Investigating the structure of the low–lying states in $^{140}\text{Ba}$

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Abstract. The neutron–rich $^{144-146}\text{Ba}$ isotopes have been studied recently in terms of their experimental $B(E3)$ values [1, 2]. Although featuring large uncertainties, the results were found to be significantly larger than any theoretical calculation. Similar questions exist for the slightly lighter isotope $^{140}\text{Ba}$, which is particularly interesting since it is located at the onset of octupole correlations. The lifetimes of the lower–lying states are completely unknown, with the sole exception of the first $2^+$ state [3].

In this work, we report on the outcome of a short test run, attempting to populate the states of interest using the $^{138}\text{Ba}(^{18}\text{O},^{16}\text{O})^{140}\text{Ba}$ reaction. The experiment was carried out at IFIN–HH using a specially manufactured nat$^{140}\text{Ba}$ target sandwiched between two Au layers. This was considered imperative due to Barium’s quick oxidation in air. Four beam energies (61, 63, 65, 67 MeV) below the Coulomb barrier have been tested. The subsequent $\gamma$ decay was measured using the Bucharest ROSPHERE array, consisting of 15 Ge detectors and 10 LaBr$_3$(Ce) scintillators.

The preliminary results from the test run report on the level population strengths and the limits in lifetime measurements, which are expected to provide new information on the structural effects in neutron–rich barium isotopes, especially regarding quadrupole and octupole degrees of freedom. The findings are also expected to act as stringent tests to theoretical modeling in this mass regime.

1. Introduction

The $^{140}\text{Ba}$ nucleus is particularly interesting because it is located at the onset of octupole correlations. Two neighbouring isotopes, the neutron–rich $^{144,146}\text{Ba}$ isotopes, were recently studied experimentally in terms of their $B(E3)$ values [1, 2], using radioactive beams and Coulomb excitation. The respective $B(E3)$ values, although featuring large uncertainties, were found to be significantly larger than any theoretical prediction. Consequently, a study of $^{140}\text{Ba}$ is important for establishing the onset of octupole correlation as well as assessing the degree of collectivity in the Barium isotopic chain as a function of the neutron number. Furthermore, the lifetimes of the lower–lying states of $^{140}\text{Ba}$ are unknown, with the sole exception of the first $2^+$ state, studied in [3]. Further measurements of lifetime values or lower/upper limits are
important, for studying the shape evolution and the strength of any quadrupole and octupole correlations.

Beyond lifetime measurements, cross section data related to the production of $^{140}$Ba, either absolute or relative, are also important for estimating the degree of level population of the reaction products. Such information is valuable for future measurements, regarding the reaction choice for the study of the particular isotope. In addition, experimental cross section data are still scarce for such reactions. Furthermore, Barium is a material that oxidizes very quickly when exposed on air, hence making the manufacturing of a target quite challenging.

In this work, we report on the relative cross sections of the 2$n$–transfer reaction $^{18}$O+$^{138}$Ba $\rightarrow$ $^{16}$O+$^{140}$Ba with respect to the fusion–evaporation reaction $^{18}$O+$^{138}$Ba $\rightarrow$ $^{152}$Gd+4$n$, as well as with respect to the total inelastic channel. These ratios can serve as a reference point for the theoretical studies, i.e. Optical Motel Potentials, as well as for further experimental studies using the same reactions. Furthermore, lower limits on lifetimes of the observed ground–state band states are reported by taking into consideration the limitations of the Doppler Shift Attenuation method (DSAM) [4, 5] for the particular system.

2. Experimental Details
The experiment was carried out at the 9 MV Tandem accelerator laboratory at the Horia Holubei National Institute of Physics and Nuclear Engineering (IFIN–HH), in Magurele, Romania. Four projectile energies were studied near the Coulomb barrier of the reaction, namely 61, 63, 65 and 67 MeV. The subsequent $\gamma$ decay was detected by the ROSPHERE array [6] using 15 HPGe detectors distributed over three rings.

As stated above, the manufacturing of a natural Barium target presents important difficulties, as it is a material that suffers from quick oxidation and brittleness. In order to prevent that, the target was made having a “sandwich–like” structure, using the vacuum evaporation technique at the Target laboratory of IFIN–HH [7]. The compound used was BaCO$_3$ powder, with the barium released on a thick gold backing of 4.88 mg cm$^{-2}$ by initiating a chemical reaction with Lanthanum, which was used as a reducing agent. A second evaporation of gold was performed right after, leading to a “sandwich-like” target, with barium between the two gold layers. This kind of structure significantly prevented barium oxidation. The respective thicknesses were: 0.5 mg cm$^{-2}$ for the front Au layer, 2 mg cm$^{-2}$ for the natBa layer (abundance of $^{138}$Ba = 71.698%), and 4.88 mg cm$^{-2}$ for the Au backing layer (see Fig. 1). The determination of the thick gold backing was done by weighing, while the other two layers were determined by calculating the thickness from the initial amount of the substance used.
3. Analysis and results

