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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification to the ISOLDE and Neutron Time-of-Flight Committee

(Following Proposal P-609)

Complementary measurements of octupole collectivity in ^{146}Ce

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Abstract: This Letter of Clarification seeks to address a number of issues raised by the INTC regarding the proposal P-609, submitted to the June 2021 meeting.

Requested shifts: 17 shifts, (split into 1 runs over 1 years)
Installations: ISS with Si array and ionisation chamber + Miniball with CD

1 Questions from the INTC

The questions raised by the committee are copied here for clarity of presentation, and answered in separate paragraphs below.

1. All theoretical calculations presented in Fig. 1 of the proposal agree within the anticipated experimental uncertainties as well as with the existing experimental data. It is unclear what the impact of one more data point, albeit for a different isotopic chain is. The final result of the ^{142}Ba measurement would help to understand the strength of the physics case.

2. While the additional probe of the (d, d') for $E3$ transitions is certainly interesting, it remains unclear if this new/old technique would then be regularly applied to future studies of octupole collectivity at ISOLDE. Why are the authors proposing a new isotope, instead of studying first ^{142}Ba where they already have the Coulomb-excitation results.

3. The uncertainties introduced by the reaction model analysis, arising from optical model ambiguities or multi-step processes should be carefully investigated and evaluated.

1.1 Importance of the new measurements

The theoretical results referred to in the question are presented again in Figure 1 of this letter of clarification.

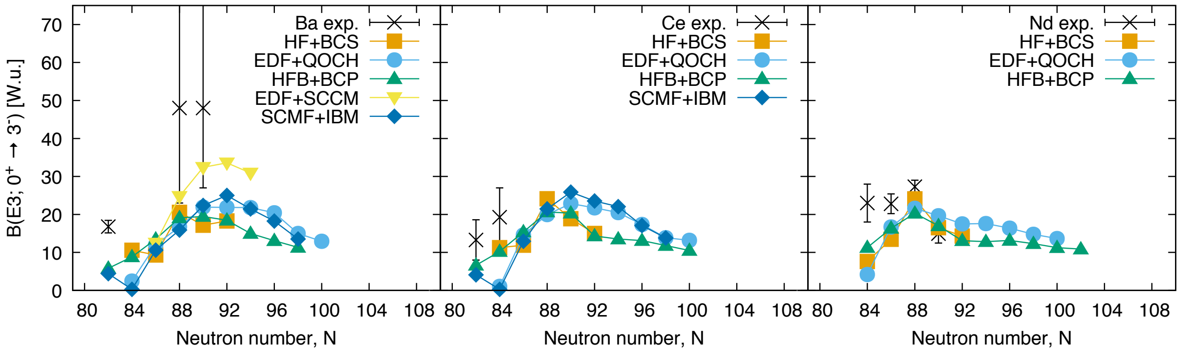

Figure 1: $B(E3; 0_1^+ \rightarrow 3_1^-)$ values in the neutron-rich Ba $(Z = 56)$, Ce $(Z = 58)$, and Nd $(Z = 60)$ isotopic chains. Experimental data from Refs [1–3] plus NNDC are shown in black. Five different theoretical predictions currently available in the literature are also shown; Ref. [4, 5] in orange, Ref. [6] in light blue, Refs. [7] in green, Ref. [8] in yellow and Ref. [9, 10] in dark blue.

We thank the committee for their comments on the current status of the experimental and theoretical $B(E3)$ values in this region. Indeed, the theoretical values generally predict similar qualitative behaviour and even agree quite well quantitatively for the three different isotopic chains shown. However, there is a drastic shortage of precision experimental data in the isotopes with $N \approx 88, 90$ where the $B(E3)$ values are predicted to be enhanced. The only data that exist so far are the values from Bucher et al. [1, 2] in the barium isotopes and Ibbotson et al. [11, 12] in the neodymium isotopes. The former of these, i.e. the barium isotopes, are too imprecise to draw any meaningful conclusions with respect to comparisons to theory or any claims of an enhanced transition strength. The latter, i.e. the neodymium isotopes, do not show a significant enhancement over the theoretical predictions or indeed the experimental values in the lighter isotopes, but $Z = 60$ is already expected by most theories to be beyond the maximum in terms of octupole correlations. As shown in a recent comprehensive study and review on octupole collectivity in the Xe, Ba, Ce and Nd isotopic chains using mean-field approaches [13], experiment is still lagging far behind theory in this region.

