Studies of nuclei far from stability in the regions $A = 80$ and $A = 130$

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Recent developments in experimental techniques have enabled the study of nuclei far from the line of stability in both the proton- and the neutron-rich sides. This work is divided in two parts. In the first part we report the identification of γ-rays in the near proton-drip line nuclei ^{130}Pm and ^{132}Pm. In the second part, preliminary results of a systematic measurement of $B(E2; 0^+ \rightarrow 2^+)$ using novel Coulomb-Excitation techniques are presented for all stable even-even isotopes of Ge and Se. The difficulties and challenges that represent the determination of the $B(E2)$ values for the exotic neutron-rich nuclei ^{78}Ge and ^{80}Ge are discussed. The measurement of these radioactive isotopes was possible thanks to the recent availability of radioactive ion beams at the Holifield Radioactive Ion Beam Facility. A comparison between the measured $B(E2)$ values and theoretical predictions obtained with the IBA2 model is also presented.

Keywords: Radioactive beams ; nuclear structure ; proton drip line

Desarrollo experimental reciente ha permitido el estudio de núcleos en ambos lados de la línea de estabilidad. Este trabajo se divide en dos partes. En la primera parte se reporta la identificación de rayos-γ en los núcleos cercanos a la línea de estabilidad de protones ^{130}Pm y ^{132}Pm. En la segunda parte se presentan los resultados preliminares de una medición sistemática de $B(E2; 0^+ \rightarrow 2^+)$ utilizando técnicas novedosas de Excitación Coulombiana para los isótopos estables par-par de Ge y Se. Se discuten las dificultades y retos que representa

la determinación de los valores $B(E2)$ para los núcleos exóticos ^{78}Ge and ^{80}Ge. Las mediciones de los isotópos radiactivos fueron posibles gracias a la reciente disponibilidad de haces de iones radioactivos en las instalaciones de HRIBF. Los resultados obtenidos de esta última medición se comparan con cálculos teóricos hechos con el modelo IBA2.

Descriptores : Haces radioactivos ; estructura nuclear ; línea de estabilidad de protones

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1 Introduction

The experimental study of nuclei far from stability can be done using two different approaches. One of them is the use of high intensity Stable Ion Beams (SIBs) in combination with very selective detection systems, and the second one is the use of Radioactive Ion Beams (RIBs). In this last case, the continuum decay of the beam, its low intensity, and isobar contamination represent challenges that require the development of novel detection techniques.

This work summarizes the results of two different experiments that are examples of the approaches mentioned above. Although in general, the portions of the nuclear regions studied are characterized by very different structures, they share a property in common, namely, they are difficult to reach experimentally.

In the former experiment, SIBs in combination with new state-of-the-art detection systems [1, 2] were used to identify the characteristic γ-rays that follow the decay of excited states formed with heavy-ion fusion-evaporation reactions in the near-proton drip line nuclei of the mass $A \sim 130$ region. In the second experiment, we used RIBs[3] and a novel technique to measure the $B(E2)$ values for the first 2^+ excited states of the neutron-rich ^{78}Ge and ^{80}Ge. With SIBs and the same technique we made a systematic measurement of the $B(E2)$ values of all even-even germanium and selenium stable isotopes. In the last part of this paper, we present the results of a theoretical calculation that extends the predictions of the Interacting Boson Model plus Configuration Mixing [4] to the unstable nuclei ^{78}Ge and ^{80}Ge.

2 Identification of ^{130}Pm

The study of this mass region is part of a successful program at ORNL [2] that has led to the first identification of γ-rays of near proton-drip line nuclei ^{125}Ce [5], ^{126,128}Pr [6] and ^{129}Nd [7]. Until now, the lower neutron boundary for the spectroscopic studies in the proton-rich $_{61}$Pm isotopes is $N = 70$ [8]. Measurements for ^{130}Pm$_{69}$ are limited to the determination of its β^+ half-life [9, 10]. The

aim of the experiment described here is to search for γ-ray transitions between the lowest energy levels of the nucleus ^{130}Pm.

