EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-INTC-2004-026
INTC-P-156 Add. 1
October 15, 2004

Proposal to the INTC Committee
Addendum to experiment IS411

Coulomb excitation of neutron-rich A ≈ 140 nuclei

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Abstract: We propose to measure reduced transition strengths $B(E2)$ between ground state and first excited 2^+ state in neutron-rich nuclei around $A \approx 140$ by γ-spectroscopy following Coulomb excitation. In particular, as a continuation of the experiment recently performed at REX-ISOLDE with MINIBALL, we want to study the nuclei ^{126}Cd and $^{138-144}$Xe. Additionally, we ask for the development of molecular BaF$^+$ beams for future studies of ^{148,150}Ba. These studies will shed further light on the recently observed unexpected reduction of the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-values in even-even Te and Sn nuclei. With this new insights will also be gained into the isospin dependence of neutron pairing as well as the phenomenological systematics of the product between the $B(E2)$-value and the $E(2^+_1)$ excitation energy.

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1 Physics case

The aim of this experiment is to study the isospin dependence of $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-values of neutron-rich even-even nuclei with $A \approx 140$ in the surrounding of the magic numbers $Z = 50$ and $N = 82$. Recent experiments have exhibited that the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-values of neutron-rich Te and Sn isotopes are considerably smaller than expected from phenomenological systematics. An extended investigation of this region will provide a deeper insight in the physics, in particular the neutron pairing in neutron-rich nuclei, behind this anomalous behaviour.

Already more than forty years ago, Grodzins found that the product between the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-value and the excitation energy $E(2^+_1)$ of the first 2^+_1 state in even-even nuclei has a smooth behaviour near to the valley of stability. The values of this product can be described by a simple $\propto Z^2 A^{-1}$ dependence [1]. An even better description could be obtained using a dependence $\propto Z^2 A^{-2/3}$ [2]. Knowing the energy of the first 2^+ state, this formula can be applied to estimate unknown $B(E2)$-values.

Going away from the valley of stability it was found that this simple parametrisation fails to reproduce measured $B(E2)$-values [3]. There is a systematic deviation as a function of isospin: for proton-rich nuclei the experimental values are above the global trend, whereas for neutron-rich nuclei the experimental values are below.

For nuclei close to the valley of stability, the proton-neutron interaction causes equal deformation for proton and neutrons and lead to a 2^+ state with predominant isoscalar character ($T = 0$). This fact was formulated concisely by R. Casten introducing the $N_\pi \cdot N_\nu$-scheme [5]. The excitation energy decreases with increasing number of valence protons N_π and valence neutrons N_ν as function of the product $N_\pi \cdot N_\nu$.

Adding more loosely bound valence neutrons to these nuclei, the additional neutrons might decouple from the core and form a different deformation. The lowest 2^+ state would have an isovector admixture which lowers its energy while the $B(E2)$-value which is dominated by the proton core remains nearly the same. The isovector contribution to the excitation energy would behave similar to the isoscalar component: the energy decreases with an increasing number of valence neutrons as a function of N^2_ν.

A significantly improved description could be obtained by multiplying the formula from [2] with a function linear in $(N - \bar{N})$ where $\bar{N}$ denotes the neutron number for which the nuclear mass within an isobaric chain reaches its minimum:

$$E(2^+_1)[\mathrm{keV}] \cdot B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)[e^2\mathrm{b}^2] = 2.57\ Z^2\ A^{-2/3}\ \Big(1.288 - 0.088(N - \bar{N})\Big)\,. \qquad (1)$$

The coefficients of the linear function have been fitted to nuclei with $48 < Z < 70$ and $E(4^+_1)/E(2^+_1) > 1.8$. The excitation energies and $B(E2)$-values are taken from [2, 4]. $\bar{N}$ is obtained by differentiating Weizsäcker's mass formula with respect to N for fixed mass number A:

$$\bar{N} = \frac{A}{2}\,\frac{1.0 + 0.0128\ A^{2/3}}{1.0 + 0.0064\ A^{2/3}} \qquad (2)$$

where the parametrisation given in [6] is applied. Fig. 1 shows the experimental $B(E2)$-values divided by the calculated values obtained with Eq. 1. It can be seen that most of the experimental values agree with this simple fit within an error better than 20%.

