of high-spin isomers will help in pinpointing the current faults in shell-model descriptions. Measured g-factors allow checks on the model space and on the parameterisations used in calculations, because of the very pure character of such often stretched configurations.

The observation of decays from in-flight separated microsecond isomeric states is an exceptionally clean technique and is, at present, the only method which allows the study of many intermediate and high-spin isomeric states in the ^{132}Sn region. Around thirty intermediate/high-spin microsecond isomers are known in this region, many being recently measured by J.A. Pinston and co-workers at the Lohengrin recoil mass separator, ILL (see [4] for a recent review on this subject) as well as at the FRS fragment separator at GSI [5]. At ILL it is very difficult (if not impossible) to measure the g-factor of these isomers, because of the spin-orientation being destroyed during the separation process (the fission fragments produced by an intense neutron beam are not fully stripped).

Aim. Even-mass Sn isotopes from mass 116-130 have microsecond 10^+ states, suggested to have a stretched $(\nu h_{11/2})^2$ configuration. These isomers are very similar to the 12^+ $(\nu i_{13/2})^2$ isomers in the neutron deficient Pb region, for which both the g-factor and quadrupole moments have been studied extensively (reviewed in [1]). In order to describe the g factors for the 12^+ isomers qualitatively, effects such as first and second order core polarization and meson exchange currents had to be taken into account [6]. The remaining difference between the experimental results and the theory is thought to arise because of a quenching of the M1 operator. Only when an effective M1 operator is used can the experimental g factors be reproduced quantitatively.
A first aim of this proposal is to investigate if the same reduction of the M1 dipole operator occurs in the ^{132}Sn region, and if the amount of quenching is the same as in the Pb region. The 10^+ isomeric state in ^{130}Sn, with two holes in N=82, is a pure maximally aligned $(\nu h_{11/2})^2$ seniority 2 configuration. Measuring its g-factor will allow to test the theoretical predictions, and to deduce an M1 effective operator for this mass region.

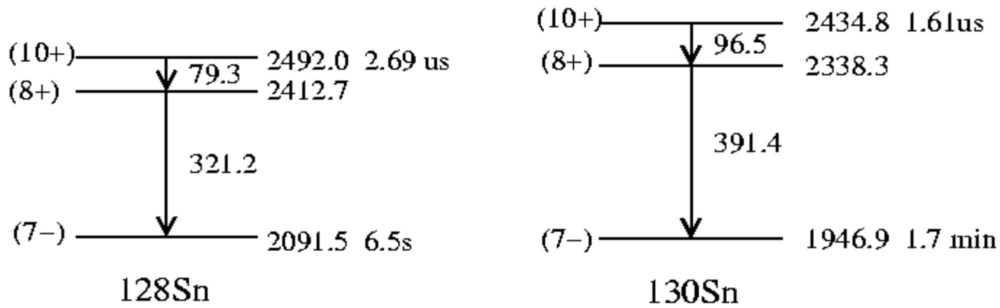

Figure 1: Decay schemes of the 10^+ isomeric states in 128-130Sn. One γ-transition can be used to construct the R(t) function, due to another long-lived isomer in which this μs-isomer decays.

The second aim of this proposal is to investigate the nature of the suggested configuration mixing in the ^{128}Sn 10^+ isomer. Fogelberg et al. [7,8] suggested that the 10^+ isomer in ^{128}Sn has a significant amount of configuration mixing. The mixing was proposed in order to explain the similar lifetime - and hence the similar B(E2) - of the isomers in $^{128-130}$Sn (Fig. 2). For pure $(\nu h_{11/2})^2$ states, the quadrupole moment - and thus also the B(E2)) - should decrease when neutrons are taken from the $\nu h_{11/2}$ (similar as for the 12^+ isomers in the Pb-region, as demonstrated e.g. in [1]). The fact that the B(E2) in ^{128}Sn does not decrease as much as expected, could be explained by a configuration mixing effect. With 4 holes in the N=82 neutron shell, this 10^+ isomer in ^{128}Sn can have e.g. two additional holes in $d_{3/2}$ yielding a $(\nu h_{11/2}^{-2}\, d_{3/2}^{-2})10^+$ configuration. Thus the emptying of the $\nu h_{11/2}$ is delayed, yielding the same B(E2) for ^{130}Sn and ^{128}Sn. If indeed this is the reason for the similar B(E2), then we expect the g-factors of ^{130}Sn and the ^{128}Sn to be the same (a coupling to a $\nu(d_{3/2}^{-2})0+$ configuration does not change the g-factor). A precision measurement on both isotopes will reveal this.