Early calculations [11] pointed out that the very light Pm and Sm isotopes, which are close to the proton-drip line, exhibit large quadrupole ground state deformations.The odd-odd nuclei represent an interesting scenario because the valence protons and neutrons occupy the same high-j shell, $h_{11/2}$, and tend to drive the nucleus into different shapes. The protons start to fill the $h_{11/2}$ shell from the bottom, and therefore the position of the Fermi surface lies in the lower mid-shell, favoring a near axially symmetric prolate shape. The neutrons however start to fill the $h_{11/2}$ shell from the middle and hence have a tendency to drive the nucleus towards an oblate shape. The final nuclear shape is therefore the result of these two competing forces.

In order to populate excited states in the residual nucleus ^{130}Pm we have made use of fusion-evaporation reactions with stable heavy-ion beams. A 98% enriched ^{96}Ru target (0.54 mg/cm^2), supported on an Au backing (2.0 mg/cm^2), was bombarded using a 193 MeV ^{40}Ca beam. The target was placed with the Au facing the beam so the energy at which the ^{40}Ca reached the ^{96}Ru was estimated as 179 MeV. The compound nucleus populated with this reaction was $^{136}_{64}$Gd. In addition to the main channel of interest αpn leading to ^{130}Pm, we were also interested in the $3pn$ and $2p2n$ channels leading to ^{132}Pm and ^{132}Sm respectively.

The experimental setup used the combination of detectors known as CHARMS (Clarion Hyball And Recoil Mass Spectrometer). The prompt γ-rays are detected with CLARION, an array consisting of 11 segmented Clover Ge-detectors plus 10 smaller HPGe detectors with a total efficiency of nearly 2.8%. The evaporated charged particles are detected with the CsI(Tl) portion of an hybrid 4π charged particle array, HYBALL, which was designed to be used with RIBs. The residual nuclei are mass-analyzed with a state-of-the-art Recoil Mass Spectrometer (RMS), and detected with a focal plane detector as described in Ref. [12]. Because the average recoil velocity of 2.9% of c was too low to identify the Z of the recoiling nuclei using an ion chamber, only the mass was determined with a Position Sensitive Avalanche Counter (PSAC).

The experimental data were stored on exabyte tapes. For the evaporation channel $3pn$, the off-line sorting conditions were a γ-γ coincidence in CLARION, $3p$ detected by HYBALL, and the mass $A = 132$ identified in the RMS. In Fig.1 we present a level scheme for ^{132}Pm built with the γ-ray transitions satisfying those gating conditions. This scheme confirms the work of Wadsworth et al. [13] who had previously suggested candidate γ transitions for ^{132}Pm. The labels in this figure are taken to match those of Ref. [13]. No links were observed between the bands starting with the transitions 219 keV and 264 keV. To illustrate our observations in Fig. 2 we display the γ-ray spectrum obtained by placing a single gate on the 219 keV transition. The yrast band of ^{132}Sm ($2p2n$ channel) previously observed in Ref. [14] was also confirmed in the present work.

In Fig. 3, we have labeled the candidates for the lowest energy γ-ray transitions of ^{130}Pm. These transitions were obtained by making a partial subtraction of the total projection of^{130}Nd [15] from ^{130}Pm. It was not possible to establish a level scheme from the corresponding low statistics γ-γ matrix due to the low production cross section of the αpn evaporation channel and the strong contamination from ^{130}Nd.

We have identified the lowest energy γ-ray transitions for ^{130}Pm and ^{132}Pm. In the case of ^{132}Pm we confirmed the preliminary results of Ref.[13]. Further work will be required to determine the structure of those bands. For ^{130}Pm additional experiments are required to determine a level scheme for this nucleus. In order to better isolate the channel with the same experimental equipment CHARMS an additional filter condition is required, such as the array of neutron detectors currently under construction at the HRIBF. Another possibility is the use of a larger array such as GAMMASPHERE that allows higher-fold γ-ray coincidences.

3 Coulomb excitation of neutron-rich Ge and Se isotopes

The neutron-rich isotopes of both Ge and Se nuclei are limited by the magic shells 28 for protons and 50 for neutrons, and in principle they are expected to be nearly spherical. However, experimental observations have shown that the character of this region is rather transitional. The challenge posed by this feature has motivated a lot of experimental and theoretical work in order to understand the structure of these nuclei. It is worth to mention, however, that most of that work was concerned only with stable isotopes. We present here a systematic study of the $B(E2; 0^+ \rightarrow 2^+)$ values, to supply fundamental information about the nuclear structure of even-even nuclei.

