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Coulomb excitation of neutron-rich ^{138,140,142}Xe at REX-ISOLDE

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Abstract. We report on “safe” Coulomb excitation of neutron-rich ^{138,140,142}Xe nuclei. The radioactive nuclei have been produced by ISOLDE at CERN and post-accelerated by the REX-ISOLDE facility. The γ-rays emitted by the decay of excited states have been detected by the MINIBALL array. Recent results are presented.

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1 Motivation

In our naive understanding of collectivity, large $B(E2)$ values of collective states are accompanied with low excitation energies, whereas less collective states with smaller $B(E2)$ values are found at higher excitation energies. The product between the excitation energy $E(2_1^+)$ of the first 2_1^+ state and the $B(E2; 0_{gs}^+ \to 2_1^+)$ value, in the following abbreviated as $B(E2\uparrow)$, in even-even nuclei has a smooth behaviour near to the valley of stability and can be described by a simple phenomenological formula, as Grodzins found already more than forty years ago [1].

A significantly improved description could be obtained by multiplying Raman's version [2] of Grodzins' formula with a function linear in $(N - \bar{N})$ [3]:

$$E(2_1^+)B(E2\uparrow) = \frac{2.57Z^2}{A^{2/3}}\left(1.288 - 0.088(N - \bar{N})\right), \quad (1)$$

where $E(2_1^+)$ is given in [keV] and $B(E2\uparrow)$ in [e^2b^2]. The neutron number $\bar{N}$ for which the nuclear mass within an isobaric chain reaches its minimum can be determined from the first derivative of Weizsäcker's mass formula:

$$\bar{N} = \frac{A}{2}\frac{1.0070 + 0.0128A^{2/3}}{1 + 0.0064A^{2/3}}. \quad (2)$$

For a large number of isotopes from Cd to Yb the experimental $B(E2)$ values agree with this simple fit within an error better than 20% (see e.g. [4]).

However, recent experiments in the vicinity of ^{132}Sn have shown that for neutron-rich nuclei far off the valley of stability the $B(E2)$ values are lower than expected from equation 1. In particular, this is the case for ^{132,134,136}Te and ^{126,128,130,134}Sn [5–7]. For the non-collective states in the magic Sn isotopes this is not unexpected, whereas for the Te isotopes it is. A new measurement for ^{136}Te indicates 30% larger $B(E2)$ values [8] compared to the previous results [5], however still lower than the expectation from systematics. In this context also a recent experiment aiming to determine the lifetime of the 2_1^+ state in ^{136}Te using the fast-timing technique has to be mentioned [9].

As theoretical explanation of this irregularity a reduced neutron pairing above $N = 82$ has been proposed [10]. QRPA calculations using the observed pairing gaps deduced from mass differences are able to reproduce the low $B(E2)$ values, in particular for ^{136}Te. Following this argumentation, collectivity in these very neutron-rich

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nuclei is build up mainly by neutrons resulting in low excitation energies accompanied by also low $B(E2)$ values, different to the naive understanding reflected in Grodzins' formula. Other theoretical approaches are the shell model, using a realistic effective interaction derived from the CD-Bonn nucleon-nucleon interaction (see [6] and a contribution to this conference [11]) or the Monte Carlo Shell Model [12]. However, the latter two approaches are not able to reproduce the reduction of the $B(E2)$ value in ^{136}Te completely.

Our aim is an extended investigation of this region which will provide a deeper insight into the physics behind this anomalous behaviour. In this contribution, we report on the study of the neutron-rich ^{138,140,142}Xe isotopes.

2 Experimental method and set-up

The radioactive nuclei were produced by the ISOLDE facility at CERN utilising spallation induced by the 1.4 GeV proton beam from the PS Booster impinging on a UC$_x$ target. For noble gases, the cold plasma ion source (Mk7) is used. From there the singly charged Xe ions were extracted, mass separated in the HRS, and transported to the REX-ISOLDE facility for post-accelaration [16].

