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Proposal to the ISOLDE and Neutron Time-of-Flight Experiments Committee

Study of the neutron deficient Pb and Bi isotopes by simultaneous atomic- and nuclear- spectroscopy

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Abstract:

We propose to study systematically nuclear properties of the neutron deficient lead $^{183\text{-}189}$Pb, ^{191g}Pb, ^{193g}Pb and bismuth isotopes $^{188\text{-}200}$Bi by atomic spectroscopy with the ISOLDE resonance ionisation laser ion source (RILIS) combined with simultaneous nuclear spectroscopy at the detection set-up. The main focus is the determination of the mean square charge radii of $^{183\text{-}190}$Pb and $^{188\text{-}193}$Bi from which the influence of low-lying intruder states should become obvious. Also the nuclear spin and magnetic moments of ground-states and long-lived isomers will be determined unambiguously through evaluation of the hyperfine structure, and new isomers could be discovered. The decay properties of these nuclei can be measured by α–γ and β–γ spectroscopy. With this data at hand, possible shape transitions around mid-shell at N~104 will be studied. This data is crucial for the direct test of nuclear theory in the context of intruder state influence (e.g. energy levels) on spins, binding energies and other global nuclear properties.

For these investigations a total of **30 shifts** of radioactive beam with the ISOLDE-RILIS and a standard UC$_x$/ graphite target is requested.

Introduction:

With the new resonance ionization laser ion source (RILIS) [Kös02, Bar00] suppression of isobaric beam contamination is improved. Previously unavailable, neutron deficient isotopes of Pb and Bi, far from stability can be studied by spectroscopic means. Due to the inherently large optical isotope shift of 2 GHz/amu in the lead-region and a magnetic hyperfine splitting of the order of 10 GHz it is feasible to not only perform element selective resonant ionisation within the RILIS, but to use the ionising lasers also for direct atomic spectroscopy. The first step of the selective ionisation is sensitive to the isotope shift (IS) and the hyperfine structure (HFS). Thus the change in the nuclear mean square charge radius $\delta\langle r_c^2\rangle$, and for non-zero nuclear spin $I \neq 0$, the magnetic moment μ_I [Ulm86, Kop58] are manifested in the optical spectra. Measured along long chains of isotopes systematic trends in nuclear structure can be extracted [Ott89].

Of particular interest is the proposed extension of the charge radii and nuclear moment determination across mid-shell at N=104 to directly test the predictions of nuclear models such as the ETFSI (extended Thomas Fermi Strutinski Integral) [Buc94,Gor01], FRDM (finite-range droplet) [Buc94,Möl95] or the RMF (relativistic mean field) [Lal99] models.

Physics interest:

The physics interest is twofold: the atomic-spectroscopy and the nuclear-spectroscopy aspects of the neutron deficient lead and bismuth isotopes.