Claims of enhanced $B(E3; 0^+_1 \to 3^-_1)$ values were made by Bucher et al. [1, 2] and as such a previous measurement was proposed and carried out at HIE-ISOLDE to investigated ^{142,144}Ba with Miniball. At HIE-ISOLDE, these measurements proved rather challenging due to isobaric contamination and a multiple target failures which limited running time. Shifts for the ^{144}Ba measurement have been carried forward after LS2 and a more data will be collected to achieve a measurement of the $B(E3)$ value in that isotope, although it will be the highest mass achievable in the barium chain at ISOLDE due to limited the yields of ^{146}Ba and heavier isotopes. As the committee highlight, the resulting value from the ^{142}Ba ($N = 86$) experiment is finalised and is awaiting publication. Here, the $B(E3; 0^+_1 \to 3^-_1)$ is slightly larger than the theoretical predictions, but is consistent with the picture that the 3^-_1 state arises predominately due to a vibrational excitation from the ground state. However, if one is to look for octupole-deformed nuclei in this region, the focus has to be on those isotopes predicted to have the largest β_3 deformations and largest $B(E3; 0^+_1 \to 3^-_1)$ values. Those nuclei are ^{146,148}Ba, currently unreachable at HIE-ISOLDE, and ^{146,148}Ce, which represent the motivation of this project.

This collaboration has been instrumental in demonstrating that measurements of $B(E3)$ values in nuclei with enhanced octupole correlations are most effective when looking at their behaviour as a function of spin, and not just the transition from the ground state to the first-excited 3^- state. Our recent results on ^{222,228}Ra from HIE-ISOLDE [14] show clearly that key $E3$ matrix elements are indicative of vibrational or rotational-like excitations, such as $\langle 1^- || E3 || 4^+ \rangle$ and $\langle 2^+ || E3 || 3^- \rangle$. Recent theoretical studies, such as those from Ref. [10], reinforce the need to map out the $B(E3)$ strength not only as a function of N and Z, but also with spin, I. These results are plotted in Figure 2 for ^{142}Ba and ^{144}Ba as an example to show how dramatic the variations on $B(E3)$ values can be with spin and how a significant can be seen in the $B(E3; 1^-_1 \to 4^+_1)$, potentially indicating a transition from a vibrational-like structure to a more rigidly-deformed one. Further, one can also see differences in the enhancement of the $B(E2; 2^+_1 \to 5^-_1)$ value between the two isotopes. In order to measure these observables experimentally, a combination of complementary techniques sensitive to single-step and multi-step excitation pathways is necessary.

