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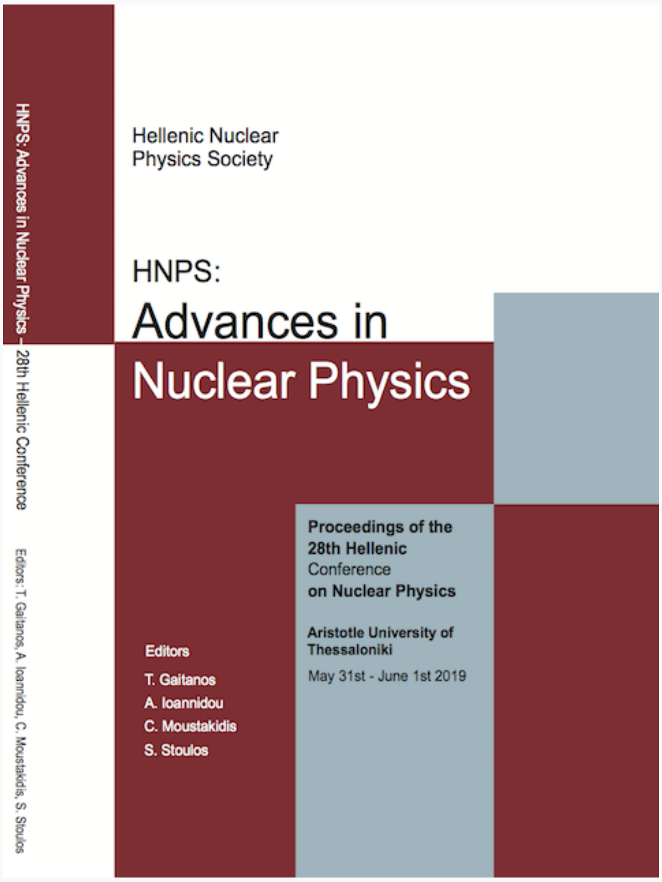


# Investigating the structure of the low-lying states in 140Ba

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# Investigating the structure of the low-lying states in $^{140}$Ba

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**Abstract** *The neutron-rich $^{144,146}$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 $^{140}$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 $^{138}$Ba($^{18}$O,$^{16}$O)$^{140}$Ba reaction. The experiment was carried out at IFIN-HH using a specially manufactured $^{nat}$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, and 67 MeV) below the Coulomb barrier have been tested. The subsequent 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–nrich 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.*

**Keywords** *$^{140}$Ba, 2n-transfer, cross section, lifetimes, neutron-rich*

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## INTRODUCTION

The $^{140}$Ba nucleus is particularly interesting because it is located at the onset of octupole correlations. Two neighbouring isotopes, the neutron-rich $^{144,146}$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 $^{140}$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 $^{140}$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 pursuing a dedicated experiment of lifetime measurements, it is important to know excitation probabilities in the production reaction involved. Cross–section data related to the production of $^{140}$Ba, either absolute or relative, are important for estimating the degree of level population of the reaction products, in particular because 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 2n–transfer reaction

$^{138}$Ba($^{18}$O,$^{16}$O)$^{140}$Ba relative to the antagonistic fusion–evaporation reaction $^{138}$Ba($^{18}$O,4$n$)$^{152}$Gd. 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.

