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Revised addendum to experiment IS411

Coulomb excitation of neutron-rich A $\approx$ 140 nuclei

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Abstract: This addendum is a resubmission of the addendum to experiment IS411 (INTC-P-156 Add. 1) with the proposal 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 this revised version we report preliminary B(E2) values for ^{122}Cd and ^{124}Cd and comment on isotope shift measurements in the region. In particular, as a continuation of the IS411 experiment at REX-ISOLDE with MINIBALL, we want to study the nuclei $^{138-144}$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

While the physics case has been already presented in INTC-P156 Add. 1, it is summarised here again for completeness and a subsection has been added discussing the isotope shift data in this context.

The aim of this experiment is to study the isospin dependence of $B(E2; 0^+_{\mathrm{gs}} \to 2^+_1)$-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 $B(E2; 0^+_{\mathrm{gs}} \to 2^+_1)$-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 $B(E2; 0^+_{\mathrm{gs}} \to 2^+_1)$-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_ν^2.

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:

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

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:

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

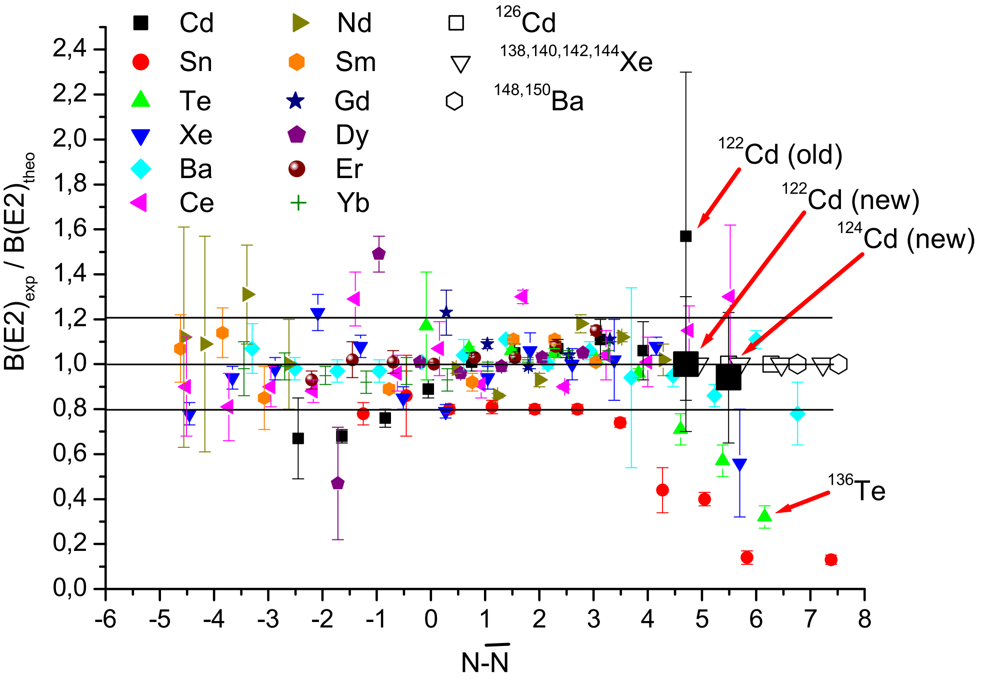

Figure 1: *Experimental $B(E2)$-values divided by values calculated with Eq. 1 (for ^{132}Sn this ratio is 3.2 and therefore outside of this diagram). The preliminary data points for $^{122,124}Cd$ are shown as larger squares. Open symbols indicate nuclei which are proposed here to be measured.*

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%.
However, recent experiments in the surrounding of ^{132}Sn have shown that for very neutron-rich nuclei far off the valley of stability the $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-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 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* $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ and not, as it is normally the case and as it corresponds to a “natural” understanding of collectivity, with an *increasing* $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$, 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 $B(E2; 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$-value in ^{132}Sn compared to the neighbouring isotopes ^{130,134}Sn, exactly what is seen in experiment [7].

1.1 Relation of isotope shifts and $B(E2)$ values

There is high quality data on isotope shifts available for the Sn, Xe, Cs, and Ba isotopes (see e.g. experiment IS383 [9, 10]), which shows a smooth trend for $\delta\langle r_c^2\rangle$ towards $N = 82$. After $N = 82$ the slope increases significantly. This slope change is also observed for the $N = 126$ shell closure in the Pb isotopes. This kink can naturally be reproduced in the relativistic mean field model using the NL3 interaction. It has been argued [11] that this kink is related to differences in the isovector spin-orbit force. A different interpretation suggests that it is related to the use of a density dependent pairing interaction (see e.g. [12]). Obviously, the case is not yet settled and no clear connection between this kink and the $B(E2)$ anomaly is visible [13].

