EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

IS548: Evolution of quadrupole and octupole collectivity north-east of ^{132}Sn: the even Xe isotopes

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Abstract: We propose to study excited states in Xe isotopes north-east of the doubly-magic ^{132}Sn by γ-ray spectroscopy following "safe" Coulomb excitation. The experiment aims to the determine $B(E2)$ and $B(E3)$ values to follow the evolution of quadrupole and octupole collectivity when going away from the shell closures at $Z = 50$ and $N = 82$. In a first experimental campaign in 2016, the isotope ^{142}Xe has been measured with the MINIBALL & C-REX set-up.

Remaining shifts: [15] shifts
Installation: [MINIBALL + C-REX]

1 Motivation, experimental setup/technique

The region around the doubly-magic nucleus ^{132}Sn is the focus of many efforts in both experimental and theoretical nuclear physics. Since the astrophysical r process is expected to pass through this region, the understanding of the nuclear structure has also an impact on the description of the $A \approx 130$ peak in the solar element abundances[1].

Unlike the neighbouring Te isotopes ($Z = 52$), the even Xe isotopes ($Z = 54$) exhibit a very regular behaviour. The $B(E2, 0^+_{\mathrm{gs}} \rightarrow 2^+_1)$ values are symmetric with respect to $N = 82$ and the trend at higher neutron-rich numbers is well reproduced by a simple Grodzins-type systematics as well as by shell-model calculations [11, 12, 15].

Various approaches have been used to generate shell-model interactions capable of predicting the behavior of neutron-rich nuclei beyond $N = 82$ using either empirical approaches (e.g. SMPN) [21] or realistic free nucleon-nucleon potentials (e.g. CD-Bonn), renormalized by either G-matrix (e.g. CWG) [22] or $V_{low\,k}$ methods [20]. For Sn isotopes, the calculations with empirical interactions predict even a new shell closure at $N = 90$ as the $\nu f_{7/2}$ orbital is filled, whereas the calculations with realistic interactions do not find such an effect. The $\nu f_{7/2}$ orbit being filled beyond $N = 82$ has an interesting analogy with the Ca isotopic chain where a $\nu f_{7/2}$ orbital is filled between $N = 20$ and $N = 28$. There was the long-standing problem that realistic interactions were not able to reproduce the shell closure at $N = 28$. This has been resolved very recently by including three-body forces [23]. Indeed, including three-body forces a shell closure at $N = 90$ occuring in ^{140}Sn is predicted also by calculations based on realistic interactions (CWG3M) [24].

^{142}Xe has with $N = 88$ a so-called "magic" octupole number. For $Z = 56$ and $N = 88$, hence ^{144}Ba, the octupole correlations are expected to be strongest. A recently published large $B(E3)$ value for this nucleus, although with large error, seems to support this [2]. ^{142,144}Ba have been investigated at HIE-ISODE too, the analysis is ongoing [3]. In ^{142}Xe, candidates for negative parity states have been identified by prompt spectroscopy of fission fragments from the spontaneous fission of ^{248}Cm [18, 9].

The neighbouring ^{140}Xe has been studied too by the same method [18, 9] and more recently with ^{252}Cf [4]. In addition to negative parity states, for the first time in this region, also candidates for members of a γ-band have been found. This is supported by state-of-the-art shell model calculations [8].

However, no $B(E2)$ or $B(E3)$ values for the side bands in Xe are experimentally known.

$B(E2)$ values in $^{138-144}$Xe have been investigated by safe Coulomb excitation already at REX-ISOLDE [11, 12]. These data were taken in inverse kinematics, beam at 2.85 MeV/u on ^{96}Mo target, with only a CD detector in forward direction for particle detection. It turned out that multiple-step excitation processes (including the reorientation effect involving the diagonal matrix elements, hence the quadrupole moments) could not be treated very well in the analysis. The isotope ^{144}Xe has been measured only briefly and the statistics did not allow for an analysis relative to the target excitation resulting in a larger systematic error in addition to the large statistical error.

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[1] In 2017, for the first time observations confirmed a binary neutron star merger as an astrophysical site of the r-process with the light curves as indicator for the composition of isotopes produced and their decay [1].

An additional information was hoped to come from a different approach: lifetime measurements performed in prompt spectroscopy of fission fragments [15]. However, the errors of the extracted $B(E2)$ values - the sign of the transitional matrix element cannot be determined by this method - turned out to be too large to constrain the multiple-step Coulomb excitation analysis much more.