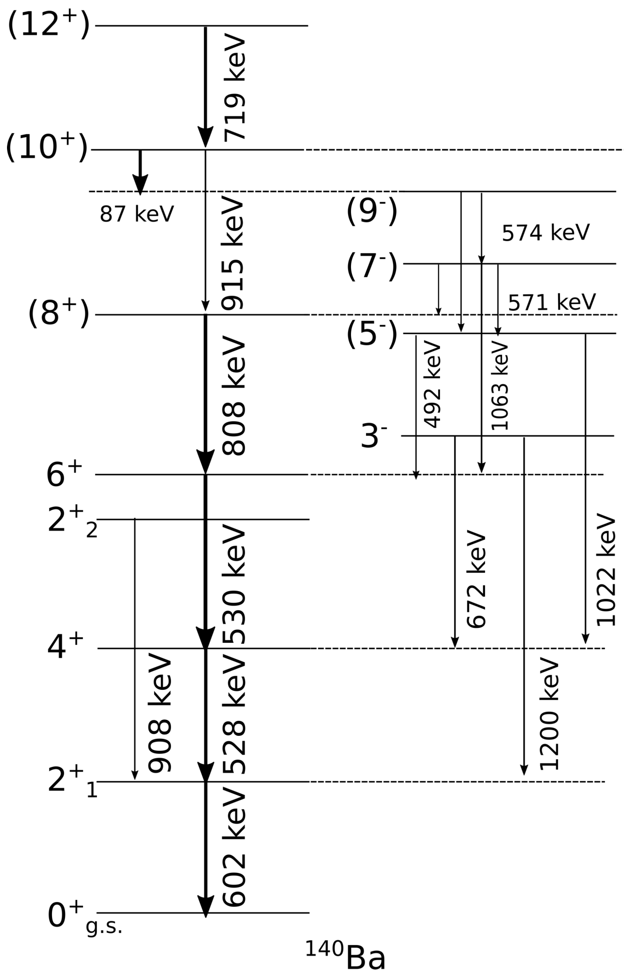


**Figure 1**. *Partial level scheme of $^{140}$Ba, showing the ground state band and the side band [6]. The alternating parity of the states of two bands is a hint for significant octupole correlations.*

## 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  decay was detected by the ROSPHERE array [7] using 15 HPGe detectors distributed over three rings.

As mentioned above, the manufacturing of a natural barium target presents important difficulties, as it is a material that suffers from quick oxidation. In the present case, a sandwiched $^{nat}$Ba target was prepared at the target laboratory of IFIN–HH [8], through a reduction–distillation method starting

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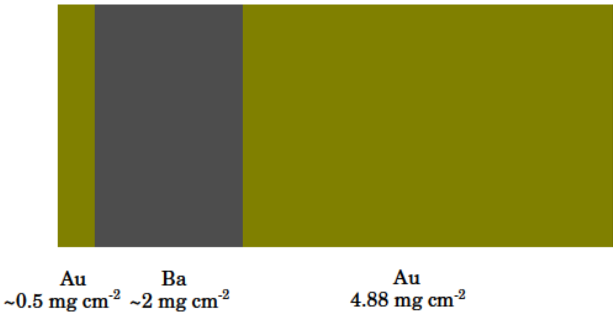
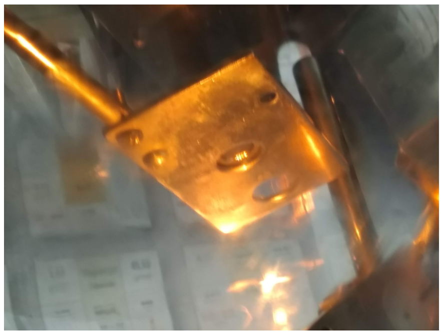
from $BaCO_3$ powder and with La metal powder as reducing agent using a gold backing. The obtained $^{nat}$Ba layer was covered with a thin gold layer of without breaking the vacuum, to protect the metallic $^{nat}$Ba against oxidation. The thicknesses were: ≈0.5 mg/cm$^2$ for the front Au layer, ≈2 mg/cm$^2$ for the $^{nat}$Ba layer (abundance of $^{138}$Ba = 71.698%), and 4.88 mg/cm$^2$ for the Au backing layer (see Fig. 2), respectively. The determination of the thick gold backing thickness was done by weighing, while the other two layers were determined by calculating the thickness from the initial amount of the substance used.




(a)



(b)

**Figure 2**. *Target layout in scale (left) and a picture during the evaporation procedure (right).*

During analysis, the data events collected were formed into angular distribution cubes, and then projected to each of the three rings HPGe rings, at angles of 37°, 90° and 143°, respectively. The full projection of a γγ-matrix is shown in Fig. 3a, while in Fig. 3b, the coincidence spectrum is projected by gating on the $2^+_1 \rightarrow 0^+_{g.s.}$ transition of $E_\gamma$ = 602 keV.

## RESULTS AND DISCUSSION

### *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.

### *Cross section ratios*

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

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

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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 $^{138}$Ba($^{18}$O,$^{16}$O)$^{140}$Ba with respect to the fusion-evaporation $^{138}$Ba($^{18}$O,4*n*)$^{152}$Gd is shown in Fig. 5.