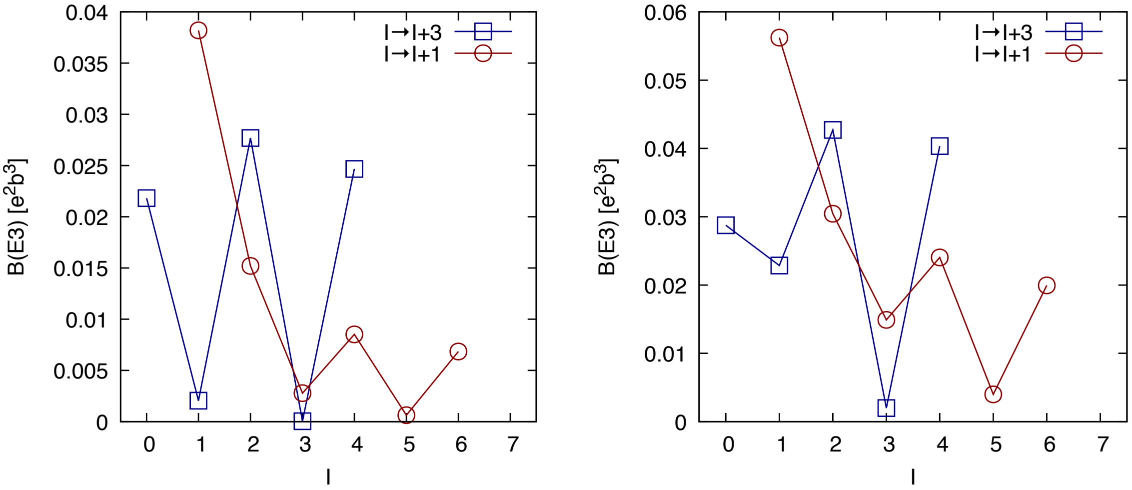

Figure 2: $B(E3)$ values as a function of spin, I, calculated in the framework described in Ref. [10], for ^{142}Ba (left) and ^{144}Ba (right).

1.2 Choice of ^{146}Ce over e.g. ^{142}Ba

The INTC is correct to not that the new/old probe of (d, d') is intended to be applied to future studies at HIE-ISOLDE, and potentially to studies utilising the SOLARIS spectrometer at FRIB to access isotopes and elements currently out of reach to the ISOL method. The key use cases that we have identified are in the lanthanide region, where the 3^-_1 excitation energy is higher than in the actinide region, reducing the excitation cross-section in the standard Coulex experiments; and in particular where γ-ray detection becomes challenging due to the large Compton backgrounds from the strongly-excited $E2$ transitions. The (d, d') probe avoids this and direct detection of the charged particle improves the efficiency to be competitive in terms of statistical precision. If successfully demonstrated, this new technique can give the first look at $B(E3; 0^+_1 \to 3^-_1)$ values in exotic isotopes and complement multi-step Coulomb-excitation experiments in the heavy actinide region where beams are now becoming available both at ReA6 at FRIB and HIE-ISOLDE [15].

The outstanding question is on the systematic uncertainties, as highlighted by the INTC's following question. In order to test the accuracy of the technique, one could indeed look to a case where Coulomb-excitation data already exists, e.g. ^{142}Ba, or one could try to simultaneously maximise the physics outputs at the same time. We have chosen to do the latter and the case of ^{146}Ce still provides an experimental benchmark that can be tested against, namely the $B(E2; 0^+_1 \to 2^+_1)$ value from fast-timing lifetime measurements [16], whilst also being one of the best candidates for octupole deformation in the neutron-rich lanthanide region [5, 17, 18]. Indeed, we have performed complementary measurements at TRIUMF using the GRIFFIN spectrometer to remeasure $\tau(2^+_1)$ to high precision with fast timing and additionally measure $\tau(3^-_1)$ for the first time [19]. The data is currently under analysis as part of a PhD project in Liverpool.

While the Coulomb-excitation part of this proposal has been optimised for multi-step excitation, the $B(E3; 0^+_1 \to 3^-_1)$ will still be determined, although not with the optimum