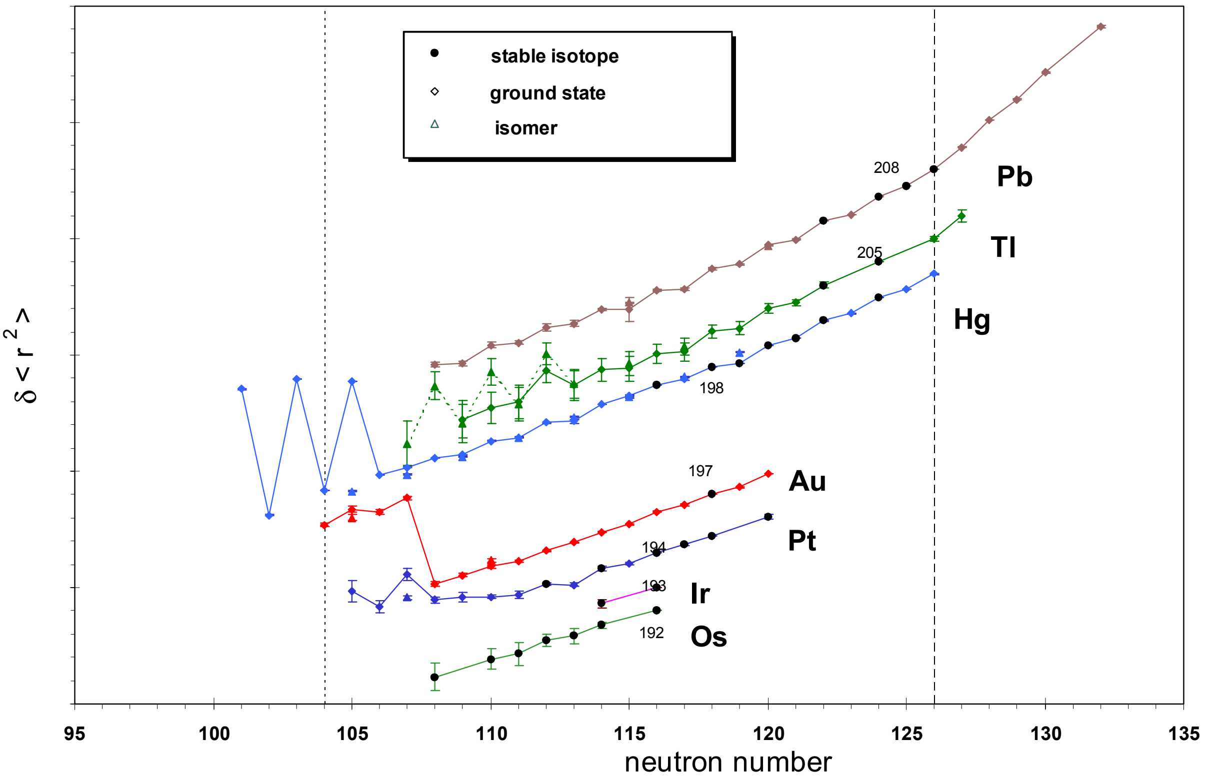

Fig. 1 Changes in mean square charge radii of the elements with $Z \leq 82$. A change in deformation at mid-shell (N~104) can be observed, as well as the immense odd-even staggering in Hg. Isotope shifts of ^{202}Bi-^{213}Bi were measured but not evaluated [Pea00].

From direct atomic spectroscopy in the RILIS the quantity $\delta\langle r_c^2\rangle$ is extracted. These charge radii far from stability are stringent tests for nuclear models. A systematic coverage of large areas of the nuclear chart is important, e.g. for those models that use a fixed effective force in microscopic calculations or for compact nuclear models used for calculations in nuclear astrophysics [Pfe97]. The results of $\delta\langle r_c^2\rangle$ for very neutron deficient isotopes in Pb and Bi together with the already measured isotope chains ($^{190-214}$Pb and $^{201-213}$Bi) should be reproduced by theory. The extension of the Pb isotope chain, with the Z=82 closed proton shell, down to ^{183}Pb is the most important piece to be added, and it can then be compared to the rather complete data on Hg and Pt (Fig. 1).

The systematics of charge radii reveals significant aspects of nuclear structure and has been one of the main sources of information concerning the surface density of nuclear matter, which is closely related with mass formulas [Ton00]. Though not always included explicitly, most modern mass formulae take at least implicitly into account shell structure, pairing effects and deformation as well as shape transitions. These will reflect in the predictions of the charge radii. The experimental data provided by the proposed laser spectroscopy in terms of spins, magnetic moments and charge radii are model independent observables and by this provide basic data for testing nuclear theories. Fig. 1 shows the changes in mean square charge radii in the lead region.

The existence of sometimes two or three "long-lived" isomers makes nuclear spectroscopy around Z~82 and N~104 very challenging. It is obvious that the availability of isomerically pure beams is a real breakthrough for nuclear spectroscopy. This we will discuss with the example of ^{189}Pb where only one isomer (with unknown spin) is presently known, while in ^{185}Pb and $^{191-197}$Pb two isomers (13/2+ and 3/2-) are known. Here searching for the second isomeric state, is of major interest. Also in ^{189}Pb, which decays by α and β^+/EC respectively, one would expect two isomers (13/2+ and 3/2-). By observing the second isomer and establishing the spin for both, the masses and relative positions (via known alpha-decays of parents) of the known 3/2- and 13/2+ isomers in the long decay chains Ra-Rn-Po-Pb-Hg can be determined. Recently the masses of the 13/2+ and 3/2- states in ^{185}Hg were accurately measured at ISOLTRAP [Sch01]. If the alpha-decay of the second isomer in ^{189}Pb could be measured together with the spins of both isomers, then immediately all masses of the 13/2+ and 3/2- isomers in the chain, up to 201Ra, would be determined. We note that ^{201}Ra is the most neutron deficient Ra isotope known and so exotic that a direct mass measurement would be extremely difficult. The proposed studies would complement past and present work on the problem of multiple spin-isomers in neutron deficient isotopes around Z=82 [Bou82, Mac84, Kil87, Sch01].