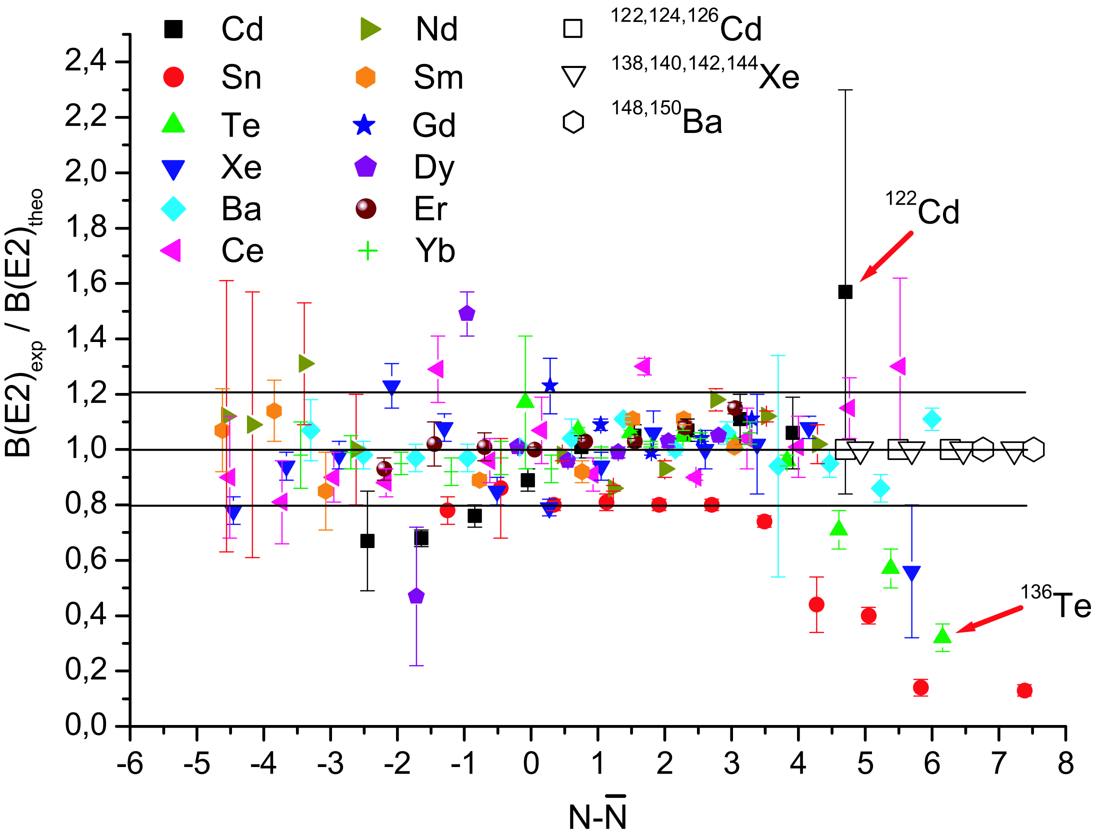

Figure 1: *Experimental $B(E2)$-values divided by values calculated with Eq. 1 (for ^{132}Sn this ratio is 3.2 and therefore outside of this diagram). Open symbols indicate nuclei which have been measured ($^{122,124,(126)}$Cd) in the experiment IS411 and nuclei which are proposed here to be measured.*

However, recent experiments in the surrounding of ^{132}Sn have shown that for very neutron-rich nuclei far off the valley of stability the $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$-values are even lower than the values expected from the extrapolation applying the improved formula given above. In particular, this is the case for Te and Sn isotopes near $N = 82$. The $B(E2)$-values for these neutron-rich isotopes measured at Oak Ridge [7], which were not known at the time of the previous proposal, are included in Fig. 1.

The irregular behaviour of ^{136}Te compared to ^{132}Te, a *decreasing* energy $E(2^+_1)$ is correlated with a *decreasing* $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$ and not, as it is normally the case and as it corresponds to a “natural” understanding of collectivity, with an *increasing* $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$, can be reproduced by QRPA calculations [8]. Essentially, a reduced neutron pairing above $N = 82$ compared to below causes this anomaly. It is interesting to note that this effect leads to a larger $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$-value in ^{132}Sn compared to the neighbouring isotopes ^{130,134}Sn, exactly what is seen in experiment [7].