Feasibility. The two 10^+ isomeric states have very suitable lifetimes (τ=3.4 μs for ^{128}Sn [7] and 1.61 μs for ^{130}Sn [8]) for measuring their R(t). The γ-flash that influences the time spectrum typically for a few 100 ns will thus not affect very much the time differential measurement for these μs isomers. The γ-transitions in the isomeric decay suitable for the g-factor analysis are respectively the 327 keV and 391 keV E1 transitions (from the 8+ to the 7- levels). Only one γ-decay per isomer can be analysed, but with a production rate of about 100 pps (see previous proposal) this should still lead to a reasonable accuracy on the g-factor of about 4%.
The estimated g-factor for the 10^+ isomers is g(10^+) ~ -0.24, based on similar measurements in the $^{116-118}$Sn isotopes [9]. A minimum of 2.10^5 γ-ion correlations need to be observed to obtain a precision of better than 1% in the g-factor. Such a precision will allow to observe if the single particle configuration of the two isomers is indeed a stretched ($\nu h_{11/2}^{-2}$) or if some admixture with other unpaired nucleon configurations occurs in the ^{128}Sn. For probing a reduction in the M1 operator, an accuracy of a few % on the g-factor is sufficient, and can be realized already with as little as 2.10^4 γ-ion correlations.

Beamtime request Because these isomers are selected simultaneously in a single FRS setting, and because also some of the isomers suggested for investigation in proposal 2.1 come in this setting, we suggest a common beam time for these two proposals.

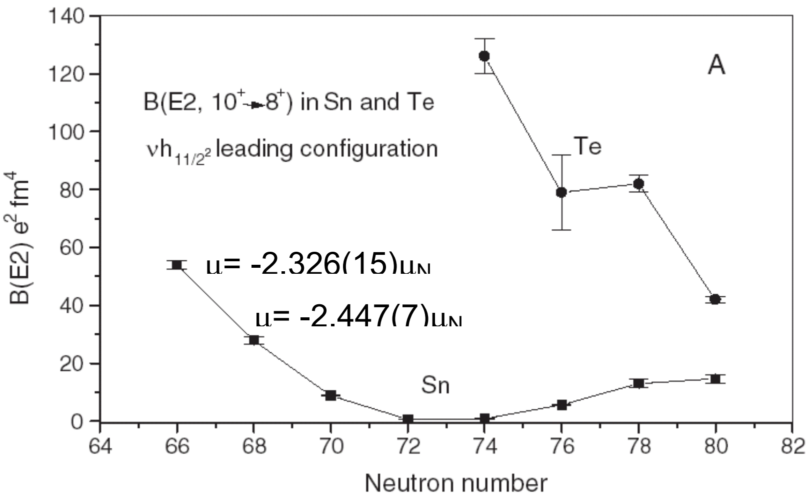

Figure 2: B(E2) values deduced from the lifetimes of the 10^+ isomeric decays in the even Sn (Z=50) and Te (Z=52) isotopes. The decrease towards Z=73 for the Sn values is due to the emptying of the νh neutron orbit, while the increase in the Te isotopes is explained due to the coupling of the neutron isomer with proton vibrations of the core.