Hence, a new measurement will cover a larger angular range with C-REX and profit from the higher beam energy available at HIE-ISOLDE which allows for the use of a high-Z target. The method is safe Coulomb excitation with γ-ray spectroscopy applying MINIBALL and a coincident particle detection by the C-REX Si detector array.

2 Status report

The isotope ^{142}Xe has been investigated in 2016 at HIE-ISOLDE applying safe Coulomb excitation at an energy of 4.5 MeV/u [13, 14]. Gamma-rays have been detected by MINIBALL [28] and the coincident particles, scattered projectiles and recoiling target nuclei, have been detected by C-REX. C-REX is version of T-REX [29], optimised to perform Coulomb excitation experiments with a large angular coverage. It consists of a forward CD[2] ($22^\circ < \vartheta_{Lab} < 60^\circ$), and in backward direction a barrel detector and a backward CD ($105^\circ < \vartheta_{Lab} < 172^\circ$).

The analysis of the excitation probabilities is done relatively (a) to the target excitation and (b), for consistency, to our experimental $B(E2, 0^+_{gs} \rightarrow 2^+_1)$ value obtained from REX-ISOLDE [11, 12] as well as from the lifetime measured at EXILL [15].

Initially, a ^{196}Pt target was used with a thickness of 1.4 mg/cm^2 (lead targets are difficult to make with such a thickness). However, it turned out from a first quick analysis that the beam intensity was much lower than expected. Therefore, we switched after roughly a day to a thicker 4 mg/cm^2 target of ^{206}Pb. This recovers a part of the statistics, but there are also considerable drawbacks due to the blur of the particle energies: (a) worse Doppler correction of the γ-rays, (b) worse kinematical separation between scattered projectile and recoiling target in the forward CD and (c) an increased systematic error as the excitation probabilities depend on the beam energy. With this target we could take data for about 3.5 days until the production target was damaged and the experiment had to be stopped. The total beam intensity was around $1.15(5)\cdot 10^5$/s. This number was consistently deduced from the elastic scattering as well as from the Coulomb excitation of the first 2^+ state in ^{206}Pb. The latter confirms that the *absolute efficiency of MINIBALL* and the *MINIBALL-C-REX coincidence efficiency* are correctly known. The shift of the actual beam spot away from the centre of the set-up has been determined and considered in this analysis.

The beam contained only isobaric contaminants which are decay products of ^{142}Xe in the EBIS. From previous experiments we know that only products from the decay of the initial beam within the EBIS (not REX-TRAP) are transported further to the MINIBALL target station [25]. Solving the Bateman equations numerically for ^{142}Xe trapped in the EBIS during charge breeding, a ^{142}Xe content of 89% is calculated. The Coulomb excitation of ^{142}Cs and ^{142}Ba could be seen in the spectra, however there are fortunately no overlaps with the γ-rays assigned to ^{142}Xe. The intensity of the $2^+_1 \rightarrow 0^+_{gs}$ transition in ^{142}Ba from

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[2] The distance between forward CD and target is adjustable if more forward coverage is desired.

Coulomb excitation clearly seen in the spectrum is fully consistent with the calculated ^{142}Ba beam intensity (for the odd-odd ^{142}Cs the level scheme is complicated and no $B(E2)$ values are known [26]).

Hence, the ^{142}Xe beam intensity was 10^5/s which is factor of 10 lower than estimated in the proposal. The shorter run time was compensated by the thicker target, so the obtained statistics are a factor of 10 lower than estimated in the proposal.

