

# Spectroscopic quadrupole moments in $^{124}\text{Xe}$

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(Dated: January 18, 2023)

**Background:** The Xe isotopic chain with four valence protons above the  $Z=50$  shell closure is an ideal laboratory for the study of the evolution of nuclear deformation. At the  $N=82$  shell closure,  $^{136}\text{Xe}$  presents all characteristics of a doubly closed shell nucleus with a spherical shape. In the very neutron-deficient isotopes close to  $N=50$ , the  $\alpha$ -decay chain of Xe was investigated to probe the radioactive decay properties near the drip-line and the magicity of  $^{100}\text{Sn}$ . Additionally, the Xe isotopes present higher order symmetries in the nuclear deformation such as the octupole degree of freedom near  $N=60$  and  $N=90$  or  $O(6)$  symmetry in stable isotopes.

**Purpose:** The relevance of the  $O(6)$  symmetry has been investigated by measuring the spectroscopic quadrupole moment of the first excited states in  $^{124}\text{Xe}$ . In the  $O(6)$  symmetry limit, the spectroscopic quadrupole moment of collective states is expected to be null.

**Method:** A stable  $^{124}\text{Xe}$  beam with energies of 4.03A MeV and 4.11A MeV was used to bombard a  $^{nat}\text{W}$  target at the GANIL facility. Excited states were populated via the safe Coulomb excitation reaction. The collision of the heavy ions with a large  $Z$  at low energy make this reaction sensitive to the diagonal E2 matrix element of the excited states. The recoils were detected in the VAMOS++ magnetic spectrometer and the  $\gamma$ -rays in the AGATA tracking array. The least squares fitting code GOSIA was used for the analysis to extract both E2 and M1 transitional and E2 diagonal matrix elements.

**Results:** The rotational ground state band was populated up to the  $8_1^+$  state as well as the  $2_2^+$  and  $4_2^+$  states. Using high precision spectroscopic data to constrain the GOSIA fit, the spectroscopic quadrupole moments of the  $2_1^+$ ,  $4_1^+$  and  $6_1^+$  states were determined for the first time.

**Conclusions:** The spectroscopic quadrupole moments were found to be negative, large and constant in the ground state band underlining the prolate axially deformed ground state band of  $^{124}\text{Xe}$ . The present experimental data confirm that the O(6) symmetry is substantially broken in  $^{124}\text{Xe}$ .

## I. INTRODUCTION

With four protons added to the Z=50 shell closure, the Xe isotopes are an ideal laboratory to investigate the collective properties of the nuclear matter. On the neutron-rich side,  $^{136}\text{Xe}$  highlights the N=82 shell closure with a maximum excitation energy of the  $2_1^+$  state and a minimum in the corresponding reduced transition probability  $B(E2, 2_1^+ \rightarrow 0_1^+)$  [1]. When removing neutrons from N=82, the Xe isotopes follow a smooth increase of collectivity reaching a maximum at mid-shell around N=66 [2]. In these isotopes, low excitation energies of the  $2_1^+$  states, rotational ground state bands and large  $B(E2)$  values were reported. Approaching the N=50 shell closure, an unexpected onset of collectivity was observed in  $^{110}\text{Xe}$  [3]. Beyond the quadrupole symmetry, harmonic octupole correlations have been identified associated with the collective  $3^-$  states at low excitation energy at the mid-shell [4], whereas in the neutron deficient  $^{114}\text{Xe}$  isotope an unexpectedly large  $B(E3, 3^- \rightarrow 0_1^+)$  was measured [5].