The concept of REX consists of cooling and bunching of the ions in the Penning trap REX-TRAP, charge breeding in an Electron Beam Ion Source (EBIS), second mass separation, and post-acceleration in a LINAC. In our case, the charge breeding time in the EBIS was 189 ms to reach the charge state Xe^{34+} in order to meet the optimal value $A/q \approx 4$ for injection into the LINAC. Here, the energy of the ions is boosted from 60 keV to energies around 2.84 MeV/u. The status of REX-ISOLDE and the upcoming upgrade to HIE-ISOLDE have been presented in further contributions to this conference [17,18].

We studied the electromagnetic properties of the radioactive beams employing "safe" Coulomb excitation. The beam energy is low enough that beam and target nuclei keep a safety distance to assure that they interact only electromagnetically. From the yields of γ-rays deexciting the populated states the cross sections and eventually the reduced transition strengths, i.e. the $B(E2)$ values, are extracted. In order to reduce the uncertainties originating from the beam intensity and the various efficiencies, the excitation probability of the exotic beam is normalised to the excitation of the target whose electromagnetic properties are well known.

The γ-rays deexciting the excited states were detected by the highly efficient MINIBALL spectrometer consisting of 8 triple clusters of six-fold segmented HPGe detectors [19]. The fully digital electronics of MINIBALL allows an on-board implementation of online pulse shape analysis (PSA) which increases the effective granularity of the detectors further. The reaction kinematics was determined by detecting the scattered particles in a double-sided segmented Si detector (DSSSD) [20] in coincidence with the γ-rays.

Most beams produced at ISOL facilities are not pure beams, but contain isobaric contaminants. However, the Xe beams delivered by REX-ISOLDE are pure beams. The beam composition has been determined with a $\Delta E - E$ telescope consisting of an ionisation chamber and a Si detector and no isobaric contamination has been found.

More experiments at REX-ISOLDE with MINIBALL employing "safe" Coulomb excitation can be found also in further contributions to this conference [21,22].

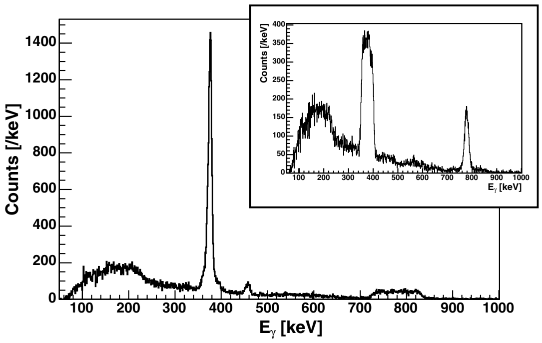

Fig. 1. Statistics obtained for ^{140}Xe. A preliminary Doppler correction has been applied (see text). The inset shows the same data, but Doppler corrected with respect to the recoiling ^{96}Mo nuclei.

3 Preliminary results

The Xe beams were delivered with intensities in the order of 10^5 particles/s. For all three beams, we used a ^{96}Mo target of 1.7 mg/cm^2 thickness.

Figure 1 shows the spectrum obtained for ^{140}Xe after 26 h of measurement. A preliminary Doppler correction has been performed with respect to the positions of the crystals of MINIBALL. The position information from the segments and the PSA has not been used so far. Clearly, the $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ transition at 376.7 keV and the $4_1^+ \rightarrow 2_1^+$ transition at 457.6 keV are seen. Performing the Doppler correction with respect to the recoiling target nuclei, the $2_1^+ \rightarrow 0_{\mathrm{gs}}^+$ transition at 778.2 keV in ^{96}Mo can be seen.

For ^{140}Xe two contradicting $B(E2)$ values obtained in β-delayed lifetime measurements are given in the literature [2,13]. Our preliminary value of 0.52 ± 0.1 e^2b^2 confirms the larger value given in [13]. For ^{138,142}Xe, $B(E2)$ values have been determined for the first time. Our preliminary values are 0.38 ± 0.1 e^2b^2 and 0.69 ± 0.1 e^2b^2, respectively [14]. Only for ^{138}Xe a theoretical prediction exists [10] but the value of 0.275 e^2b^2 is considerably lower than our experimental value.