3.1. Lifetime lower limits
Lower limits on lifetimes of the states up to $8^+$ in the ground state band [8], corresponding to the observed transitions can be set, by taking into account the limitation of the Doppler Shift Attenuation Method (DSAM). In Fig. 2a, the two overlapping transitions of energies 528 and 530 keV are shown, depopulating the $4^+$ and $6^+$ states of the ground state band. As it can be seen for the spectra recorded in the backward (143°) and forward ring (37°), no visible lineshapes are induced. The same holds for Fig. 2b, where the transition of 808 keV is depopulating the $8^+$, also in the ground state band.

The maximum recoil velocity in the particular reaction mechanism is 2% the speed of light. At such recoil velocities, the range of lifetimes that can be measured with DSAM should be lower than approximately 1 ps. Further simulations have to be done in order to accurately set the limit, by using DSAM simulation codes.

3.2. Relative cross sections
The ratio of the cross sections of two reaction exit channels can be estimated with the relation:

$$\sigma_r = \frac{N_{R1}}{N_{R2}}$$

where $N_{R1}$ and $N_{R2}$ are the numbers of photodisintegrations feeding the ground state of the residual nuclei for the respective channels. These ratios can be easily determined by measuring the ratios of the areas of each photopeak feeding the ground state of the residuals, and by correcting with the detector efficiencies.

By extracting the ratios and taking into account the energy loss inside the Barium foil of the target using the SRIM2013 code [9], the results for the relative cross section of the two–neutron transfer reaction $^{18}$O+$^{138}$Ba $\rightarrow$ $^{16}$O+$^{140}$Ba with respect to the fusion–evaporation $^{18}$O+$^{138}$Ba $\rightarrow$ $^{152}$Gd+4n and the total inelastic channel are shown in Fig. 3a and Fig. 3b, respectively.

3.3. Theoretical calculations
Theoretical Calculations have been performed, using the codes GRAZING 9 [10] and PACE4 [11]. The former uses the grazing model [10], which has been proven successful for the description
Figure 3: Relative cross sections of the two neutron-transfer reaction \(^{18}\text{O} + ^{138}\text{Ba} \rightarrow ^{16}\text{O} + ^{140}\text{Ba}\) with respect to the fusion evaporation reaction \(^{18}\text{O} + ^{138}\text{Ba} \rightarrow ^{152}\text{Gd} + 4\text{n}\) (a) and with respect to the total inelastic channel \(^{18}\text{O} + ^{138}\text{Ba} \rightarrow ^{18}\text{O} + ^{138}\text{Ba}^*\) (b). Normalized cross section with respect to PACE4 calculations (c) and deduced cross section for the two-neutron transfer reaction (d). Energies and their respective errors have been deduced by SRIM2013 calculations for the energy loss inside the target for each beam energy. See text for a detailed discussion.

4. Discussion and future directions
Within the present framework, a feasibility study of the nucleus \(^{140}\text{Ba}\) has been performed. By considering the kinematics of the reaction studied and the limitation of DSAM, lower limits on the lifetimes of 3 states of the ground state band have been set over 1 ps. Of course, further studies are necessary in order to further constrain the above limit. The present results also sets the path for using a different technique for the measurement of the particular lifetimes, such
as the plunger technique or the fast–timing technique. For direct measurement of the reduced transition probabilities, especially for the $B(E3)$ corresponding to the first $3^-$ state, the use of radioactive beams and Coulomb excitation technique can override a lot of issues, such as possible target contamination and the level population strength.

The relative cross section ratios between the reactions $^{18}$O + $^{138}$Ba → $^{16}$O + $^{140}$Ba and $^{18}$O + $^{138}$Ba → $^{152}$Gd + 4$n$, have been deduced by taking into account the relative yield of the two observed transitions feeding the ground state of the two produced nuclei. The relative cross section behaviour seems to follow a reducing pattern across the 4 beam energies, showing that the fusion–evaporation channel becomes stronger at a greater rate, as we approach the Coulomb barrier. This is expected, as the reactions happen in the pure–tunnelling energy range.

The measurement of the cross section of the reaction $^{18}$O+$^{138}$Ba → $^{16}$O+$^{140}$Ba in the energy range 58-64 MeV has been attempted by normalizing the experimental counting rates of the $^{18}$O+$^{138}$Ba → $^{152}$Gd+4$n$ channel with respect to the highest energy PACE4 calculation, as shown in Fig. 3c. Then, by using the normalized cross section for the $^{18}$O+$^{138}$Ba → $^{152}$Gd+4$n$ and the cross section ratios, it was possible to extract the cross section for the $2n$–transfer reaction $^{18}$O+$^{138}$Ba → $^{16}$O+$^{140}$Ba. The results are shown in Fig. 3d.