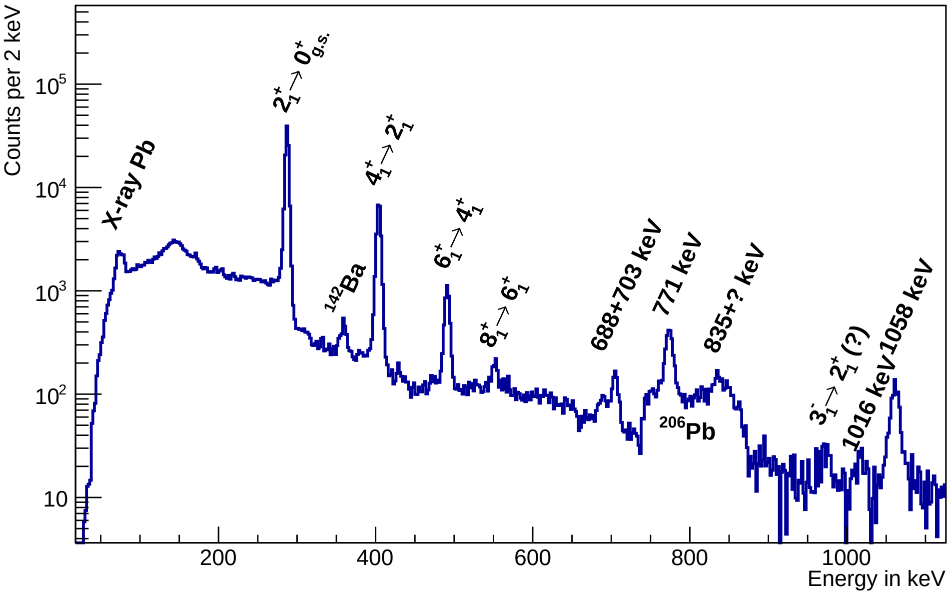

Figure 1: *Preliminary γ-ray spectrum Doppler corrected with respect to beam-like particles. Peaks with transitions energies are new.*

Fig. 1 shows a preliminary Doppler corrected γ-ray spectrum. It contains only part of the statistics as a conservative cut on the kinematical line of the projectile in the forward CD was set. The backward hemisphere will add only few statistics on a absolute scale, but the relative intensities will allow for a better analysis of multiple-step excitation.

The spectrum looks very similar to the spectrum obtained for the isobar ^{142}Ba [3]. Apart from the dominating transitions within the ground state band, several transitions are seen depopulating side bands of negative and positive parity. However, the low-spin level scheme of ^{142}Xe is much less known compared to ^{142}Ba.

Several new γ-transitions in ^{142}Xe have been observed. Some, unfortunately, overlap with the $2^+ \to 0^+$ transition in ^{206}Pb. The often useful argument that from the relative intensities observed following multiple-step Coulomb excitation already the ordering of the respective states can be deduced is only partially applicable if excitation and decay path are different!

Concerning the excitation of the (3^-) state, its decay at 971 keV (assigned in Ref. [18]) is seen only very weakly. This intensity is consistent with the expected ratio of the excitation cross sections of about 1/1000 compared to the first 2^+ state. Anything much larger would point to a much larger $B(E3)$ value which we consider as quite unphysical if compared to the systematics [19]. There are more transitions in this energy region of similar intensity which could be assigned to the decay of negative-parity states as well.

From this, we assume that the more stronger new transitions seem to belong rather to new positive-parity states. E.g. a state at 1058 keV which decays to the ground state (no coincidences seen) and to the 2_1^+ state at 287 keV (coincidences seen with 771 keV). The excitation probability would be inconsistently large for a 1^- state, hence it's rather a 2^+ state and therefore a good candidate for the head of a γ-band. However, gating on the 771 keV transition not only the $2_1^+ \to 0_{gs}^+$ transition is seen, but also the $4_1^+ \to 2_1^+$ transition indicating that the 771 keV transition is a doublet. Our preliminary findings have already initiated new state-of-the-art shell model calculations [27].

All this needs a closer look on the weak transitions (with best Doppler correction and background subtraction achievable), their coincidences and the excitation probability as function of the scattering angle. There is also the hope that new decay data from the neutron-induced fission of ^{232}Th (nuBall with LICORNE at IPN Orsay) allows for the observation of the feeding states. This may help to construct the level scheme.

For the strongly populated states of the ground-state band the statistics will allow for the determination of the diagonal matrix elements. For short-lived states, this quantity is only accessible by safe Coulomb excitation. The large statistics will also allow for a determination of the g factors applying the RIV method [6, 7]. Only for the 2_1^+ states of ^{140,142}Xe g factors are known [5] which had to be corrected as the lifetimes used in the original analysis were incorrect [15]. Theoretical predictions are in any case much too small compared to the experimental values.

The amount of information on the evolution of quadrupole and octupole collectivity in this region accessible by our approach cannot be obtained by other methods. Lifetime measurements do not allow for determination of diagonal matrix elements and, in most cases, also not of $B(E3)$ values. The low-lying states apart from the ground-state band in ^{142}Xe could not be investigated in prompt spectroscopy of fission fragments [15, 16, 17] because they are not populated. On the other hand, Coulomb excitation at intermediate beam energies turned out to be more difficult to be analysed than previously done, e.g. demonstrated for ^{136}Te at RIKEN [10]. But more important is the fact that excitations beyond the first 2^+ state are very suppressed.