Systematic measurements of the Q_{2^+} values [16] show that stable even-even Ge isotopes exhibit a gentle shape transition from an almost spherical or moderately deformed oblate spheroid (^{70}Ge) to moderately deformed prolate spheroids (^{72}Ge, ^{74}Ge, ^{76}Ge). After having reached a maximum value at $N = 42$ (^{74}Ge) the deformation tends to decrease, as the neutron number increases. In addition, transfer reactions [17] and Coulomb excitation measurements [18, 19] strongly suggest, both the coexistence of states with different types of deformation in the same nucleus and the presence of a structural change in the ground state of $N = 40$.

For the even-even Se isotopes the measurement of the Q_{2^+} values [20] showed that this chain of nuclei favor a prolate deformation, and the Q_{2^+} values and the energies of the first 2^+ states seem to remain fairly constant for all the isotopes, even as N approaches to the closed shell at N=50.

In our study, the first 2^+ states in Ge and Se isotopes were Coulomb excited

[21] using an inverse-kinematics reaction. A ^{12}C target (~ 0.83 mg/cm^2) was bombarded with the SIBs ^{70,72,74,76}Ge, ^{74,76,78,80,82}Se, and the RIBs ^{78,80}Ge at 2.23 MeV per nucleon. The technique was specifically developed for the measurement of $B(E2)$ with RIBs [22]. The experimental setup includes: HYBALL, to record the scattered ^{12}C in the three forward rings of CsI(Tl) detectors, at the polar angles $10.5°, 21.0°$, and $36.0°$; 8 Clover Ge detectors of CLARION to record the prompt γ-rays coming from Ge and Se excitation; and a SiLi-LEPS behind the achromatic focal plane of the RMS to identify the Z of the projectile ions by means of its characteristic X-ray, emitted by the beam when slowing down in a thick foil (~ 4 mg/cm^2) of Pd. When RIBs were injected, two additional Micro Channel Plate detectors (MCPs) were used in combination with thin foils. One of the MCPs was placed at the entrance and the second one at the achromatic focal plane of the momentum separator, to keep track of the beam intensity.

The neutron-rich RIBs are obtained from the proton induced fission spectra of ^{238}U. A carbon matrix coated with uranium carbide is bombarded with a high intensity proton beam, supplied by the Oak Ridge Isochronous Cyclotron (ORIC). The radioactive atoms diffuse out of the target, are transported to an ion source, ionized, extracted and separated according to their mass. These ions are charge exchanged and once again mass separated, with a higher resolution. The resulting beam is then injected into the 25MV Tandem electrostatic accelerator. One of the main challenges related to the use of RIBs is the fact that the beam consists of a "cocktail" of isobars. In our case ^{78}Ge had ^{78}Se (stable) and a small amount of ^{78}As as contaminants while ^{80}Ge was strongly contaminated by ^{80}Se (stable).

To determine the $B(E2; 0^+ \rightarrow 2^+)$ values we compare the experimental and theoretical ratios of Coulomb excitation to Rutherford scattering cross sections. These ratios are combined to get a correction factor to an estimated reduced transition probability. Experimentally, the Rutherford cross section was determined by counting all the carbon recoils detected by HYBALL, while the Coulomb cross section was measured by counting the number of events that present a γ-ray transition, with the proper energy, in coincidence with a detected carbon. The theoretical value was obtained from the DeBoer-Winther COULEX code and integrated over the beam energy through the target and the relevant HYBALL angles.

It is important to mention that, although the same procedure was used for both stable and radioactive ions, this last case is a little more complicated. Because the RIB was contaminated with isobars the theoretical ratio $\sigma_{\text{Coulomb}}/\sigma_{\text{Rutherford}}$ has to be corrected by the fraction of the beam associated with the nucleus of interest, which is determined by the X-rays. Additional corrections are also needed in order to determine properly the number of γ-^{12}C coincidence events that belongs to germanium and selenium. This separation is difficult because ^{78,80}Se $B(E2)$ values are larger than those predicted for ^{78,80}Ge

respectively. Also the γ-ray peaks in the coincidence spectra appear very close to each other because the lowest γ-ray transitions $2^+ \rightarrow 0^+$ of ^{78}Ge and ^{78}Se differ only by 4keV, and the corresponding transitions for ^{80}Ge and ^{80}Se differ by 7 keV. In principle, the information of the electrically segmented Clover detectors and the kinematic reconstruction using the detected recoils in the HYBALL allows to correct for the Doppler broadening of the γ-rays. However, even with this correction it is difficullt to improve the separation of the peaks as the obtained FWHM for the corrected peaks is between 5 to 6 keV.

