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Addendum to experiment IS411

Coulomb excitation of neutron-rich A ≈ 140 nuclei

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Abstract: This is a addendum to experiment IS411 (INTC-P-156) aiming at the measurement of 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 continuation of our previous runs at REX-ISOLDE with MINIBALL, we propose to investigate the nuclei ^{140,148,150}Ba extending our studies towards more collective, maybe even octupole deformed, nuclei. A necessary step for the proposed experiment is the development of molecular BaF^+ beams. We report also on the status of the analysis of the previous runs of IS411 aiming at the Coulomb excitation of ^{122,124}Cd and ^{138,140,142}Xe. The experimental programme of IS411 will shed further light on the recently observed unexpected reduction of the $B(E2; 0^+_{\text{gs}} \rightarrow 2^+_1)$-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 the original proposal and the subsequent addenda, it is summarised here again for completeness.
The aim of this experiment is to study the isospin dependence of $B(E2; 0^+_{gs} \rightarrow 2^+_1)$-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 $B(E2; 0^+_{gs} \rightarrow 2^+_1)$-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 $B(E2; 0^+_{gs} \rightarrow 2^+_1)$-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:

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

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:

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

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

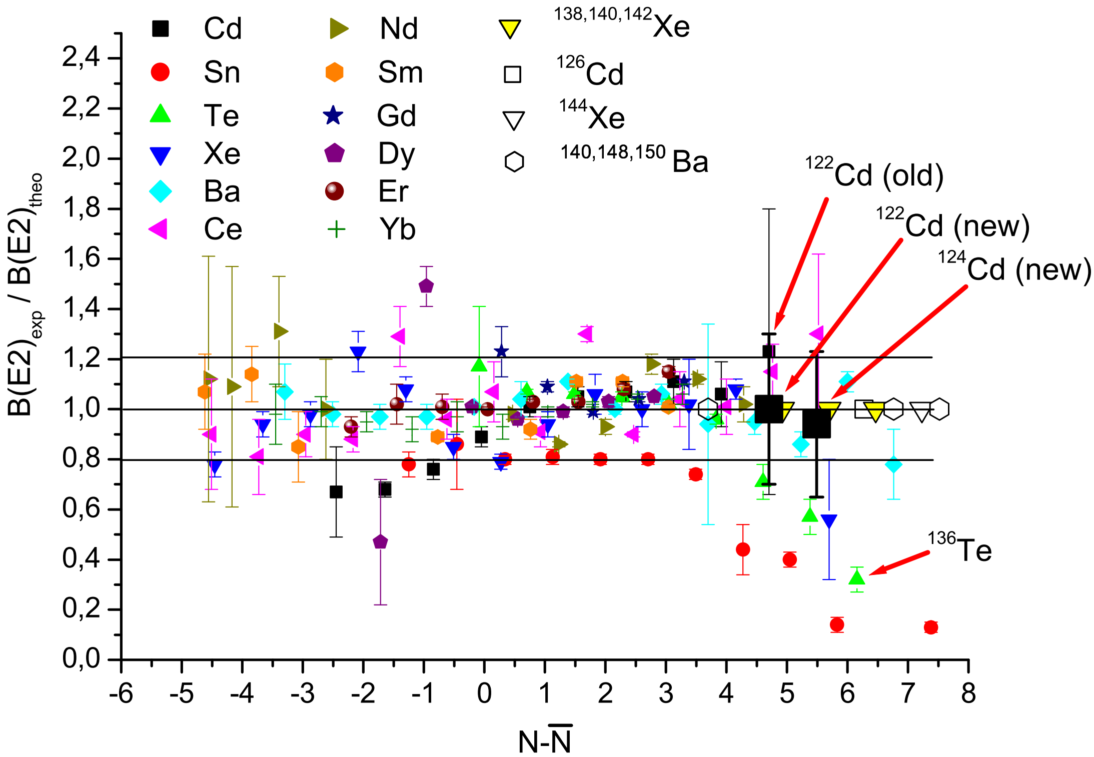

Figure 1: *Experimental $B(E2)$-values divided by values calculated with Eq. 1 (for ^{132}Sn this ratio is 3.2 and therefore outside of this diagram). Our preliminary data points for ^{122,124}Cd are shown as larger squares. ^{138,140,142}Xe have been measured in 2005. Open symbols indicate nuclei which are proposed to be measured.*