The collective properties of the stable Xe isotopes have been scrutinized in the light of dynamical symmetries to describe the transition from spherical shape at the closed shells to large deformation in the mid-shell region. The transition region should involve  $\gamma$ -soft and  $\gamma$ -rigid deformation [6, 7]. Fingerprints of such deformations were observed in the even-A mass Xenon isotopes with  $R_{4/2} \approx 2.5$  and low lying  $2_2^+$  band heads. Using dynamical symmetries to describe the observed collective structures, the X(5) symmetry was proposed for the description of the  $^{128,130}\text{Xe}$  isotopes [8–10] while the O(6) symmetry [11] was also invoked for the description of lighter stable Xe isotopes [12]. The O(6) symmetry imposes that the spectroscopic quadrupole moment is null in spite of the large  $B(E2)$  and low excitation energy of the  $2_1^+$  state. The low-energy Coulomb excitation experiments performed for the  $^{126,128}\text{Xe}$  isotopes suggest, based on the measured  $B(E2)$  and spectroscopic quadrupole moments, the deviations from the O(6) symmetry [13]. In [14], the low energy Coulomb excitation of a  $^{124}\text{Xe}$  beam on a light target has been performed to investigate the transition probabilities from non yrast states gathered in so-called  $\gamma$ -band, 3-phonon K=0 band and  $\beta$ -band and compared to IBM-1 calculations. As a result it was proposed that the O(6) symmetry in  $^{124}\text{Xe}$  is also substantially broken. Safe Coulomb excitation cross sections on a high-Z target is the only method sensitive to the diagonal E2 matrix elements of the quadrupole operator of the states with the non-zero spin, i.e. spectroscopic quadrupole moment [15–17]. In this paper, we report the results from the first measurement of spectroscopic quadrupole moments

of short-lived excited states in  $^{124}\text{Xe}$  obtained by safe Coulomb excitation.

## II. EXPERIMENTAL SETUP

The experimental data used in this study was collected in an experiment with a different objective. The main goal of the experiment was the study of the fission yield distribution of the neutron deficient  $^{178}\text{Hg}$  isotope populated in the fusion of a  $^{124}\text{Xe}$  beam with a  $^{54}\text{Fe}$  target deposited on a carbon backing [18, 19]. Stable  $^{124}\text{Xe}$  beams with energies of 4.03A MeV and 4.11A MeV were accelerated by the GANIL cyclotron complex and delivered to the VAMOS++ AGATA setup in the G1 cave [20–23]. Fission fragments and target-like products were identified in the VAMOS++ magnetic spectrometer and the prompt  $\gamma$ -rays were detected in the AGATA tracking array surrounding the target. The Doppler correction was performed on an event-by-event basis using the velocity vector measured by the VAMOS++ instruments and the first interaction points of tracked  $\gamma$ -rays energies deduced from the AGATA OFT tracking algorithm [24].

The analysis of the  $\gamma$ -ray spectrum in AGATA revealed that the Fe target contained an admixture of  $^{nat}\text{W}$ . The Xe (beam) and W (target) X-rays are observed at the energies below 80 keV. The VAMOS++ detection system was optimized for the identification of the fission fragments [18]. Heavy ( $A \approx 120$ -180) and slow ( $\beta \leq 10\%$ ) recoils such as Xe and W were detected at the VAMOS++ focal plane but could not be uniquely identified since they are were stopped within the Bragg peak ionization chambers. Therefore the experiment did not allow to determine the mass for Xe-like or W-like nuclei, however, but provided the mass-over-charge ratio for W-like ions in agreement with masses 182, 184 and 186. The clear and unique identification of the  $\gamma$  ray transitions of  $^{182,184,186}\text{W}$  supports the hypothesis of the contamination by  $^{nat}\text{W}$  of the target.

The VAMOS++ magnetic spectrometer was equipped with a Dual Position Sensitive MWPC detector placed at the entrance of the first quadrupole, providing a precise measurement of the scattering angle with respect to the axis of the incoming beam [22]. Combining this angle with the velocity measurement allowed to obtain an accurate kinematic correlation. Figure 1 shows the corresponding matrix with the experimental kinematic lines for the Xe beam scattered on W ions detected in VAMOS++, the W target ions scattered by the Xe beam detected in VAMOS++ and the Xe beam scattered on the Fe target ions. The corresponding theoretical kinematic lines for Xe+W (red and blue, see later in the text),