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Letter of Intent

Quadrupole moment measurement of the 8^+ isomer in ^{96}Pd

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on behalf of the g-RISING collaboration

Motivation

The study of nuclear spectroscopic quadrupole moment is of particular and complimentary interest to g-factor measurements since it directly probes the deformation aspect of the nuclear structure of the investigated level. Here we suggest to measure the quadrupole moment of the 8^+ isomer in ^{96}Pd (E_{ex} = 2530 keV, $T_{1/2}$ = 2.2 μs) [1]. The main motivation for this experiment is related to the recently observed break down of the seniority scheme in ^{96}Pd [2].
Experimentally well-developed seniority schemes have been established in many isolated proton and neutron high-spin orbits, such as $\pi\nu\, f_{7/2}{}^n$ in the Ca isotopes, $\nu\, g_{9/2}{}^n$ in the Ni isotopes, $\pi\, g_{9/2}{}^n$ in the N=50 isotones, $\nu\, h_{11/2}{}^n$ in the Sn isotopes, $\pi\, h_{11/2}{}^n$ in the N=82 isotones and $\pi\, h_{9/2}{}^n$ in the N=126 isotones. In spite of distortions of the pure seniority scheme due to neighbouring orbitals and peculiarities of the residual interaction two-body matrix elements, the seniority v is a pure and well defined quantum number, even in the heavily distorted N=126 case.
Recently seniority mixing has been experimentally established from a measurement of B(E2) transitions from the 4^+ states in ^{96}Pd and ^{94}Ru [2]. Large scale shell model calculations fully account for the experimental data in ^{96}Pd , ^{94}Ru and the long-standing B(E2) puzzle in the mid-shell ^{95}Rh and prove that the mixing is due to ph excitations across the N=50 closed shell. The same calculations show that ph excitations of the ^{100}Sn core do not affect the relative strengths of B(E2;$8^+ \rightarrow 6^+$), B(E2;$6^+ \rightarrow 4^+$) and Q(8^+) in the v=2 two-hole nucleus ^{98}Cd [3]. Therefore the close to mid-shell nucleus ^{96}Pd, where due to the occupation dependence of Δv=0 E2 matrix elements the undistorted values are small (1/3 of the two-particle (hole) case), is the most sensitive study ground.

Experimental procedure

The experiment can be done by applying the TDPAD technique on isomers stopping in a non-cubic crystal with an appropriate electric field gradient. It will be done under the same conditions (beam energy, FRS settings, etc.) as the g-factor measurement of the same isomer which is suggested to be measured within the g-RISING campaign proposal “g-factor measurements on relativistic projectile fragments around the doubly magic N = Z nucleus ^{100}Sn” and these data will be used to determine the amplitude of the TDPAD curve for the quadrupole moment measurement.

The proposed experiment takes advantage of the high yield with which ^{96}Pd is produced in the projectile-fragmentation of ^{112}Sn with an energy of about 600 MeV/u, which makes the experiment feasible. So far no measurement of a quadrupole moment of an isomeric state in projectile fragmentation experiment has been performed. A test experiment is accepted in at GANIL in the case of ^{61}Fe [4]. However, in order to access the mass A = 100 nuclei, beams at relativistic energies are needed which are available at GSI.

The theoretical estimate for the spectroscopic quadrupole moment of this isomer as inferred from the known B(E2;$8^+ \rightarrow 6^+$) is Q_s = 19 efm^2 . The effect of the seniority mixing on the B(E2;$4^+ \rightarrow 2^+$) in ^{96}Pd (and ^{94}Ru) is a factor of four, i.e. a factor of two in the matrix element. Therefore even in the case of poor statistics clear evidence should be obtained.

While from a point of view of production of the isomer, the experiment is straightforward, in order to perform it we need to investigate the possibility to use the RISING set up for the passive stopper, where all the Cluster detectors (and possibly the Miniball detectors) can be used in the experiment. In order to perform realistic TDPAD simulations of the experiment, we need to know the precise angles at which these detectors will be placed. This information is not available till now. A second option which is under consideration is to use the g-RISING set up with some rearrangement, e.g. by removing the magnet.