the experimental values agree with this simple fit to within ±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 $B(E2; 0^+_{\rm gs} \to 2^+_1)$-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 $N = 82$ [7]. A new measurement indicates 30% larger $B(E2)$ values [8] compared to the previous results, however still lower than the expectation from systematics.
The irregular behaviour of ^{136}Te compared to ^{132}Te, a *decreasing* energy $E(2^+_1)$ is correlated with a *decreasing* $B(E2; 0^+_{\rm gs} \to 2^+_1)$ and not, as it is normally the case and as it corresponds to a "natural" understanding of collectivity, with an *increasing* $B(E2; 0^+_{\rm gs} \to 2^+_1)$, can be reproduced by QRPA calculations [9]. 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 $B(E2; 0^+_{\rm gs} \to 2^+_1)$-value in ^{132}Sn compared to the neighbouring isotopes ^{130,134}Sn, exactly what is seen in experiment [7].
For Ba isotopes at $N > 86$, experimental neutron pairing gaps extracted from odd-even mass differences indicate a strong decrease above $N = 86$. However, theoretical HFB calculations with the Skyrme force SLy4 and an intermediate delta pairing force predict only the dip at $N = 88$ and an increase to $N = 90$ [9]. Aim of the experiments proposed

in this addendum is to test these predictions and their effect on the $B(E2)$ values.
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. This may shed new light on the physics lying beneath the systematical description given by Eq. 1.
Already in the previous addendum to the proposal IS411 (CERN-INTC-2005-011/P156 Add. 2) we discussed the possibility to relate $B(E2)$ values and isotope shifts for which high quality data are available for the Sn, Xe, Cs, and Ba isotopes (see e.g. experiment IS383 [10, 11]). We remind that a direct connection between the results obtained by these independent methods can only be investigated if both $B(E2)$ values and isotope shifts will become available for $N > 82$ isotopes in the same nuclei. By measuring $B(E2)$ values in the Ba isotopes, as proposed here, such a comparison would become possible.

2 Experimental method

The nuclei of interest are studied with γ-spectroscopy following Coulomb excitation of the radioactive ions impinging on a target with similar A (see below). 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. It has to be noted that the condition for "safe" Coulomb excitation is fulfilled for all scattering angles.
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. By choosing a target with sufficiently different mass compared to the beam, scattered beam particles and recoiling target nuclei can be distinguished by their different kinematics.
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.
By developing a molecular BaF^+ beam, as described in Section 5, there should be no isobaric contaminants anymore in the beam. Nevertheless, the beam purity will be checked 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 is under development.

3 Status of experiment IS411

3.1 Run in August 2004

In August 2004, the first part of experiment IS411 has been performed successfully (12 shifts). Details on this run have been already given in the previous addendum (INTC-P156 Add. 2).
Preliminary $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ values have been determined for the neutron-rich isotopes ^{122,124}Cd, for the latter for the first time. Both values agree well with the expectation from systematics given by Eq. 1.
Meanwhile the Doppler correction of the γ-rays with respect to the positions of the segments of the MINIBALL crystals has been completed improving the obtained resolution considerably. On the way is the final Doppler correction including the information from the pulse shape analysis. This will increase the effective granularity of the detectors and therefore the capability for Doppler correction further and will lead to highest-quality spectra.
The determination of the beam purity needs some further work which will be finished soon. These values then will be the last ingredient for our final results for the $B(E2)$ values in ^{122,124}Cd.