With the same set-up at REX-ISOLDE we determined also $B(E2)$ values for neutron-rich Cd isotopes [4,14]. Already with our preliminary $B(E2)$ value we improved for ^{122}Cd the error compared to a previous measurement (note that a wrong $B(E2)$ value for ^{122}Cd is given in Raman's compilation [2], the correct $B(E2)$ value taken from [15] is shown in figure 2). For ^{124}Cd a $B(E2)$ value has been determined for the first time.

Figure 2 shows the $B(E2)$ values in the vicinity of ^{132}Sn normalised to the systematic values calculated with

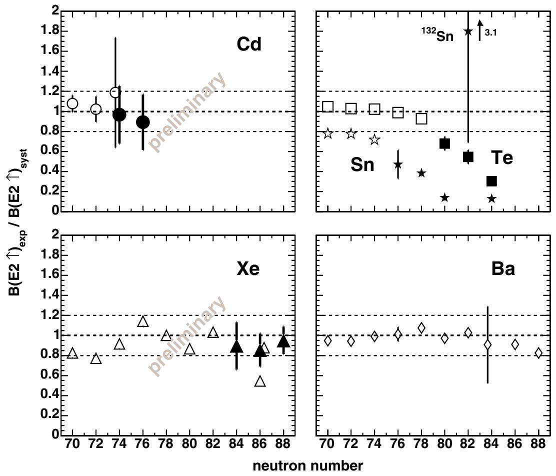

Fig. 2. Experimental $B(E2)$ values normalised to the systematic values calculated with equation (1). Shown are experimental values taken from [2] (open symbols), recent measurements of Te and Sn from [5,7] (filled symbols), and our preliminary results for Cd and Xe (filled symbols).

equation (1). ^{132}Sn is outside of the range of this plot, as expected the formula for collective states can not reproduce the $B(E2)$ values in a doubly-magic nucleus. It can be seen that our new preliminary $B(E2)$ values for Cd and Xe isotopes do not deviate dramatically, as it is the case in particular for the Te isotopes, from the simple systematics given by the modified Grodzins' rule equation (1).

A more direct probe for the neutron content in the wave function are g-factors. Taking into account that above $N = 28$ neutrons occupy the $f_{7/2}$ orbital, a negative g-factor is predicted for the 2_1^+ state in ^{136}Te [10, 12], different from the normal value $Z/A > 0$ for collective states. It has to be pointed out that it is therefore essential to determine the sign of the g-factor since the absolute values from both predictions are expected to be similar.

In order to determine the g-factor experimentally we apply the transient magnetic fields method [23] which is also sensitive to the sign in contrast to measurements already performed employing the recoil in vacuum method (see [24] and a contribution to this conference [25]).

The measurement of the g-factors of the 2_1^+ states in ^{132,134,136}Te and ^{138}Xe is planned [26]. The feasibility of such a measurement at REX-ISOLDE has been demonstrated recently with a ^{138}Xe beam, since Te beams at REX-ISOLDE are still under development. However, the statistics obtained in a short run was not sufficient to extract the g-factor. The results of these experiments can eventually prove if the low $B(E2)$ value of ^{136}Te is indeed due to a large neutron contribution in its wave function.

4 Outlook

Our programme will be continued with the determination of $B(E2)$ values in ^{126}Cd, ^{144}Xe, and neutron-rich Ba isotopes which are more, maybe even octupole, deformed. For the latter a strong isobaric contamination from Cs is expected. Because Cs decays to Ba this contamination is particularly disturbing and has to be suppressed completely. Therefore, a special ISOLDE target is under development, which allows to extract molecular BaF beams which can be separated from the Cs and later cracked in the EBIS to obtain an atomic Ba beam. Additionally, the g-factor measurements mentioned above will be performed in full statistics runs. It is worth to be mentioned that Cd, Xe, and Ba are beams unique to ISOLDE.

Such investigations will shed further light on the irregular behaviour of $B(E2)$ values in this region and allow deeper insights into the isospin dependence of neutron pairing as well as the underlying physics of the phenomenological systematics.

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