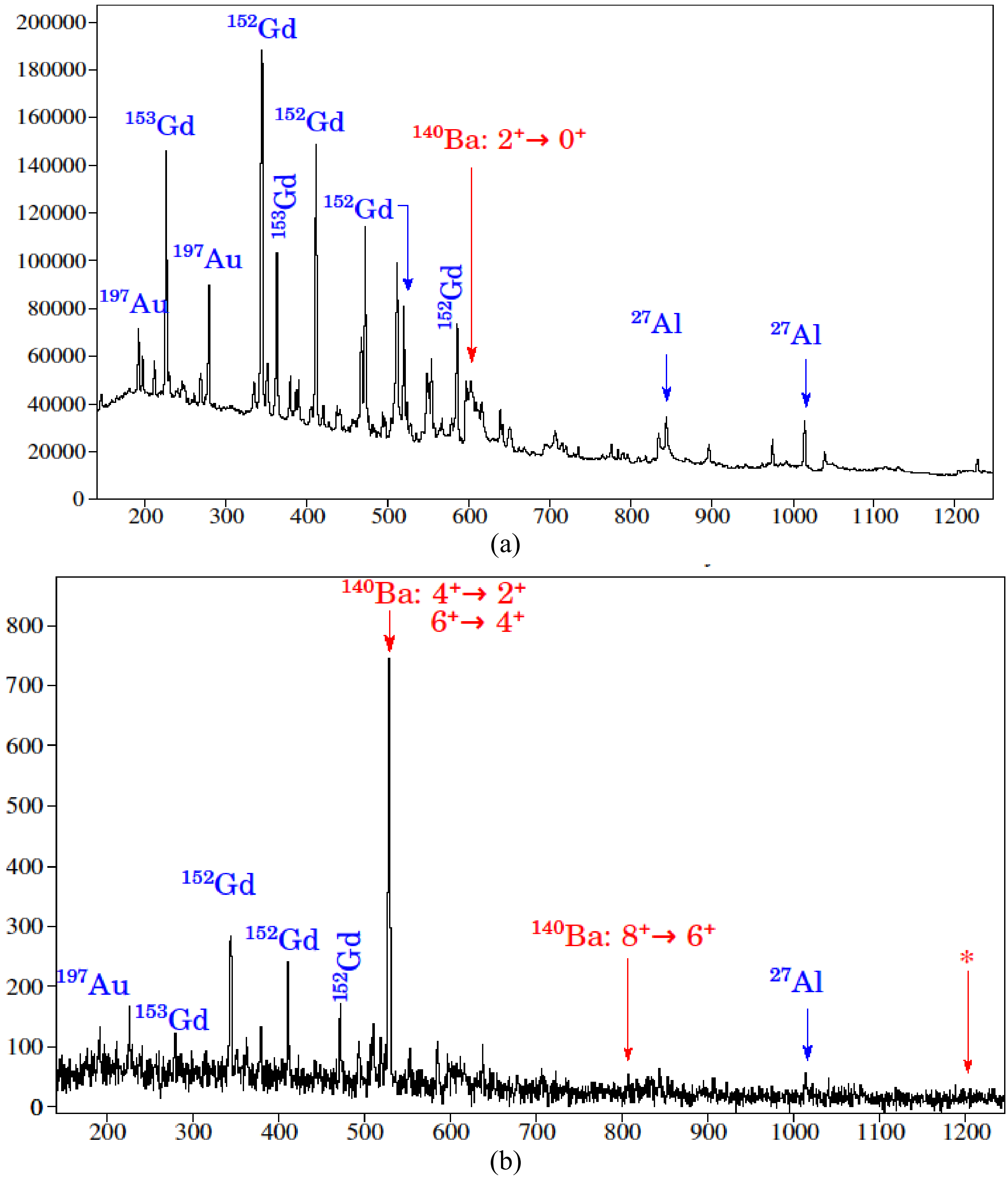
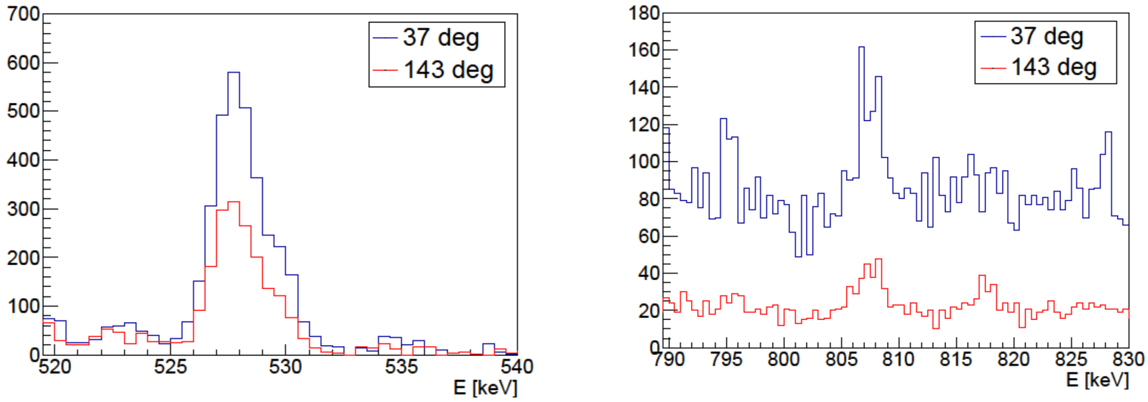