2 Experiment

The nuclei of interest are studied with γ-spectroscopy following Coulomb excitation of the radioactive ions impinging on a target with similar A. Lighter targets give less excitation probability. Using heavier targets increases the elastic scattering into the particle detector, but the excitation probability cannot be increased much because the beam energy of REX is currently limited to ≈ 2.9 MeV/u.

The set-up consists of the MINIBALL array to detect γ-rays and the CD detector in forward direction for particles. The CD detector is a double-sided segmented Si detector (DSSSD). It has four quadrants, each of them is segmented in 16 annular stripes (ϑ-coordinate) on the front and in 12 radial segments (ϕ-coordinate) on the back. The CD detector enables a determination of the reaction kinematics and an improved Doppler correction of the γ-rays.

Depending on the scattering angle, either the scattered beam particle or the recoiling target nucleus is detected, but in some cases also both of them. Since they have nearly the same energies at the same angle, they cannot be distinguished by the kinematics. However, the cross section for Coulomb excitation is largest at small angles in the CM system. Therefore, the assignment of the detected nucleus or nuclei to projectile and/or target is done using the more probable alternative.

Downstream of the target a two-dimensional position-sensitive PPAC allows to control both the beam position and intensity. This detector is essential for focusing the beam and monitoring the experiment.

A major problem is created by isobaric contaminants in the beam, in particular Cs and, for the Cd, In. There are three different methods to determine the purity of the beam:

- Downstream of the target the beam is stopped in the beam dump. Decays of implanted ions are detected by a Ge detector. If the lifetimes of the beam particles are smaller or comparable to the time of measurement, the contaminants can be identified by their decay (if they decay with emission of a gamma-ray). The longest $T_{1/2}$ of interest in this proposal is 33.41 min of ^{138}Cs, all other isotopes (Cd, In, Cs, Xe, and Ba) have lifetimes below 1 min.

- A shutter in front of the laser of the RILIS, which will be used only for the Cd beam, can be closed every second supercycle of the PS Booster ("Laser ON/OFF"). Without the laser the isotope of interest is reduced in the beam and the counting rate decreases correspondingly. Additionally, the number of decays in the beam dump is reduced. The Coulomb excitation of the target is then mainly due to the contaminants in the beam which remain unaffected by the laser.

- A detector telescope consisting of a an ionisation chamber (ΔE detector) and a Si detector (E detector) is mounted on one of the neighbouring beam lines of REX. The beam can be switched to this beam line and analysed. In particular, this detector allows also to identify contaminants in the beam which have long lifetimes or are even stable and, therefore, offers information complementary to the beam dump detector.

All three methods have been utilised during the run of IS411 this year.