In conclusion, the results provide useful information for the specific case study, either from the experimental or the theoretical point of view. $2n$–transfer reactions are a very useful tool to study moderately neutron–rich nuclei, and the use or the prediction the $2n$-transfer–to–fusion cross section ratio can benefit, for example, the reduction the fusion background, especially in nuclear structure studies. In addition, cross section ratios can help in constraining the optical model potential phenomenological parameters, in order to facilitate the better understanding of systems involving heavy–ion reactions.

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References
[1] Bucher B, Zhu S, Wu C Y, Janssens R V F, Cline D, Hayes A B, Albers M, Ayangeakaa A D, Butler P A, Campbell C M, Carpenter M P, Chiara C J, Clark J A, Crawford H L, Cromaz M, David H M, Dickerson C, Gregor E T, Harker J, Hoffman C R, Kay B P, Kondov F G, Korichi A, Lauritsen T, Macchiavelli A O, Pardo R C, Richard A, Riley M A, Savard G, Scheck M, Seweryniak D, Smith M K, Vondrasek R and Wiens A 2016 Phys. Rev. Lett. 116(11) 112503
[2] Bucher B, Zhu S, Wu C Y, Janssens R V F, Bernard R N, Robledo L M, Rodríguez T R, Cline D, Hayes A B, Ayangeakaa A D, Buckner M Q, Campbell C M, Carpenter M P, Clark J A, Crawford H L, David H M, Dickerson C, Harker J, Hoffman C R, Kay B P, Kondov F G, Lauritsen T, Macchiavelli A O, Pardo R C, Richard A, Riley M A, Savard G, Scheck M, Seweryniak D, Smith M K, Vondrasek R and Wiens A 2017 Phys. Rev. Lett. 118(15) 152504
[3] Bauer C, Behrens T, Bildstein V, Blazhev A, Bruyneel B, Butterworth J, Clément E, Coquard L, Egido J L, Ekström A, Fitzpatrick C R, Fransen C, Gernhäuser R, Habs D, Hess H, Leske J, Kröll T, Krücken R, Lutter R, Marley P, Möller T, Otsuka T, Patronis N, Petts A, Pietralla N, Rodríguez T R, Shimizu N, Stahl C, Stefanescu I, Stora T, Thirolf P G, Voulot D, van de Walle J, Warr N, Wenander F and Wiens A 2012 Phys. Rev. C 86(3) 034310
[4] Alexander T K and Forster J S 1978 Lifetime Measurements of Excited Nuclear Levels by Doppler-Shift Methods (Boston, MA: Springer US) pp 197–331 ISBN 978-1-4757-4401-9
[5] Petkov P, Tonev D, Gableske J, Dewald A and von Brentano P 1999 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 437 274 – 281 ISSN 0168-9002
[6] Bucurescu D, Cta-Danil I, Ciocan G, Costache C, Deleanu D, Dima R, Filipescu D, Florea N, Ghi D, Glocariu T, Ivacu M, Lie R, Mrginean N, Mrginean R, Mihai C, Negret A, Ni C, Olcei A, Pascu S, Sava T, Stroe L, erban A, uvil R, Toma S, Zamfir N, Cta-Danil G, Gheorghe I, Mitu I, Suliman G, Ur C, Braunroth T, Dewald A, Fransen C, Bruce A, Podolyk Z, Regan P and Roberts O 2016 Nuclear Instruments and
Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 837 1 – 10 ISSN 0168-9002

[7] Florea N M, Stroe L, Mărginean R, Ghiță D G, Bucurescu D, Badea M, Costache C, Lică R, Mărginean N, Moșu D V, Niță C R, Pascu S and Sava T 2015 Journal of Radioanalytical and Nuclear Chemistry 305 707–711 ISSN 1588-2780

[8] accessed 2019 The Evaluated Nuclear Structure Data File (ENDSF), http://www.nndc.bnl.gov/endsf/ URL http://www.nndc.bnl.gov/endsf/

[9] Ziegler J F, Ziegler M and Biersack J 2010 Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268 1818 – 1823 ISSN 0168-583X 19th International Conference on Ion Beam Analysis URL http://www.sciencedirect.com/science/article/pii/S0168583X10001862

[10] Winther A 1994 Nuclear Physics A 572 191 – 235 ISSN 0375-9474

[11] Gavron A 1980 Phys. Rev. C 21(1) 230–236

[12] Samarin V V 2013 Bulletin of the Russian Academy of Sciences: Physics 77 820–824 ISSN 1934-9432

[13] Bass R 1977 Phys. Rev. Lett. 39(5) 265–268

[14] Reisdorf W 1994 Journal of Physics G: Nuclear and Particle Physics 20 1297–1353