In Fig.4 we compare our measurements for the $B(E2)$ values for the even-even Se isotopes with the adopted values [23], while in Fig.5 we present the $B(E2)$ values for the stable Ge even-even isotopes compared with our theoretical calculations. For these nuclei we find a good agreement between our measurements and the IBA2 calculations.

We have presented here, a novel experimental technique, to measure the $B(E2)$ values of radioactive isotopes. We have used inverse kinematics reactions and the Coulomb-Excitation mechanism. Determinant aspects in our measurements were the high resolution of the Ge detectors, the detection of the ^{12}C target recoils scattered in the reaction and the continuous monitoring of the beam, using projectile-X-ray emission. The same technique was used to measure the $B(E2)$s of the chain of stable Ge and Se isotopes. This information is important for several reasons: *i*. the agreement obtained between our results, for stable nuclei, and the adopted values, indicate that our technique is reliable; *ii*. the use of the same experimental procedure for RIBs and SIBs will allows us to make a meaningful comparison of the new ^{78,80}Ge values; and *iii*. because Se isobars were the main contaminant, when RIBs were injected, we can use that information to check the consistency of our results.

4 Theoretical Calculations for $A \sim 80$

As it was mentioned before, one of the most interesting aspects that characterize the isotopic chain of the Ge nuclei, is the coexistence of different types of deformation in the same isotope chain. The shape coexistence phenomena is due to the presence of intruder states, which are particle-hole excitations across the closed shells. A successful description of this kind of nuclei has been done by means of the IBA2 plus configuration mixing formalism [25]. This theoretical framework has been applied to the stable Ge isotopes in Ref.[4].

We want to extend this theoretical study to describe the radioactive isotopes ^{78}Ge and ^{80}Ge. More than a close reproduction of the whole energy-level scheme, we are concerned in getting an estimate for the $B(E2; 0^+ \rightarrow 2^+)$ values. In this contribution we neglect the mixing with the intruder configurations, and use only the normal configurations associated to the ground state bands of the Ge isotopes. The calculations were made using the codes NPBOS and NPBEM [26], with the model Hamiltonian given by

$$H = \epsilon n_d + \kappa Q_\pi \cdot Q_\nu + M_{\pi\nu} \,,$$

where n_d denotes the number of quadrupole bosons, Q_ρ is the quadrupole operator with $\rho = \pi$, and ν. Finally $M_{\pi\nu}$ is the Majorana term, which acts on the states antisymmetric under the interchange of proton and neutron bosons. The parameters in this Hamiltonian are: ϵ which gives the difference of the single particle energies between the d and s bosons, κ the quadrupole-quadrupole interaction strength, the quadrupole structure parameters χ_π, and χ_ν, and the parameters ξ_i with $i = 1, 2, 3$ of the Majorana term.

Table I lists the values of the parameters in the IBA2 Hamiltonian that describe fairly well the low energy levels of the Ge isotopes, with $A = 68$ to 80. Using the associated energy surfaces by means of the F-spin formalism [27, 28] and the intrinsic geometric structure of the IBA1 [29], we have verified that the previous parameters reproduce qualitatively the ground state shape transition between spherical or quasi-spherical (^{68,70,72}Ge) and γ-unstable deformed (^{74,76,78,80}Ge) nuclei.

The $B(E2)$ theoretical values, displayed in Fig. 5, were obtained using $e_\pi = e_\nu = 0.0582e$b for $A = 68, 70, 72$ while $e_\pi = e_\nu = 0.0834e$b for $A = 74$ to 80. These effective charges were adjusted to reproduce exactly the $B(E2)$ of ^{68}Ge and ^{76}Ge, respectively. As it can be seen in that figure, our theoretical results are very close to our experimental measurements for all the stable isotopes even though this calculation does not yet consider the configuration mixing.

Finally is worthwhile to mention that ξ_i , $i = 1, 2, 3$ are not essential for the yrast bands. The variation of the remaining parameters is quite smooth with neutron number. As future work in this direction, we will study how the mixing with the intruder configurations affects this first calculation for the $B(E2)$ values of Ge isotopes.