Within this report, we do not discuss the isotope ^{136}Te, which was part of the original proposal and for which time had been requested to develop the beam at ISOLDE, as it has meanwhile been approved in another proposal (IS596) [32].

Accepted isotopes: ^{142}Xe
Performed studies: 15 shifts

3 Future plans

Future plans with available shifts:

(i) Envisaged measurements, beam energy, and requested isotopes

The analysis of ^{142}Xe is not finished yet. A second run with the same parameters will increase the total statistics by a factor 2-3 which may not help considerably. The use of the remaining 15 shifts to improve the data quality, e.g. by using a thinner target, or the sensitivity on particular parameters by using a different beam energy and/or a target material with a different Z will result in even lower statistics for the second data set. However, these two data sets can also not be just added up. We propose to go for an Addendum asking a full beamtime only when the most suited experiment to improve the quality of the results for ^{142}Xe concerning their significance for the physics interpretation can clearly be defined. This can take into account also possible new results for the level scheme from prompt spectroscopy of fission fragments. The analysis of the data has just started.

We ask to use the remaining 15 shifts for the study of ^{140,144}Xe.

The level scheme of ^{140}Xe is much better known than that of ^{142}Xe, in particular the side bands with both positive (except the 2^+_2 state, the band head of the candidate for a γ-band) and negative parity (build on an octupole vibration). The $B(E2, 0^+_{gs} \rightarrow 2^+_1)$ is very well known from a lifetime measurement giving an additional anchor point for the analysis [30]. However, no $B(E2)$ or $B(E3)$ values for the side bands are known [9, 8]. The yield for ^{140}Xe is, at least, a factor of 10 higher compared to ^{142}Xe. So, even using a thinner target a data set with 10 times more statistics compared to ^{140}Xe can be collected in 12 shifts.

As ^{140}Sn and ^{142}Te are absolutely out of reach for a Coulomb excitation experiment, the isotope ^{144}Xe is the isotone nearest to ^{140}Sn where $N = 90$ can be reached. A shell closure or no shell closure at $N = 90$ may have an effect on the systematic behaviour of the $B(E2)$ values. The yield for ^{144}Xe is about a factor of 10-30 lower compared to ^{142}Xe. Measuring compared to the 2016 run with ^{142}Xe three times shorter (3 shifts), around 30-100 times less statistics can be expected. Hence, there are several thousands of counts for the $2^+_1 \rightarrow 0^+_{gs}$ transition enabling to determine the $B(E2, 0^+_{gs} \rightarrow 2^+_1)$ value, one of the most significant properties to characterise an even-even nucleus, with a statistical error much less than 10%.

(ii) Have these studies been performed in the meantime by another group?

No. Beams of neutron-rich Xe isotopes at this energy are not available anywhere else.

(iii) Number of shifts (based on newest yields and latest REXEBIS and REXtrap efficiencies) required for each isotope

The Xe isotopes of interest are produced using a standard UC$_x$/graphite target irradiated with the proton beam from the PS Booster. As Xe is a noble gas, the cold plasma source will be used, e.g. [31].

In the original proposal, an expected yield of $3.7 \cdot 10^7/\mu$C was used [31]. With a proton current of 2 μA the expected max. beam intensity was estimated to be around $3.7 \cdot 10^6$/s assuming an efficiency of HIE-ISOLDE of 5 %. The loss due to the radioactive decay of ^{142}Xe within the EBIS is in the order of 10 %. The half-life of ^{140}Xe is much longer (13.6 s) and that of ^{144}Xe (1.15 s) is similar compared to ^{142}Xe (1.23 s).

The beam rate in 2016 was 10^5/s, hence an order of magnitude lower than expected, but roughly consistent with the more recent lower yield reported in the table. The difference between the two yields is presumably due to a lower target temperature which is recom-

Isotope	Yield (/μC)	Target - ion source	Shifts (8h)
^{140}Xe	$8 \cdot 10^7$	cold plasma	12
^{142}Xe	$2 - 7 \cdot 10^6$	cold plasma	
^{144}Xe	$1.8 \cdot 10^5$	protons on target, cold plasma	3
^{144}Xe	$9.4 \cdot 10^4$	protons on converter, cold plasma	

Table 1: Priv. communication by S. Rothe (ISOLDE-TISD).

mended for HIE-ISOLDE and was used in 2016 in order to enable a stable operation for a longer run.
Total remaining shifts: 15

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