3.2 Run in September 2005

On September, 21-25, 2005, also the second part of experiment IS411 has been performed successfully.
The neutron-rich isotopes ^{138,140,142}Xe have been measured and spectra with very good statistics have been collected. For the isotope ^{140}Xe, for which two experimental $B(E2)$-values, differing by nearly a factor 2, are reported in literature [4], the experimental ambiguities will be resolved. For the isotopes ^{138,142}Xe, the $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ values will be determined for the first time.
For the analysis of these data, we have changed to a new data analysis system which will allow, after being implemented completely, a much more efficient and therefore faster analysis compared to the previously used system. The change of the analysis system, however, caused some delay in the process of analysis. As a first result, Fig. 3 shows part of the statistics obtained for ^{140}Xe where a preliminary Doppler correction has been applied to the data.
For ^{138,140}Xe we ran the PS Booster at $5 \cdot 10^{12}$ protons per pulse, for ^{142}Xe we used the maximum intensity of $2 \cdot 10^{13}$ protons per pulse. The Xe nuclei were ionised by the Mk7 ion source and were separated by the HRS. The breeding time in the EBIS was 198 ms to reach the charge state 34^+. Eventually, the Xe ions were postaccelerated by the linac to 2.83-2.85 MeV/u. Measurements with the IC/Si detector telescope, in 2005 mounted on the 0° degree beamline of REX, have shown no isobaric contaminants in the beam.
For all three beams we used a ^{96}Mo target of 1.7 mg/cm^2 thickness. The larger difference in mass between beam and target, compared to Pd targets as originally proposed, allowed a better distinction of both in the CD detector. In Fig. 2, the energy of the detected particles versus the angle in the laboratory system is shown. The two kinematical branches,

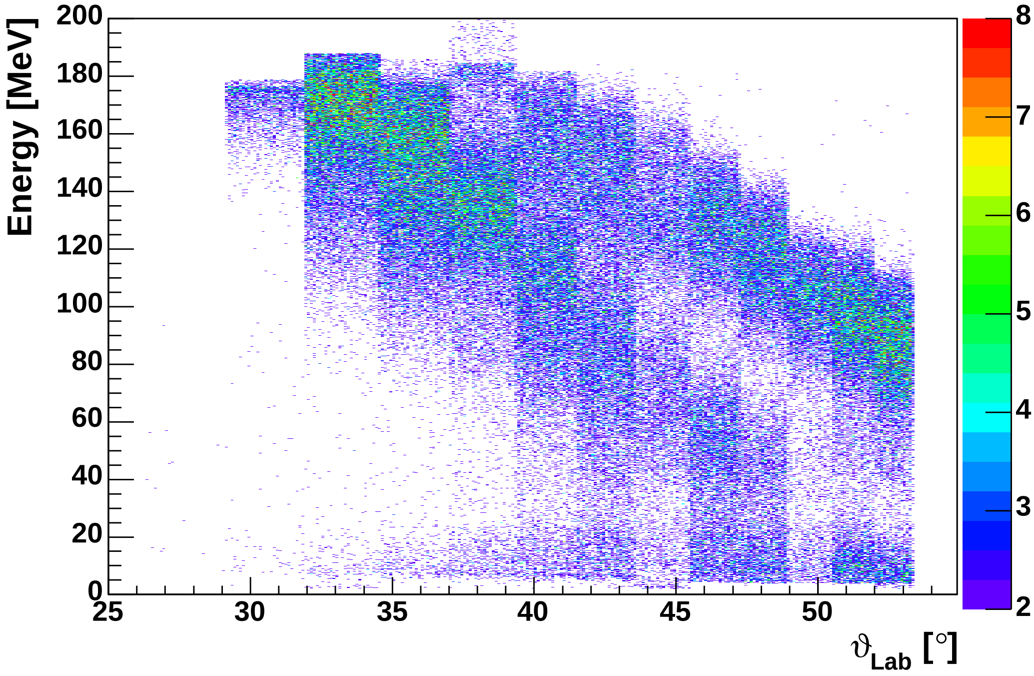

Figure 2: *Energy of particles detected in the CD detector versus angle in the laboratory system (see text for details).*

scattered projectiles (lower branch) and recoiling target nuclei (upper branch), are clearly separated. In order to reduce the counting rate in the CD detector due to elastic scattering by more than a factor 2, we shielded the inner 4 annular stripes, hence the sensitive angular range was limited from approximately 29° to 53° in the lab system. The yield for Coulomb excitation was reduced by approximately 30%, but the total count rate was optimised to our DAQ system. However, the energies of the beam particles below roughly 30° drove the preamplifier into saturation and the corresponding energies are omitted from Fig. 2. These data can partly be recovered using the kinematical correlation of the two particles.