Acknowledgments

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Figure Captions

Fig 1. Level scheme for ^{132}Pm deduced from the present experiment. The energies of the γ-ray transitions are given in keV.

Fig 2. γ-ray spectra obtained from the ^{132}Pm matrix by gating on the $E_\gamma =$ 219keV transition.

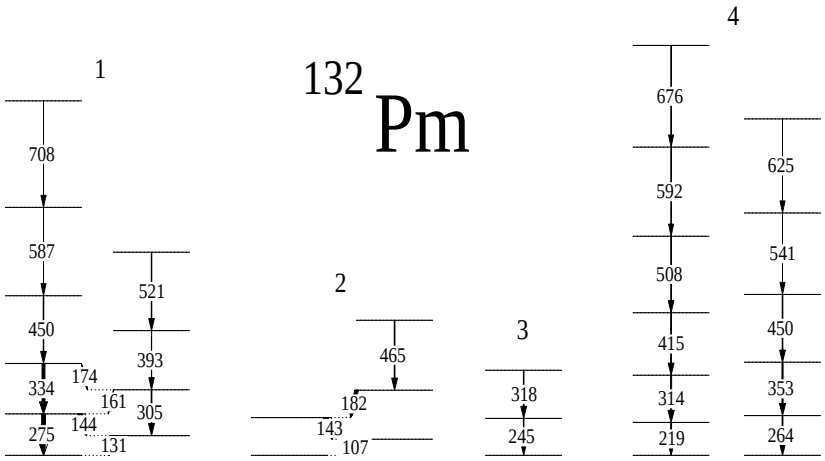
Fig 3. Proposed γ-ray transitions for ^{130}Pm. The peaks marked by $*$ correspond to the contaminant channel $(\alpha 2p)$ ^{130}Nd.

Fig 4. $B(E2; 0^+ \rightarrow 2^+)$ values, in e^2b^2, for the isotopes of selenium as a function of the neutron number. The panel shows a comparison between the adopted values and the corresponding preliminary results obtained in the present work. The error bars only reflect statistical errors.

Fig 5. $B(E2; 0^+ \rightarrow 2^+)$ values, in e^2b^2, as a function of the neutron number, for the germanium isotopes. For the stable nuclei, the panel shows a comparison between the theoretical aproximation presented in Section 4 and the corresponding experimental results obtained in the present work. For ^{78}Ge and ^{80}Ge only the theoretical prediction is plotted.

Table Captions

Table I. The IBA2 parameters used in this calculation.