Production:

Neutron-deficient mercury beams (initially down to ^{181}Hg) were among the first beams produced at ISOLDE [Han69, Bon76]. Important experiments, among them atomic spectroscopy studies (see above) were performed with these pure and intense showcase beams. This led to the unexpected discovery of the odd-even staggering in Hg. With subsequent upgrades of the driver accelerator now mercury beams down to ^{177}Hg can be produced from liquid lead targets [Let97]. Clean thallium beams are produced with UC_x/graphite or ThC_x/graphite targets coupled to a surface ionisation source. The elements Pb and Bi were available from UC_x/graphite targets coupled to a "hot-plasma"

(MK5) ion source. However, the missing chemical selectivity of this ion source prevented spectroscopy applications of the Pb and Bi beams on the neutron-deficient side due to massive isobaric background. Only recently, with the use of the resonance ionisation laser ion source (RILIS) it has become possible to ionise Pb and Bi selectively [Kös02], and hence to produce rather pure beams. Fig. 2 shows the used ionization schemes. A yield survey with a standard UC_x/graphite target and the RILIS allowed to produce lead beams down to ^{183}Pb and bismuth beams down to ^{188}Bi, see Fig. 3.

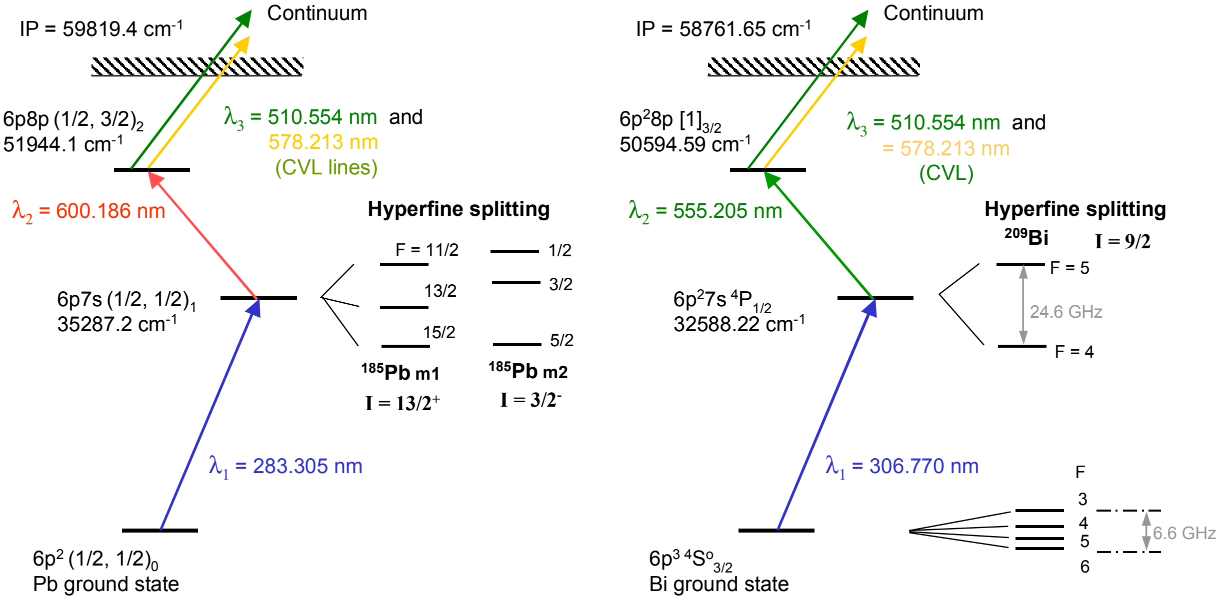

Fig. 2 RILIS laser excitation scheme for Pb and Bi ionisation. The wavelengths used are obtained from two copper vapour laser (CVL) pumped dye-lasers, one of which is frequency doubled. The CVL radiation (green and yellow) is also used for non-resonant excitation of the doubly excited Pb states into the ionising continuum. Indicated is also the hyperfine structure for particular nuclear spins. With J=0 in the electronic ground state, Pb exhibits HFS only in the first excited state, resulting in 3 HFS lines. In Bi the HFS gets richer, as also the electronic ground state exhibits hyperfine structure.