Altogether we had 52 h (6.5 shifts) beam on target. Additionally, the beams were delivered for approximately 0.5 shift to the beam line with the IC/Si detector telescope. Approximately 2 shifts were needed to prepare the beam and 10 h for 3 changes of isotopes. Just before the last shift of the run a part of the IH structure of REX broke and the last scheduled shift had to be cancelled.

It has to be noted that considerable excitation probability of the 4^+ states is seen for ^{140,142}Xe, reflecting the increasing collectivity for increasing number of neutrons. Since this multiple Coulomb excitation affects the determination of the $B(E2; 0^+_{\mathrm{gs}} \to 2^+_1)$ values, we assured sufficient statistics also for the respective $4^+ \to 2^+$ transitions.

The measurement of the proposed isotope ^{144}Xe has been postponed to the next run because the lack of time to do the optimisation of the settings necessitated by the low

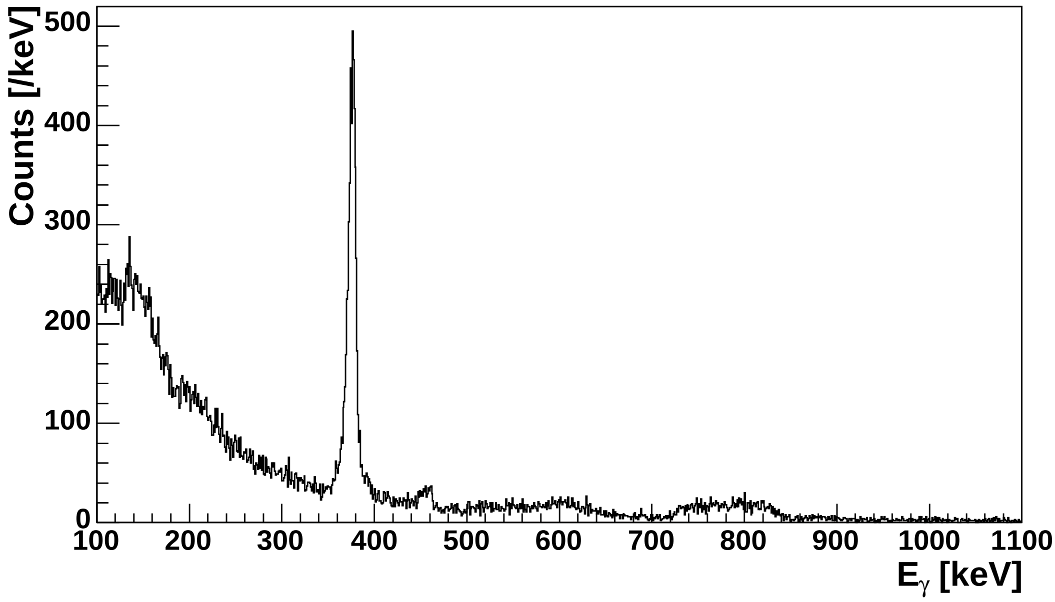

Figure 3: *Part of the statistics obtained for* ^{140}*Xe. A preliminary Doppler correction has been applied with respect to the positions of the segments. The transitions* $2^+_1 \rightarrow 0^+_{gs}$ *at* 376.7 *keV and the* $4^+_1 \rightarrow 2^+_{gs}$ *at* 457.6 *keV are seen, as well as the wrongly Doppler corrected* $2^+_1 \rightarrow 0^+_{gs}$ *transition at* 778.2 *keV in* ^{96}*Mo. No random coincidences have been subtracted from the spectrum.*

production rate of this nucleus. Additionally, one of the daughter nuclei has a long half life (^{144}Ce: $t_{1/2}$ = 284.9 d) and the impact on the following experiments due a possible contamination of the CD detector and the scattering chamber in terms of background rate has to be investigated carefully.