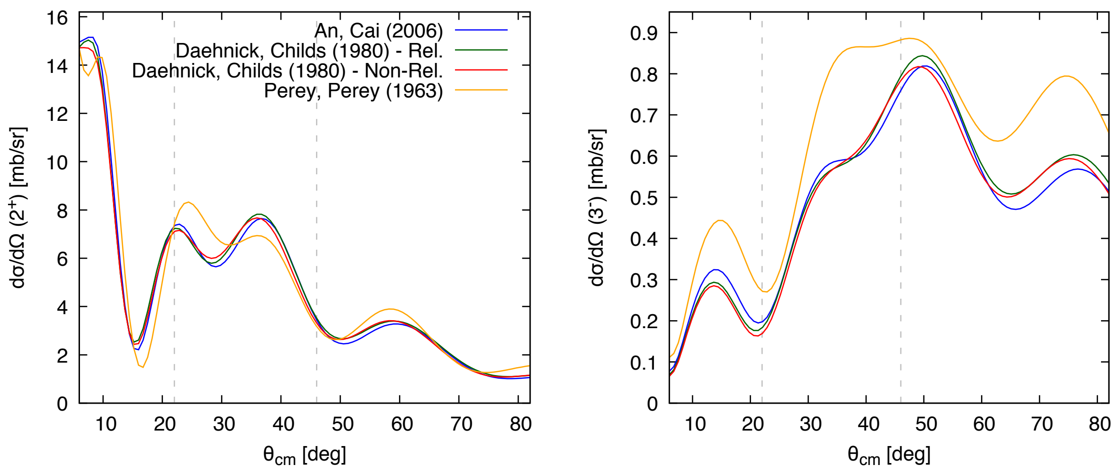

Figure 3: Comparison of calculated cross sections for excitation to the 2_1^+ (left) and 3_1^- (right) states for four different optical-model parameterisations from Refs. [20–22].

precision. Therefore, carrying out both complementary parts of this proposal will allow for further consistency checking between the different techniques. In summary, the choice of ^{146}Ce is a optimal to both extract the maximum physics output and demonstrate the applicability of the (d, d') technique.

1.3 Evaluation of model uncertainties

Uncertainties due to the reaction modelling, in particular the optical model parameters, are expected to be dominant over the statistical uncertainty in this technique and the INTC is right to highlight this issue. In order to begin investigating this issue, a number of global optical-model parameters from the literature have been compared in Fig. 3 and Fig. 4. Differences between the parameterisations are obvious, although the more modern evaluations have a greater consistency. A simultaneous measurement of the elastic scattering over the same angular range as the inelastic scattering to the 2^+ and 3^- states will be performed in this experiment, which can help to select the best set of model parameters (see left side of Fig. 4).

A preliminary quantitive analysis has been performed by integrating the cross-sections over the angular range covered in the proposed experiment and making comparisons. Using the optical-model parameters of Ref. [20], we obtain an excitation cross-section for the 3_1^- state of $\sigma = 0.53$ mb, while the two parameterisation from Ref. .[21] give $\sigma = 0.51$ mb and $\sigma = 0.50$ mb, and Ref. [22] gives $\sigma = 0.71$ mb. This corresponds to differences of 3.8%, 2.1% and 40%, respectively. For the 2_1^+ state these differences are 1.7%, 0.5% and 1.9%, respectively. If one instead looks at the ratio of the excitation cross-sections to the elastic scattering, for the 3_1^- state, the differences are 3.4%, 2.1% and 38%, respectively, which are similar to the difference in raw cross-sections. A full and detailed estimation of the systematic uncertainties stemming from these differences will be carried out as part of the data analysis.

On the question of multi-step excitation contributions to the (d, d') inelastic-scattering