In addition, since the EFG of Pd is not known in any material, extensive *ab ignitio* solid-state calculations are needed with the WIEN97 code [5,6] in order to define the optimal conditions for this measurement, taking into account the small expected value for the quadrupole moment and the needed sensitivity for the experiment. An estimate of the EFG of Pd in Cd (PdCd) yields a value ~ $4{\cdot}10^{17}$ V/cm^2 [7]. This can be compared to some known typical values: FeCd = $2.7{\cdot}10^{17}$ V/cm^2, GeCd = $1.8{\cdot}10^{17}$ V/cm^2, GaCd = $4.8{\cdot}10^{17}$ V/cm^2. In Fig. 1 we present TDPAD simulations of ^{96}PdCd for different quadrupole frequencies, relative to that of FeCd (with Q=50 efm^2 assumed for the 10^+ isomer in ^{54}Fe). Having in mind the estimates for the spectroscopic quadrupole moment and the EFG of PdCd, we expect that experiment will yield a TDRAD curve in between the top two curves. This means that within the first $T_{1/2}$ of the isomer the first oscillation will clearly be observed.

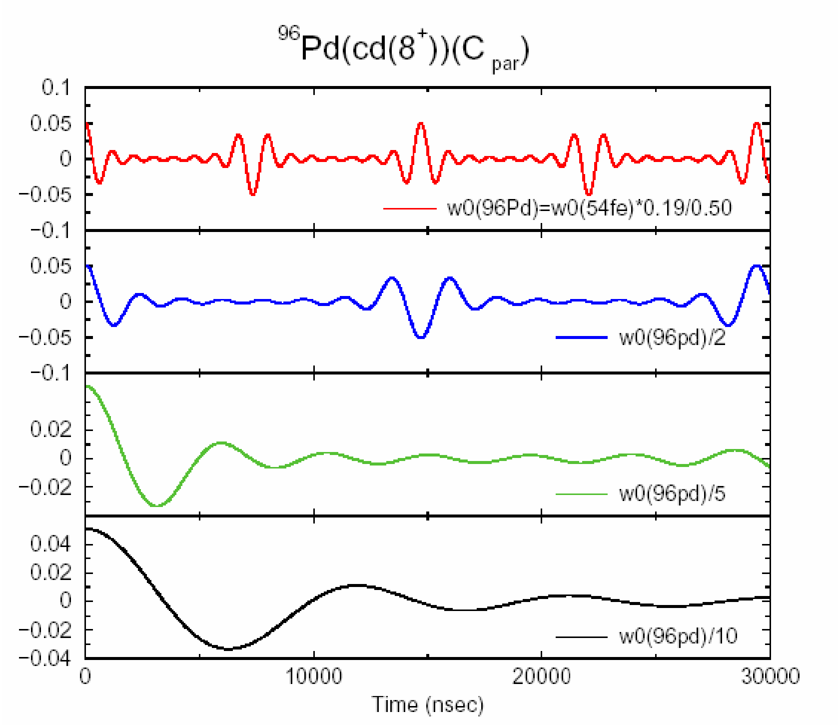

Fig.1. Sample TDPAD curves, indicating the change of the TDPAD pattern as a function of the ratio of the quadrupole interaction frequency of ^{54}FeCd compared to ^{96}PdCd. The crystal c-axis is parallel to the orientation axis.

At this stage, on the basis of the calculated production rate for this isomer, we estimate that **it can be done within 21 shifts**, including the FRS tuning. An official proposal will follow up for the next PAC meeting, once the above mentioned issues have been clarified.

This experiment will serve as a proof of principle and open the avenue to quadrupole moment measurements of exotic isomeric states at the future FAIR facility.

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