132 Pm
1
2
3
4
708
587
450
334
275
174
161
144
131
521
393
305
465
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353
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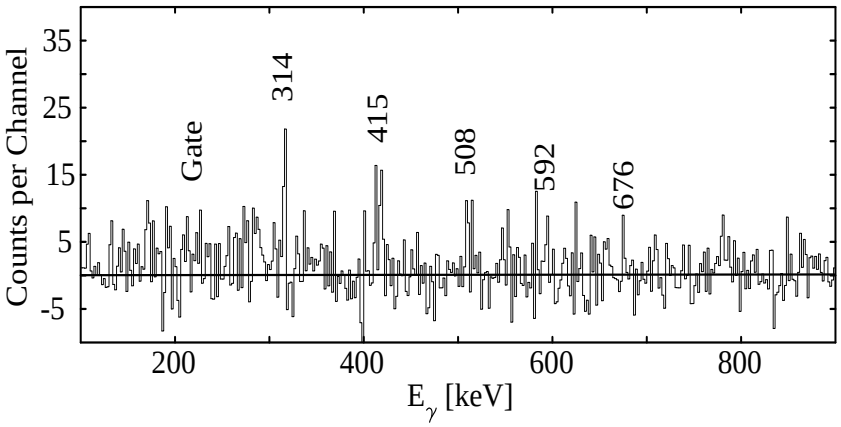
Counts per Channel
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25
15
5
-5
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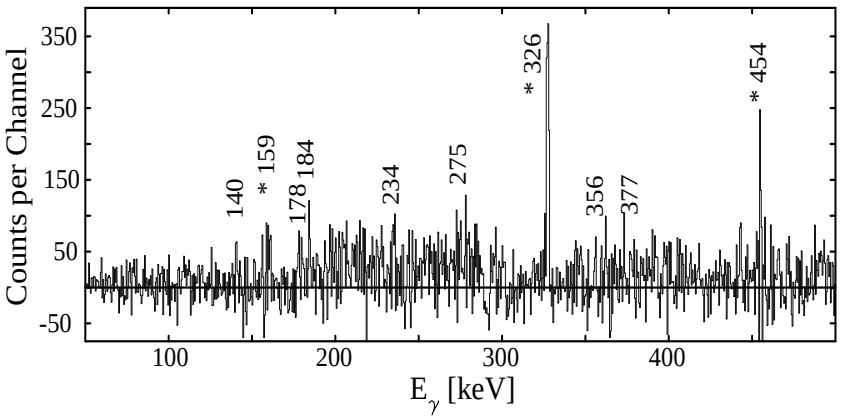
415
508
592
676
200
400
600
800
E$_\gamma$ [keV]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150
50
-50
100
200
300
400
E$_\gamma$ [keV]
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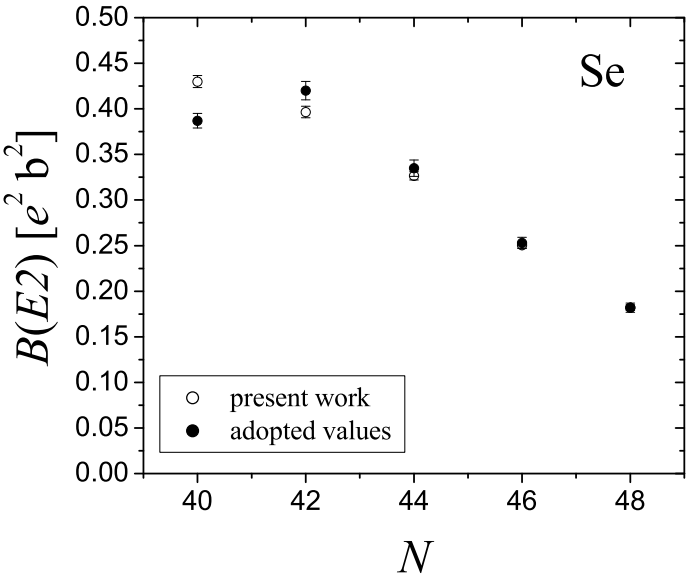
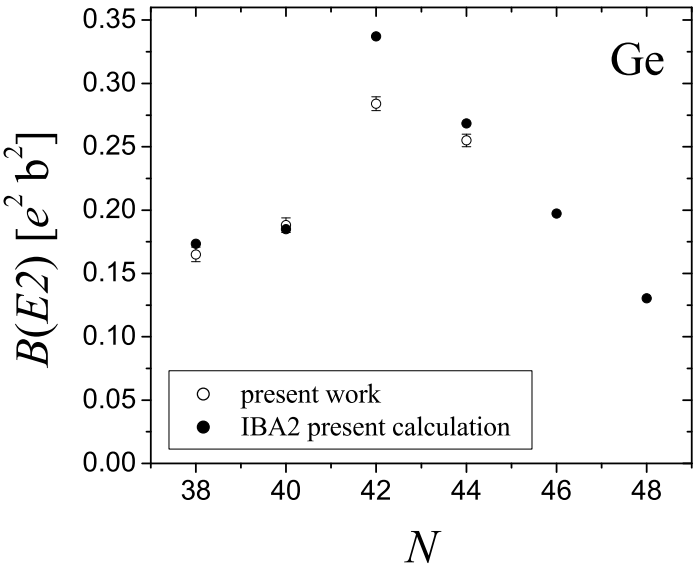
* 159
178
184
234
275
* 326
356
377
* 454


Se
$B(E2)$ [e^2 b^2]
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
40
42
44
46
48
N
present work
adopted values



	ϵ[MeV]	κ[MeV]	χ_π	χ_ν	$\xi_1 = \xi_3$	ξ_2
^{68}Ge	1.4	-0.20	-1.2	1.0	0.05	0.05
^{70}Ge	1.4	-0.20	-1.2	1.2	0.05	0.05
^{72}Ge	1.2	-0.21	-1.2	1.1	0.05	0.05
^{74}Ge	1.0	-0.25	-1.4	1.0	0.00	0.10
^{76}Ge	0.9	-0.25	-1.4	1.0	0.00	0.10
^{78}Ge	0.9	-0.25	-1.4	1.0	0.00	0.10
^{80}Ge	0.9	-0.25	-1.4	1.0	0.00	0.10