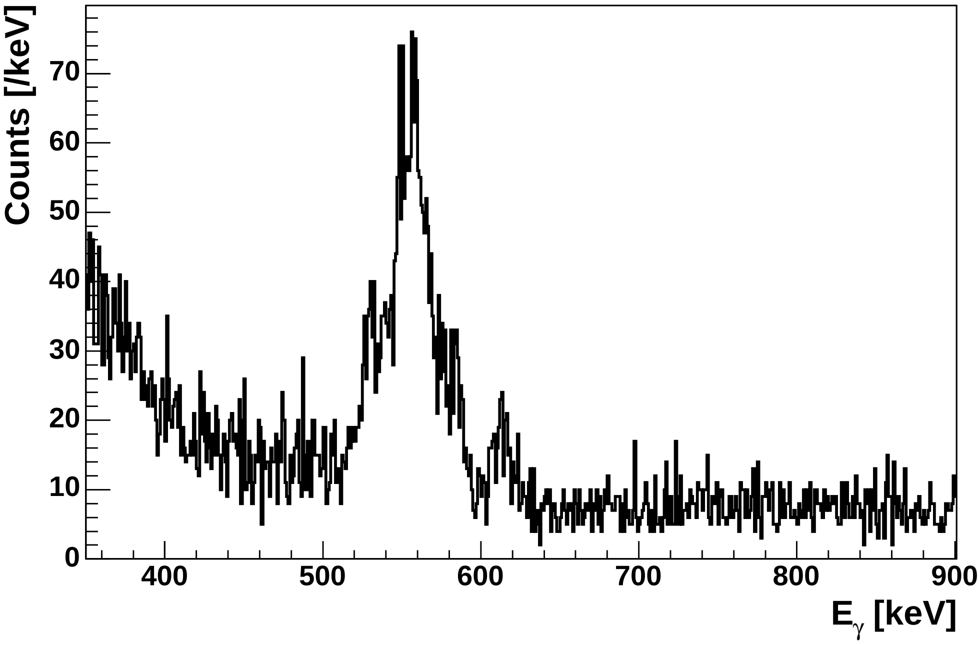

Figure 2: *Part of the statistics obtained for* ^{124}*Cd. A preliminary Doppler correction has been applied (see text). The* $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ *transition at 613.3 keV is clearly seen, as well as the wrongly Doppler corrected* $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ *transition at 555.8 keV in* ^{104}*Pd. No random coincidences have been subtracted from the spectrum.*

3 Status of experiment IS411

In August 2004, the first part of experiment IS411 (proposal [3]) has been performed successfully (12 shifts).
The isotope ^{122}Cd, the heaviest Cd isotope for which an experimental $B(E2)$-value is known, has been measured first in order to demonstrate the feasibility of the experiment and to obtain the $B(E2)$-value more precisely than the 50% error of the current value.
For the heavier isotope ^{124}Cd, the $B(E2; 0_{\mathrm{gs}}^+ \rightarrow 2_1^+)$ will be determined for the first time. Fig. 2 shows part ($\approx$ 20%) of the statistics obtained in the experiment. A preliminary Doppler correction with respect to the core positions of the MINIBALL detectors has been performed assuming that the scattered Cd nucleus as only particle is detected in the CD detector, an assumption which is justified for the selected angular range.
As a test, the isotope ^{126}Cd was measured for a couple of hours. Despite of problems with the control of the electrostatic optics of REX during this period, we were able to collect some statistics which show that the measurement of this nucleus is feasible.
Table 1 summarises the times with beam on target and preliminary values of the beam current and purity as well as the number of collected gamma-particle coincidences. Main contaminants were the respective In isotopes. For the ^{126}Cd beam even with the converter target $\approx$ 40% of the beam was ^{126}Cs.

Isotope	Laser ON [h]	Laser ON/OFF [h]	total [h]	total current [10^4 part/s]	beam purity [%]	counts ($2_1^+ \to 0_{\mathrm{gs}}^+$)
^{122}Cd	15.5	6	21.5	0.8 - 2	60 - 80	$\approx 1100^{\#}$
^{124}Cd	27	11	38	2 - 3	30 - 45	≈ 1200
^{126}Cd	6	2	8	≈ 1.5	≈ 9	≈ 100

Table 1: *Times with beam on target during the run of experiment IS411 in August 2004. The counts in the last column are collected during the runs with "Laser ON" ($^{\#}$ 9 h with ^{108}Pd target).*

Altogether we had 67.5 h (8.5 shifts) beam on target. Additionally, the beams were delivered for approximately 0.5 shift to the beam line with the IC/Si detector telescope. The remaining time was necessary to prepare the beam and to change between the different isotopes.

The production yields of the even isotopes $^{120-128}$Cd with the converter target and the RILIS have also been measured during this experiment. From a preliminary analysis of these yields and the obtained currents on target, the efficiency of REX for such heavy beams is estimated to be around a few per mill.

The detailed analysis of the data is on the way.

4 Proposed experiment

Sn and Te isotopes have been already studied extensively in this region [7]. Therefore we propose to study Cd (two protons less than Sn) as well as Xe (two protons more than Te) and Ba (four protons more than Te) in order to clarify if the anomalous behaviour observed in Sn and Te continues. These beams are only available at REX-ISOLDE. From theory it is expected that the pairing gap behaves as function of N for Cd as for Sn and for Xe as for Te [8]. In particular, this means that ^{138}Xe should be as anomalous as ^{136}Te. Furthermore, we will be able to study the Xe isotopes all the way to $N = 90$. Calculations of the pairing gap show a dip at $N = 88$ for $Z > 50$ [8] which has not been studied in Te, but can be reached for Xe and Ba.