Since there is no isotope shift data available for the Te isotopes, there is also no way to directly compare the $B(E2)$ anomaly observed in ^{136}Te with measured isotope shifts. If the theoretical interpretation of the reduced $B(E2)$ value in ^{136}Te is correct, the $B(E2)$ value is changed because of differences in neutron pairing and the charge density distribution is not necessarily affected. Thus one would not necessarily expect any visible effect on the isotope shifts. However, a direct connection can only be investigated if $B(E2)$ values and isotope shifts will become available for $N > 82$ isotopes in the same nuclei. By measuring $B(E2)$ values in the Xe and Ba isotopes, as proposed here, such a comparison would become possible.

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. It has to be noted that the condition for "safe" Coulomb excitation is fulfilled for all scattering angles.

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.

Isobaric contaminants in the beam are a minor problem for Xe beams compared to Cd

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

beams [22]. Nevertheless, the beam purity will be determined by two different methods: a Ge detector detecting decays of the ions implanted in the beam dump and a detector telescope consisting of an ionisation chamber (ΔE detector) and a Si detector (E detector). An improved version of the latter, which in 2004 was mounted on a different beam line, in 2005 will be included in the beam dump enabling a continuous monitoring of the beam contaminants.

3 Status of experiment IS411

3.1 Run in August 2004

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. For the heavier isotope ^{124}Cd, the $B(E2; 0_{gs}^+ \rightarrow 2_1^+)$ has been determined for the first time. 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 results from the data analysis.

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 the preliminary analysis of these yields and the determined luminosities (see Subsection below), the efficiency of REX for such heavy beams is estimated to be around a few per mill.

3.2 Status of data analysis

Fig. 2 shows part ($\approx 2/3$) of the statistics obtained for ^{124}Cd. So far the Doppler correction with respect to the core positions of the MINIBALL detectors has been performed

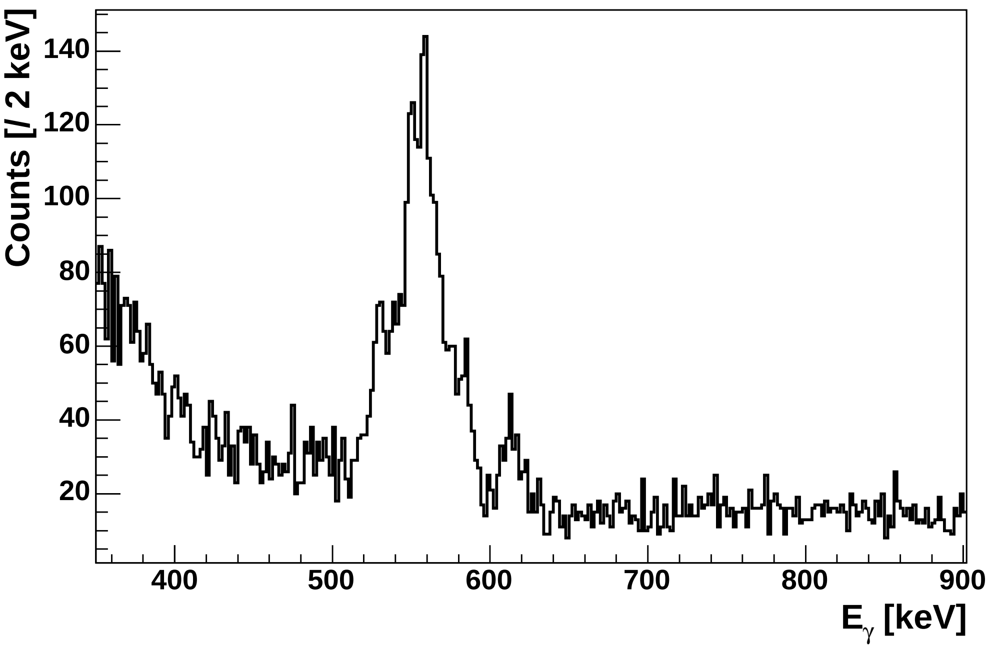

Figure 2: *Part of the statistics obtained for* ^{124}*Cd. A preliminary Doppler correction has been applied (see text). The* $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ *transition at 613.3 keV is clearly seen, as well as the wrongly Doppler corrected* $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ *transition at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

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.

The luminosities can be determined from the count rates for elastic scattering as well as Coulomb excitation of the Pd targets for which the matrix elements are well known. These processes have different angular distributions. A second observable is the ratio of events for which only the scattered beam nucleus was detected and events for which both the scattered beam nucleus and the recoiling target nucleus were detected. In Table 1, the maximum range of possible values for the beam intensities are given.

Currently, no consistent values for the luminosities have been extracted from the experimental data because the beam spot was not in the centre of the CD detector. The correction of this effect is on the way. The values determined from the Coulomb excitation of Pd are the values which are the least sensitive to the position of the beam spot, therefore we know the beam intensity currently within an error 25%.