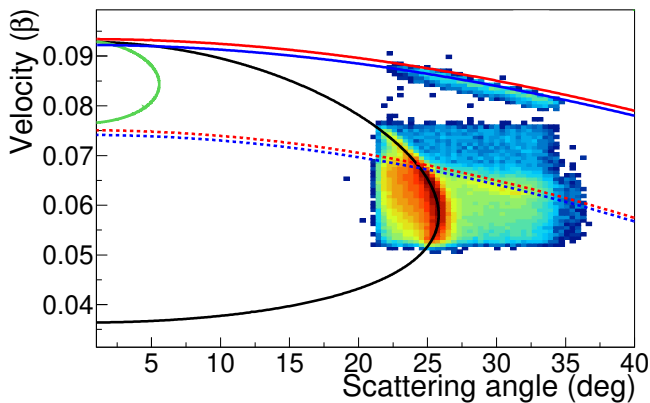


FIG. 1. (Color online) Kinematic lines (scattering angle as a function of the velocity) measured at the entrance of VAMOS++. Continuous red (blue) shows the Xe beam scattered at maximum (minimum) energy on W detected in VAMOS++ ; Dashed red (blue) shows the W target scattered by the Xe beam at maximum (minimum) energy detected in VAMOS++. Green is kinematic line for the Xe beam scattered on the carbon backing, excluded by the detection system; Black shows Xe beam scattered on the iron target.

Xe+Fe (black) and Xe+C (green) are also shown. The combination of the VAMOS++ magnetic rigidity analysis and Doppler correction in AGATA was used to determine the position of the W in the target. First, the charge state measurement of  $^{124}\text{Xe}$  scattered into VAMOS++ was optimized from the analysis of the time of flight in the spectrometer. This time of flight was used to determine the velocity between the center of the entrance PPAC detector and the stop detector at the focal plane and to deduce the mass over charge ratio. A small correction of this velocity was needed to optimize the Doppler correction in AGATA due to the energy loss in the first gas volume of the PPAC. The optimum velocity for Doppler correction was then reported in the 2D matrix of figure 1. The kinematic lines for direct scattering of  $^{124}\text{Xe}$  on  $^{nat}\text{W}$ , at the actual beam energy, are plotted in red. The blue lines show the same calculations assuming that the beam was losing energy in the  $^{54}\text{Fe}$  material and  $^{12}\text{C}$  backing before scattering on the  $^{nat}\text{W}$ . The data shows a best compatibility with the second hypothesis constraining very well the kinematics of the reactions for the Coulomb excitation analysis.

Figure 2 shows the prompt, Doppler corrected for W, tracked  $\gamma$ -ray spectrum selected on the kinematic lines of the Xe + W reaction confirming the identification of the  $^{nat}\text{W}$ . The Coulomb excitation of the  $2_1^+$ ,  $4_1^+$ ,  $6_1^+$  and  $8_1^+$  states in  $^{182,184,186}\text{W}$  are observed. The reduced intensity of the  $2_1^+$  decay is due to a shadowing effect of the target chamber arising from the long lifetime of the states. The inelastic scattering on W fulfilled the Cline's criterion of safe Coulomb excitation [25] for the beam energies of 4.03A MeV and 4.11A MeV further slowed down in the Fe target. The inelastic scattering of the Xe beam on the W target is selected from the kinematic lines for two ranges

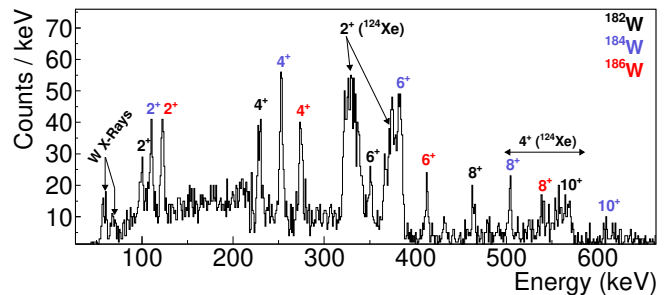


FIG. 2. (Color online) Prompt  $\gamma$ -ray spectrum following the de-excitation of  $^{182,184,186}\text{W}$  after Coulomb excitation measured in AGATA.