In the first instance, we propose to complete the study of the isotope ^{126}Cd. The short test during the experiment IS411 has demonstrated that this measurement is feasible. At present the investigation of ^{128}Cd towards $N = 82$ is out of range, because the production rate for ^{128}Cd is a factor 7 weaker than for ^{126}Cd.

For the isotope ^{140}Xe, the lifetimes of the 2^+ and 4^+ states have been measured by β-γ-γ-coincidences [10]. The deduced $B(E2)$-value is well described by formula Eq. 1. It has to be noted that a second measurement resulted in a considerably smaller $B(E2)$-value for the 2^+ state which has been taken as adopted value in [2] and is shown in Fig. 1. However, for the estimate in Table 2 the values extrapolated following Eq. 1 have been used. We want to study the isotopes $^{138-144}$Xe in order to follow the structure of these nuclei above $N = 82$ and, in particular, to investigate possible anomalies at $N = 88$.

For Ba isotopes at $N > 86$, experimental data indicate a neutron pairing gap which decreases strongly above $N = 86$. However, theory predicts only the dip at $N = 88$ and an increase to $N = 90$ [8]. In fact, the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ of ^{144}Ba is lower than expected from the systematic trend given by Eq. 1 (see Fig. 1). Since Ba isotopes are more deformed than Te or Xe, such a study of $E(2^+_1)$ and $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ values will potentially provide some new insight into the interplay of deformation and pairing correlations as one moves away from the $Z = 50$ shell closure.

5 Rate estimate and beam time request

The isotopes are produced with a standard UC$_x$/graphite target irradiated with the proton beam from the PS Booster. In order to reduce the isobaric contaminants, in particular Cs in the Cd beam, the proton beam will be focused on a converter target. Usually, Xe beams are already very pure [13], therefore the use of a converter target is not mandatory, but increases the lifetime of the ISOLDE target and reduces the period after the experiment when the produced Rn has to abate [14]. The proton beam current is assumed to be 2 μA. The yields from ISOLDE are taken from [12, 13, 14], but the values given in Table 2 will be reduced roughly by a factor of 3 for the converter target [13, 14]. This factor is included in the rate estimate. For the Cd the RILIS will be used [12], whereas for the Xe the MK7 source [13]. Afterwards the ions are postaccelerated by the REX-ISOLDE facility. From our experience during the IS411 run this year, we estimate the efficiency of REX for such heavy beams to be $5 \cdot 10^{-3}$.

The large production yields of ^{138,140}Xe mean an average current of more than 200 pA into REXTRAP. Such a high current would cause space charge problems resulting in reduced trapping efficiency and a larger emittance to the EBIS due to less cooling [15]. The amount of charge collected in the trap becomes even larger for nuclei with high Z which require a longer breeding time in the EBIS. Conclusively, the measurement of ^{138,140}Xe has to be run at production rates reduced by a factor of 10-20 compared to the numbers given in Table 2 going down to values which have worked fine i.e. with ^{122}Cd. The reduced beam intensity is also required by the maximum rate the experiment, especially the CD detector, can accept. A further limitation for intense beams of radioactive noble gases which already occurred for some Kr isotopes is the radioactivity flowing into the primary pumps of REXTRAP. It is planned to address this problem by installing a balloon which recovers the radioactive gas coming from the trap [15].

The gamma yield is estimated from Coulomb excitation calculations [9]. We included the first 2^+ and 4^+ states in the calculations. The values of the reduced transition strength $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ are estimated applying Eq. 1. The $B(E2; 2^+_1 \rightarrow 4^+_1)$-values are calculated from the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-values in the vibrational limit for Cd and Xe, whereas in the rotational limit for Ba. The reorientation effect is included in the calculations as well.