**Figure 3**. *(a) The projection of the symmetric γγ-matrix of events recorded in all ROSPHERE detectors, (b) The coincidence spectrum obtained by gating on the 2$^+$ → 0$^+$ transition of E$_\gamma$=622 keV.*




(a) (b)

**Figure 4.** *Backward (143°) and forward (37°) spectra for the (a) 528 and 530 keV overlapping transitions, and the (b) 808 keV transition. The spectra show no prominent backward–forward lineshapes.*

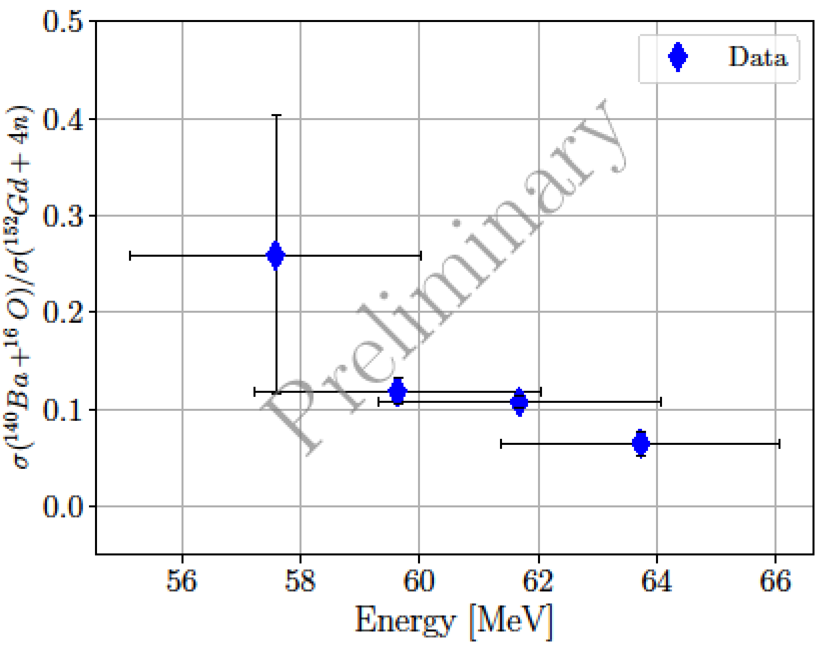



**Figure 5.** *Relative cross sections of the $^{138}Ba(^{18}O,^{16}O)^{140}Ba$ with respect to the fusion evaporation channel $^{138}Ba(^{18}O,4n)^{152}Gd$.*

## CONCLUSIONS

Within the present framework, a feasibility study of the nucleus $^{140}$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. Additional research is necessary to further constrain this limit in the lifetime. 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 fasttiming 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 $^{138}$Ba($^{18}$O,$^{16}$O)$^{140}$Ba and $^{138}$Ba($^{18}$O,4$n$)$^{152}$Gd, 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 four beam energies, showing that the fusion–evaporation channel becomes stronger at a greater rate, as the Coulomb barrier is approached. This is expected, as the reactions happen in the pure–tunnelling energy range.

In conclusion, the results provide useful information for the specific case study, either from the experimental or the theoretical point of view. 2*n*–transfer reactions are a very useful tool to study moderately neutron-rich nuclei, and the knowledge of the 2*n*–transfer–to–fusion cross section ratio can be beneficial, 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.

## Acknowledgements

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