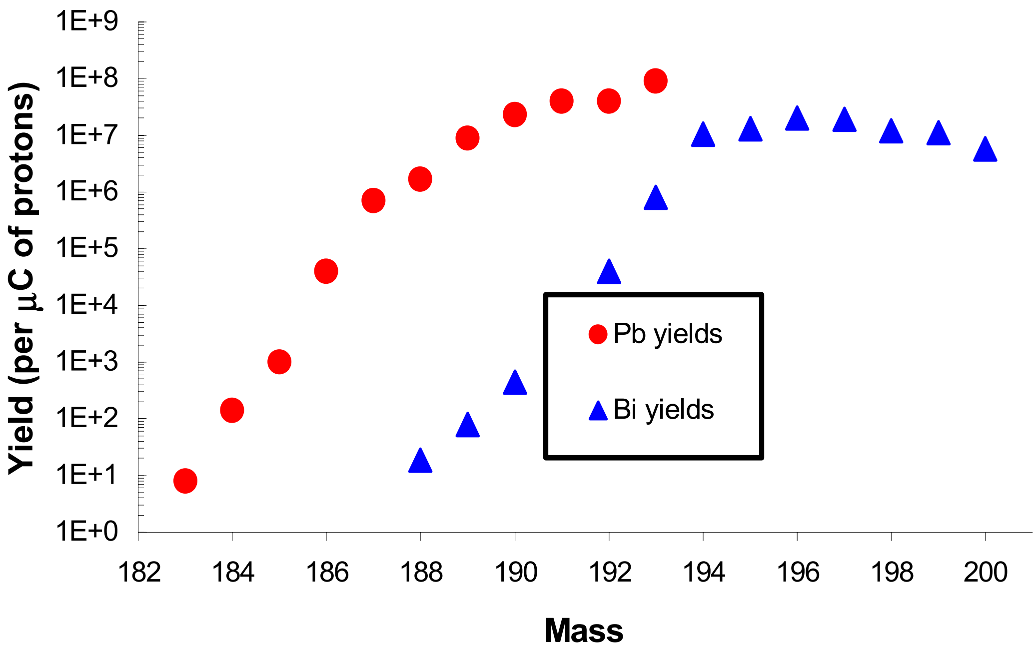

Fig. 3 Measured RILIS yields for Pb and Bi. The yields show the sum of all detected isomers. The yields of different isomers at one mass often differ by one order of magnitude and more. By adapting the measurement cycle appropriately, clear signals for all the isomers to be studied can be obtained.

Due to the shorter half-life of the Pb and Bi isotopes of interest compared to the main contaminant Tl (surface ionized in the hot ionizer cavity) in all cases a suitable combination of measurement timing and detection method can be chosen to keep the Tl background on an acceptable level and to detect the Pb and Bi isotopes unambiguously. An example for the purity of a RILIS beam is given in Fig. 4. Only for the masses A>203 isobar contamination from francium would add significantly.