4 Proposed experiment

Sn and Te isotopes have been already studied extensively in this region [7]. We have already studied successfully Cd isotopes (two protons less than Sn) and Xe (two protons more than Te). These studies will be continued with the studies of ^{126}Cd and ^{144}Xe, both beam times are already approved by the INTC and beam time will be requested for 2006. These two are the most neutron-rich isotopes of these elements which are produced at rates suitable for Coulomb excitation studies. The planned upgrades of REX-ISOLDE will push these limits to more neutron-rich isotopes.
We propose to extend our studies to Ba isotopes (four protons more than Te) in order to clarify if the anomalous behaviour observed in Sn and Te continues.
The current situation for Ba isotopes is shown in Fig. 4. ^{146}Ba is the heaviest isotope for

which a $B(E2)$ has been measured. However, the $B(E2)$ value of ^{140}Ba is known only within an error of 50%. Since this isotope is of particular interest because it is just across the $N = 82$ closure, we propose to remeasure this $B(E2)$ value with higher precision. For ^{148}Ba a new measurement of the $B(E2)$ value has to be noted [13] which has been included in Figs. 1 and 4.
We propose to extend the study of neutron-rich Ba nuclei towards the more exotic isotopes ^{148,150}Ba. For the heavier ^{150}Ba not even the excitation energy of the first 2^+ state is known [14, 15]. These beams are only available at REX-ISOLDE. For lighter Ba isotopes beams are also available at Oak Ridge, but only at low intensities, i.e. 10^3/s for ^{142}Ba.

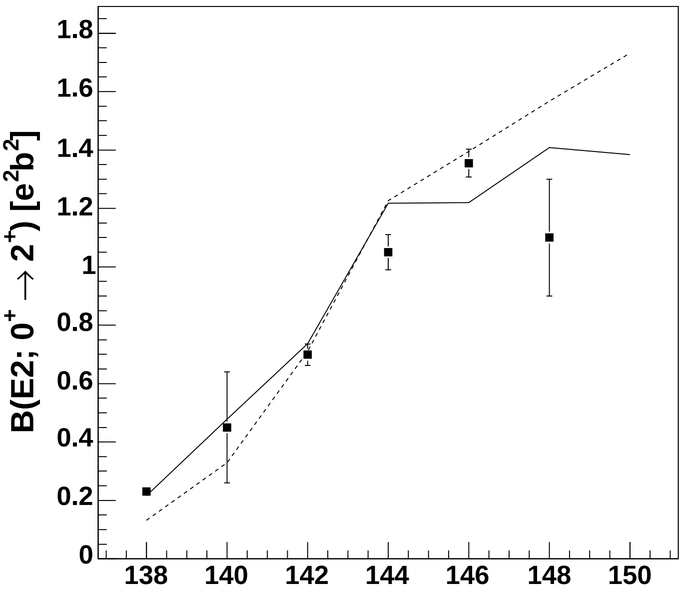

Figure 4: *Experimental $B(E2)$ values for neutron-rich Ba isotopes [2, 13]. Theoretical calculations [15] (dashed line) and expectations from systematics following Eq. 1 (solid line) are shown. The excitation energy of the 2^+ state in ^{150}Ba is taken from theory [15].*

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 [14]. For Xe isotopes the octupole correlations are lower than in the corresponding Ba nuclei [16]. These experimental findings are in accordance with theoretical predictions [17]. Therefore, our measurements of $B(E2)$ values will contribute also to the study of octupole phenomena in neutron-rich Xe and Ba isotopes.

5 Request for target development

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 separated from the Cs and other isobaric contaminants from ISOLDE. The molecules are later cracked in the EBIS. Pure Ba beams without any isobaric contamination will be produced in this way. However, the separation of BaF^+ from ions or molecules of the same mass, the behaviour in the trap, and the splitting in the EBIS have to be checked under realistic conditions, i.e. with protons on the ISOLDE target.
The production of BaF^+ 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 [18]. We request to build and test such a target.
This request has been already presented to the INTC in 2005 (CERN-INTC-2005-011/P156 Add. 2) and has been approved with "The Committee also encouraged the development of the Ba beams subject to the availability of beam development time at ISOLDE."