As in the IS411 run this year, Pd targets of 2 mg/cm^2 thickness are assumed. The cross sections for Coulomb excitation of the first 2^+ and 4^+ states are approximately 2.5 b and 0.07 b for ^{104}Pd and 4.5 b and 0.3 b for ^{108}Pd, respectively. Hence, we will get counting rates from the excited target nuclei in the same order of magnitude as from the beam. The appropriate Pd isotope is chosen that the γ-transitions from the target do not coincide with transitions from the beam. The intensity of the transitions from the target is used

	^{126}Cd	^{128}Cd	^{138}Xe	^{140}Xe	^{142}Xe	^{144}Xe	^{148}Ba	^{150}Ba
$t_{1/2}$ [s]	0.507	0.34	844.8	23.6	1.22	1.15	0.607	0.3
$E(2_1^+)$ [keV]	652.2	645.	588.8	376.8	287.1	252.6	141.7	$95^{\#}$
$E(4_1^+)$ [keV]	1467.	1429.	1072.5	834.3	690.7	644.3	423.1	$315^{\#}$
$B(E2\uparrow)$ [$e^2\mathrm{b}^2$]	0.266	0.241	0.407	0.580	0.689	0.703	1.408	1.881
$\sigma_{\mathrm{CLX}}(2_1^+)$ [b]	1.01	0.96	1.44	3.16	4.32	4.65	8.00	9.29
$\sigma_{\mathrm{CLX}}(4_1^+)$ [b]	0.01	0.01	0.04	0.12	0.23	0.27	1.37	2.34
Y_{ISOLDE} [/μC]	$7\cdot 10^5$	10^5	$6\cdot 10^8$	$3.5\cdot 10^8$	$3.7\cdot 10^7$	10^6	$\approx 600^+$	?
$Y_\gamma(2_1^+\to 0_{\mathrm{gs}}^+)$ [/h]	8.6^*	1.2	10^4	$1.3\cdot 10^4$	$1.9\cdot 10^3$	57	?	?
shifts	15	/	1	1	1	4	/	/

Table 2: *Rate estimate and requested beam time for the isotopes proposed to be measured. The reduced transition strengths $B(E2;0_{\mathrm{gs}}^+\to 2_1^+)$, abbreviated as $B(E2\uparrow)$, are extrapolated applying Eq. 1 (* experimental rate has been ≈ 15 h^{-1}, $^+$ "minimum" [14], $^{\#}$ estimates taken from [11]).*

for normalisation, since the $B(E2)$-values are well known. The single rate of the CD detector will be below 100 Hz in average.

All calculations were done at an energy of 2.6 MeV/u. This takes into account the energy loss of beams at 2.8-2.9 MeV/u, the energies obtained in IS411, in a Pd target of 2 mg/cm^2 thickness. The cross section is integrated over the solid angle of the CD detector. An efficiency of 10% for MINIBALL in the range of interest and of 90% for the CD detector is assumed.

We are aiming at the determination of $B(E2)$-values within an error of around 10%. Therefore, we need at least 1000 counts in the γ-photopeak in coincidence with particles to have a statistical contribution to the total error of below 3%.

In the case of ^{126}Cd, we collected approximately 100 counts within 6 hours of beam. Therefore, we need 5 days (15 shifts) to complete the investigation of this nucleus including "Laser ON/OFF" measurements. Since we still have 9 shifts for IS411 available, we ask for an **additional 6 shifts** to complete the experiment.

Sufficient statistics can be obtained for the isotopes ^{138,140,142}Xe within 3 shifts and for ^{144}Xe within 4 shifts, in total **7 shifts** to measure the Xe isotopes.

Additionally, we ask for 3 shifts for each element to prepare the beam and in total 2 shifts for changing between the four Xe isotopes, together **8 shifts**.

We request in total 21 shifts (7 days) of beam time additional to the 9 shifts we have still available for IS411.

6 Request for target development

We would like to measure also the isotopes ^{148,150}Ba. The study of such neutron-rich Ba isotopes requires a special beam development, because atomic Ba$^+$ beams have a very large contamination from Cs. Since Cs decays into Ba, the prompt transitions from Ba will be interfered by Ba transitions following the β-decay of Cs. Therefore, we would like to use molecular BaF^+ beams. These can be easily separated from the Cs and later cracked in the EBIS. The production of such beams will be done with a standard UC_x/graphite target, a tungsten surface ioniser, and a "CF_4 leak" which allows to let in CF_4 into this special ISOLDE target [14]. We request to build and test such a target.

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