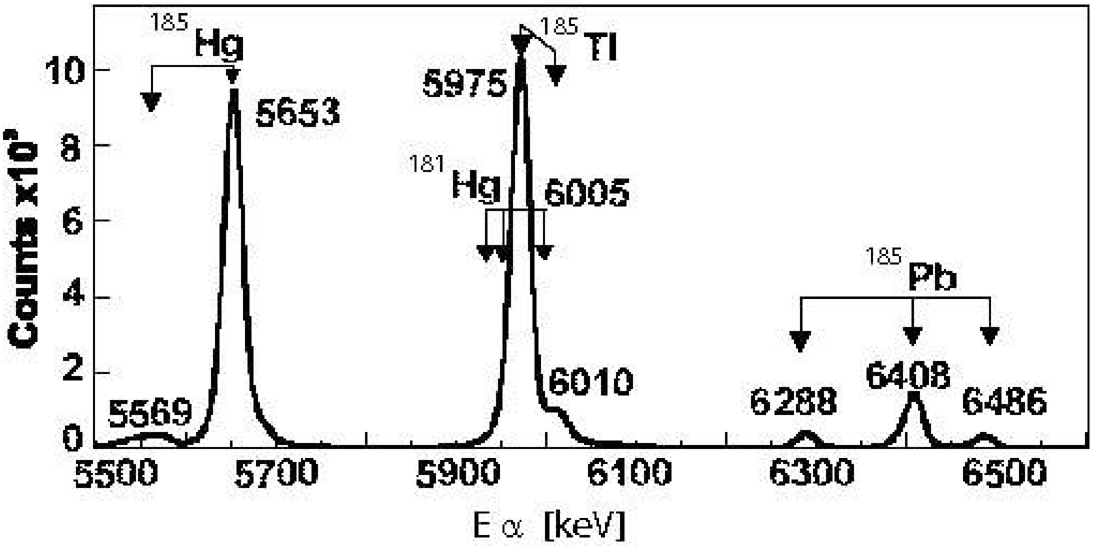

Fig. 4 Typical alpha spectrum obtained at mass 185 with the ISOLDE RILIS tuned to ^{185}Pb with broadband excitation (laser linewidth about 10 GHz) in the first excitation step. The mercury isotopes are produced only indirectly at the detection station: ^{181}Hg is the daughter nucleus from the alpha decay of ^{185}Pb, and ^{185}Hg is the EC/β+ daughter of the surface ionised ^{185}Tl contamination.

The proton beam energy increase of the PS Booster from 1.0 GeV to 1.4 GeV provides a major gain in deep spallation cross-sections. In particular the production cross-sections of very neutron-deficient isotopes around Z=82 show a strong increase, e.g. the ^{182}Tl yield increased by a factor >6 when using protons beams with 1.4 GeV instead of 1.0 GeV [Geo02].

Atomic spectroscopy with the ISOLDE RILIS:

For heavy elements the isotope shift (IS) is dominated by the field-shift which is related to the mean square charge radius $<r_c^2>$ of the element. A resolution of 1/10 of the linewidth is needed for this investigation. For isotopes with non-zero nuclear spin a splitting of the atomic energy levels into a number of hyperfine components is observed. During the yield survey of neutron-deficient Pb isotopes a single rapid scan was performed (see fig. 5) and for ^{185}Pb immediately a new isomer was found [And02].

The magnetic HFS is 10-100 times larger than the quadrupole HFS in the selected optical transition. The determination of I and μ_I is therefore unambiguous even with low resolution spectra [Kös00].

For the ISOLDE hot cavity RILIS the resolution of atomic spectroscopy is limited by the Doppler broadening and currently available laser linewidth (about 1.2 GHz). The Doppler broadening is smaller for heavier elements (about 2 GHz for Pb), and at the same time the field-shift is more pronounced. Hence the best spectroscopic results can be obtained for heavy elements. Pb and Bi are the ideal elements to demonstrate the power of this technique in addition to their nuclear physics merit.

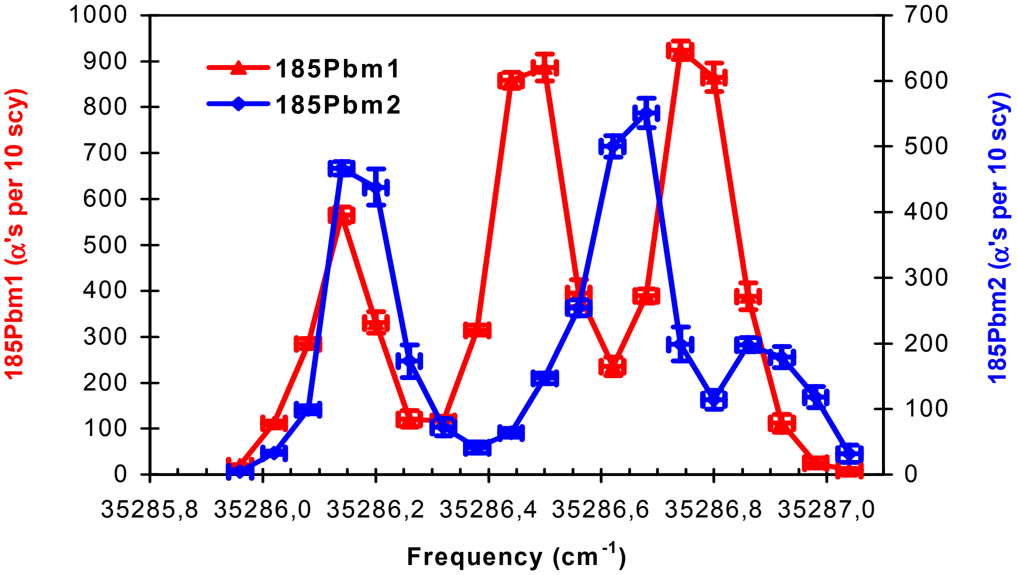

Fig. 5 Selective isomer excitation in ^{185}Pb. The dependance of the yield of different alpha lines of ^{185}Pb as a function of the first excitation laser frequency shows that the ^{185}Pb isomers with I=13/2 and I=3/2 have different hyperfine structures. Thus the relative ion yield of the spin isomers depends directly on the laser tuning.