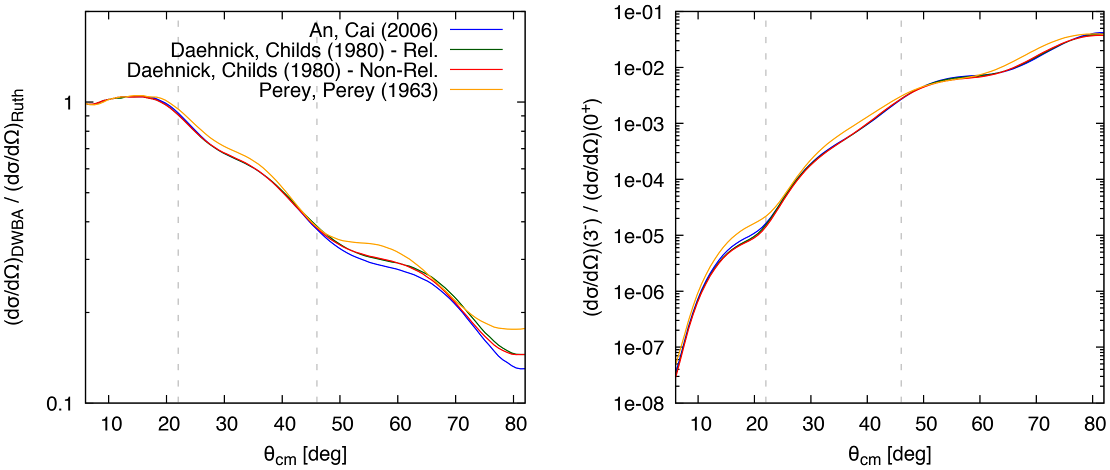

Figure 4: Calculated cross section ratios for elastic scattering to Rutherford (left) and for the 3^-_1 excitation to the elastic scattering (right). As in Fig 3, the comparison is for four different optical-model parameterisations from Refs. [20–22].

cross-sections, it has been found that these are below the 1% level for the 3^-_1 state under a range of assumptions for the $B(E3;2^+_1 \rightarrow 3^-_1)$ value and over a range of scattering angles. Similarly, the population of the 1^-_1 state via multi-step processes is also below 1% for a range of assumptions of the $B(E3;2^+_1 \rightarrow 1^-_1)$ value. This is consistent with the observation in previous experimental studies, e.g. ^{150}Sm. [23] which was performed at more backwards scattering angles than proposed here, so we would expect this effect to be even smaller. In the case of ^{226}Ra [24], the ratio of the cross-sections for the 1^-_1 and 3^-_1 states is 4.2% at 90°, which is again larger than the scattering angles proposed in this experiment. The analysis will nevertheless be carried out with a full coupled-channels code, such as FRESCO [25] or CHUCK-3 [26], in order to correctly consider these contributions, particularly since the 1^-_1 and 3^-_1 states will form an unresolved doublet in the proposed experiment.

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A Appendix

Figure 5 is a reprint of the simulated spectra from the original proposal with an additional cut to select larger centre-of-mass scattering angles where the peak of the 3_1^- excitation cross-section is.

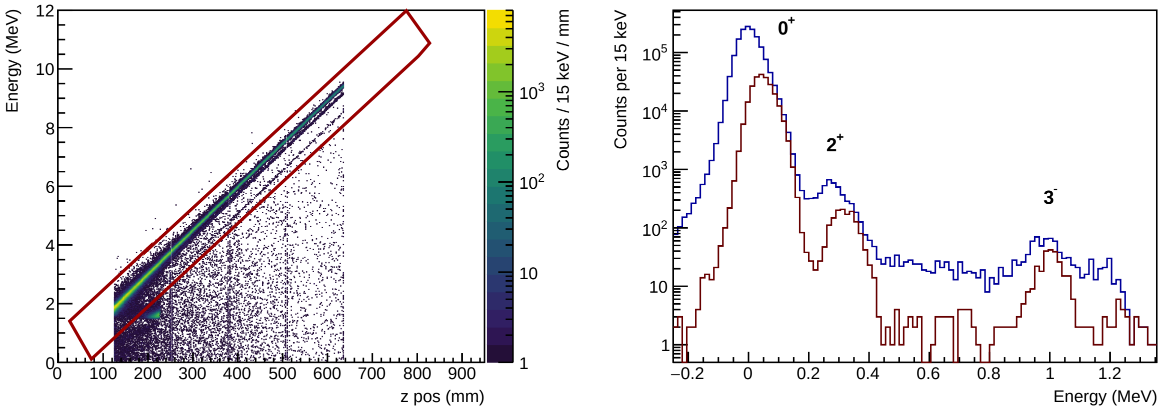

Figure 5: NPTool simulations as described in the text: (Left) Deuteron energy versus z position measured in the on-axis array. (Right - blue) The derived excitation energy spectrum for all events after applying the ROI cut indicated in red in the left panel. (Right - red) Same as the blue spectrum, but with the additional condition that the z position is greater than 400 mm.