The beam purities are determined from the relative peak intensities seen by the beam dump detector (except for ^{122}Cd which decays only to the ground state of ^{122}In) and from peak intensities for Coulomb excitation of the Pd as well as of the Cd recorded in the “Laser ON” and “Laser ON/OFF” modes, respectively. Because the latter does also depend on the actual range of scattering angles covered by the Cd detector, again no consistent values for the beam purities were found (see Table 1). The intensities

extracted from the beam dump detector may be affected by a correction due to dead time effects because its DGF was treated different to the other electronics. The IC/Si telescope detector has not been analysed quantitatively yet. However, since Cd and In are not clearly separated clearly, we expect not more than a moderate improvement of the accuracy. 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. Currently, the beam purity is known within an estimated error of 15%.
Our results for beam intensities and purities are included in Table 1.
It has to be noted that the relative efficiencies of both MINIBALL and the beam dump detector have been calibrated. The errors of the relative efficiency calibration small in comparison with other errors mentioned above. Since the excitation of Cd is analysed relative to the excitation of Pd, the absolute efficiency of MINIBALL, which has been determined as well, does not affect the result.
Up to now, 2/3 of the statistics is analysed which corresponds to several hundred counts in the peaks. Therefore, we estimate an additional error of 5% which comprises the statistical error, errors from the efficiency calibration and so on.
Altogether, combining the three errors given above, we estimate the error of our preliminary $B(E2)$ values at the current status of the analysis to be 30%. We anticipate that after optimising the luminosity analysis the total uncertainty will be about 10%.
The preliminary values of the reduced transition strengths $B(E2)$ for ^{122,124}Cd are $0.37 \pm 0.11\ e^2\mathrm{b}^2$ and $0.29 \pm 0.09\ e^2\mathrm{b}^2$, respectively. Together with the energies of the 2_1^+ states the ratios $B(E2)_{\mathrm{exp}}/B(E2)_{\mathrm{theo}}$ are 1.0 ± 0.3 and 0.94 ± 0.29. Hence, there are no significant deviation from the systematics. Our values have been included in in Fig. 1.

4 Proposed experiment

Sn and Te isotopes have been already studied extensively in this region [7]. Therefore we propose to study Xe (two protons more than Te) and Ba (four protons more than Te) isotopes 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 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.
For the isotope ^{140}Xe, the lifetimes of the 2^+ and 4^+ states have been measured by β-γ-γ-coincidences [15]. The deduced $B(E2)$-value is well described by 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]. 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 follow the trend for more collective nuclei. For ^{148}Ba a new measurement of the $B(E2)$ value has to be noted [16] which has been included in Fig. 1. For the heavier ^{150}Ba not even the excitation energy of the first 2^+ state is known [17, 18]. The study of these Ba isotopes potentially provides also some new insight into the interplay of deformation and pairing correlations as one moves away from the $Z = 50$ shell closure.

There are strong indications for octupole correlations in neutron-rich Ba isotopes [17]. For Xe isotopes the octupole correlations are lower than in the corresponding Ba nuclei [19]. These experimental findings are in accordance with theoretical predictions [20]. In particular, from experimental $B(E2)$ values the electric dipole moments D_0, one fingerprint of octupole deformation, can be determined. Therefore, the proposed measurement of $B(E2)$ values will contribute also to the study of octupole phenomena in neutron-rich Xe and Ba isotopes.

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. Usually, Xe beams are already very pure [22], 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 [23]. The proton beam current is assumed to be 2 μA. The yields from ISOLDE are taken from [21, 22, 23], but the values given in Table 2 will be reduced roughly by a factor of 3 for the converter target [22, 23]. This factor is included in the rate estimate. For the Xe the MK7 source will be used [22]. Afterwards the ions are postaccelerated by the REX-ISOLDE facility. From our experience during the IS411 run in 2004, 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 [24]. 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 [24].

The gamma yield is estimated from Coulomb excitation calculations [14]. 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 in 2004, Pd targets of 2 mg/cm^2 thickness are assumed. The cross

	^{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^2b^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	$15^\dagger$	/	1	1	1	4	/	/

Table 2: *Rate estimate and requested beam time for the Xe and Ba isotopes proposed to be measured. For comparison also the rates for neutron-rich Cd isotopes are given. 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 $\approx$ 15 h^{-1}, $^+$ "minimum" [23], $^{\#}$ estimates taken from [18], † already approved by the INTC).*

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 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%.

For the isotopes ^{138,140,142}Xe sufficient statistics can be obtained 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 to prepare the beam and in total 2 shifts for changing between the four Xe isotopes.

We request in total 12 shifts (4 days).

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 [23]. We request to build and test such a target.

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