Experimental set-up:

For the reliable determination of the HFS and IS the first step laser has to be operated with a spectral linewidth of about 1 GHz and its frequency must be controlled and monitored to assure reproducible scans across the HFS of the radio-isotope and a stable reference isotope. This is done by using a ultra-precise lambdameter for wavelength recording and control of the dye laser as well as a Pb hollow cathode lamp for optogalvanic spectroscopy. The laser scans will be automated to allow repeated and reproducible scans over the frequency range of interest.

We will use the ISOLDE spectroscopy station for the nuclear spectroscopy set-up. A metallized tape is used to collect the ions and to transport off the long-lived activities in regular intervals. Alpha decays are detected with a Si detector mounted in backward direction which views the implantation area. A low-energy Germanium detector will be used for gamma detection. This set-up is similar to the one used successfully for the test run with ^{185}Pb. We will further improve the alpha detection efficiency and add thin plastic scintillators and a small beta telescope to complete the set-up for beta detection. Hence alpha-single, gamma-single, beta-gamma and alpha-gamma spectroscopy can be performed. Thus also branching ratios (α, β+/EC and IT respectively) can be measured simultaneously. The nuclear spectroscopy output data will be:

(a) used for on-line supervision of the laser scan by monitoring the number of α or γ-counts respectively within a region of interest

(b) and written as listmode file to identify off-line the assignment of weaker α or γ-lines and to perform off-line coincidence spectroscopy.

New developments:

In preparation of the proposed measurements the data acquisition and RILIS will be interfaced in order to synchronize RILIS scans and data acquisition. The laser wavelength control and recording of scans will be improved and automated by computer control via the ATOS lambda-meter. The possible integration of an absolute wavelength reference, such as a hollow cathode for optogalvanic spectroscopy into such a system improves the absolute reliability of the measurements. These measures will ensure a higher data rate, better statistics for the laser scans, as well as improved ease of use of the RILIS.

In this proposal we presented our request to perform in-source atomic spectroscopy on neutron deficient Pb and Bi isotopes. However, the same technique can be extended to the neighbouring elements. For thallium the existing RILIS ionisation scheme needs to be modified for isotope shift measurements. Efficient ionisation schemes or Po and Hg still need to be developed, the latter requiring an upgrade of the available pump laser power. These developments are under way and, when available, we will submit an addendum to complement the present investigations with atomic spectroscopy studies of the neighbouring Tl, Hg and Po isotopes.

Beamtime request:
We plan to carry out the measurements on Pb and Bi isotopes down to mass 183 and 188 respectively. To this end it is necessary to (i) test the automated RILIS and data acquisition system, then (ii) perform the measurements with narrow-band laser excitation for hyperfine structure and isotope shift measurement, spin determination and isomer detection and measurement. Afterwards (iii) nuclear spectroscopy will be done on particular isomers for decay chain measurements and state identification.

(i)	final, life RILIS & data acquisition tests	off-line	
(ii)	HFS and IS measurements on Pb	12	shifts
(iii)	dedicated Pb nuclear spectroscopy (α, β, γ) on selected isomers	3	shifts
(iv)	HFS and IS measurements on Bi	12	shifts
(v)	dedicated Bi nuclear spectroscopy (α, β, γ) on selected isomers	3	shifts
	This represents a **total** of	**30**	**shifts**

This experiment can be performed either at GPS or HRS. The latter has a lower RILIS efficiency (longer distance to focus laser beams to the ion source) which prolongs the scans of the most exotic isotopes. For the short-lived isotopes ($T_{1/2}$~10 s) regular proton pulse sequences are needed, similar to the requirements for collinear fast beam laser spectroscopy. The target should be equipped with stable Pb and Bi mass markers.

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