6 Required beam intensities and beam time request

The ions from ISOLDE are postaccelerated by the REX-ISOLDE facility. From our experience during the previous runs of IS411, we estimate the efficiency of REX for such heavy beams to be $5 \cdot 10^{-3}$.
The gamma yield is estimated from Coulomb excitation calculations [12]. The values of the reduced transition strength $B(E2; 0^+_{\mathrm{gs}} \to 2^+_1)$ are estimated applying Eq. 1. For further states the reduced matrix elements are extrapolated. For ^{140}Ba, we included the first 4^+ state and calculated the corresponding reduced matrix element in the harmonic oscillator limit. The level scheme of ^{148}Ba (as well as it is expected for ^{150}Ba) exhibits a rotational behaviour, therefore we extrapolated the reduced matrix elements for a rotational band up to the 8^+ state. The reorientation effect is included in the calculations as well.
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 Mo target of 1.7 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.
As in the IS411 run in 2005, a ^{96}Mo target is considered. The $2^+ \to 0^+_{\mathrm{gs}}$ transition is at 778.2 keV and therefore does not coincide with transitions from the beam. The intensity of the transitions from the target is used for normalisation, since the electromagnetic properties of ^{96}Mo are well known [4]. All transitions with known transition strengths in this nucleus have been taken into account. The cross section for Coulomb excitation of the first 2^+ state is approximately 0.8 b. In order to serve as a normalisation, the $2^+ \to 0^+_{\mathrm{gs}}$ transition is needed with similar statistics as the transitions from the beam.
We are aiming at the determination of $B(E2)$-values within an error of around 10%.

	^{140}Ba	^{148}Ba	^{150}Ba
$t_{1/2}$	12.75 d	0.61 s	0.3 s
$E(2_1^+)$ [keV]	602.4	141.7	129.1$^{\#}$
$E(4_1^+)$ [keV]	1130.6	423.1	433.6$^{\#}$
$B(E2\uparrow)_{\mathrm{exp}}$ [e^2b^2]	0.45 $\pm$ 0.19	/	/
$B(E2\uparrow)_{\mathrm{syst}}$ [e^2b^2]	0.478	1.408	1.881
$\sigma_{\mathrm{CLX}}(2_1^+)$ [b]	1.28	6.97	8.10
$\sigma_{\mathrm{CLX}}(4_1^+)$ [b]	0.06	1.03	1.51
Y_{ISOLDE} [/s]	$2.3 \cdot 10^6$	$4.3 \cdot 10^5$	$3.7 \cdot 10^5$
$Y_\gamma(2_1^+ \rightarrow 0_{\mathrm{gs}}^+)$ [/h]	50	50	50
$Y_\gamma(4_1^+ \rightarrow 2_1^+)$ [/h]	2.1	7.4	9.3
shifts	3	3	3

Table 1: *Required beam intensities and requested beam time for Ba isotopes proposed to be measured. The reduced transition strengths $B(E2; 0_{\mathrm{gs}}^+ \rightarrow 2_1^+)$, abbreviated as $B(E2\uparrow)$, are extrapolated applying Eq. 1 ($^{\#}$ theoretical values taken from [15]).*

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%.
Currently we do not know the actual production rate of the BaF^+ ions and the actual efficiency for cracking the molecules and later charge breeding in the EBIS. The values given in Table 1 are the *required* yields from ISOLDE in order to obtain a particle-γ rate of 50/h (or 1000 counts per day), assuming $5 \cdot 10^{-3}$ as an overall efficiency.
It has to be noted that for ^{148,150}Ba, the cross section for target excitation is nearly an order magnitude lower than for the beam. Therefore, the given minimum beam intensities should be regarded as lowest values. However, if the available yields for ^{148,150}Ba are below this limit, a more collective target can be used. E.g. for a ^{100}Mo target the cross section to excite its first 2^+ state at 535.6 keV, still high enough not to coincide with transitions from the beam, is approximately 2.9 b, hence a factor 3.5 can be gained.
The single rate of the CD detector will be below 100 Hz in average. Since currently the beam intensity is concentrated mainly in the first some 20 μs of each EBIS pulse, the instantaneous rate is much higher and has to be limited to avoid pile-ups. Additionally, only a few particles per pulse can be processed by the ADCs ($\approx$ 15 μs deadtime per event).
The implementation of the slow extraction from the EBIS will improve this situation. It will allow to accept also higher beam currents if available and to make more efficient use of the beams. It is therefore highly desirable, in particular, for beams with long breeding times and low EBIS rate.
If the production rates given in Table 1 can be reached, sufficient statistics are obtained within 3 shifts for each isotope, in total **9 shifts** to measure the Ba isotopes. Additionally, we ask for 6 shifts to prepare the beam and for changing between the isotopes.
We request in total 15 shifts (5 days).

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