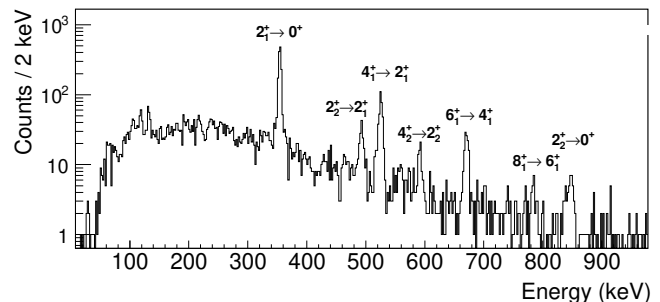


FIG. 3. Prompt  $\gamma$ -ray spectrum following the de-excitation of  $^{124}\text{Xe}$  after safe Coulomb excitation at the beam energy of 4.03A MeV.

at each energy, between  $27.2^\circ$  and  $34.4^\circ$  when  $^{124}\text{Xe}$  is measured in VAMOS++ and between  $26.9^\circ$  and  $33.4^\circ$  when  $^{nat}\text{W}$  is transmitted (see figure 1).

### III. ANALYSIS AND RESULTS

The prompt Doppler corrected tracked  $\gamma$ -ray spectrum, gated on the  $^{124}\text{Xe}$  scattered on  $^{nat}\text{W}$  events, for the 4.03A MeV beam energy is shown in figure 3. The rotational ground-state band was populated up to the  $8_1^+$  state, the  $2_2^+$  and  $4_2^+$  states were also populated. The statistics is further divided by ranges in scattering angle to take full advantage of the differential Coulomb excitation sensitivity.

The  $\gamma$ -ray intensities, without efficiency correction, for several bins in scattering angle at different beam energies are reported in table I. The Coulomb excitation analysis were performed using the least squares fitting code GOSIA [26, 27]. The code uses a standard  $\chi^2$  function constructed from the measured  $\gamma$ -ray yields and those calculated from a set of electromagnetic matrix elements, both transitional and diagonal, between all states involved in the excitation process. Known spectroscopic data, such as lifetimes of excited states,  $\delta(E2/M1)$  mixing and decay branching ratios, were used as additional data points in the minimization procedure. The  $2_1^+ \rightarrow 0_1^+$  transition in  $^{124}\text{Xe}$  was used for normalization.

TABLE I. Observed  $\gamma$ -ray transitions in  $^{124}\text{Xe}$  with their intensities (without efficiency correction), collected on W target, for ranges of center-of-mass scattering angles used in the Coulomb excitation analysis.

Data set	$I_i^\pi$	$I_f^\pi$	$E_\gamma$ (keV)	Counts	Error
4.03A MeV (45.2° – 56.9°)	$2_1^+$	$0_1^+$	354	724	30
	$4_1^+$	$2_1^+$	525	62	10
	$6_1^+$	$4_1^+$	670	7	3
	$2_2^+$	$2_1^+$	493	16	5
	$2_2^+$	$0_1^+$	846	4	2
4.03A MeV (113.1° – 126.1°)	$2_1^+$	$0_1^+$	354	559	30
	$4_1^+$	$2_1^+$	525	253	52
	$6_1^+$	$4_1^+$	670	107	12
	$8_1^+$	$6_1^+$	783	15	5
	$2_2^+$	$2_1^+$	493	84	20
	$2_2^+$	$0_1^+$	846	19	5
	$4_2^+$	$2_2^+$	591	48	9
4.11A MeV (45.2° – 56.9°)	$2_1^+$	$0_1^+$	354	635	30
	$4_1^+$	$2_1^+$	525	79	12
	$2_2^+$	$2_1^+$	493	16	6
4.11A MeV (113.1° – 126.1°)	$2_1^+$	$0_1^+$	354	772	35
	$4_1^+$	$2_1^+$	525	295	20
	$6_1^+$	$4_1^+$	670	92	14
	$8_1^+$	$6_1^+$	783	17	6
	$2_2^+$	$2_1^+$	493	86	13
	$2_2^+$	$0_1^+$	846	35	8
	$4_2^+$	$2_2^+$	591	53	10

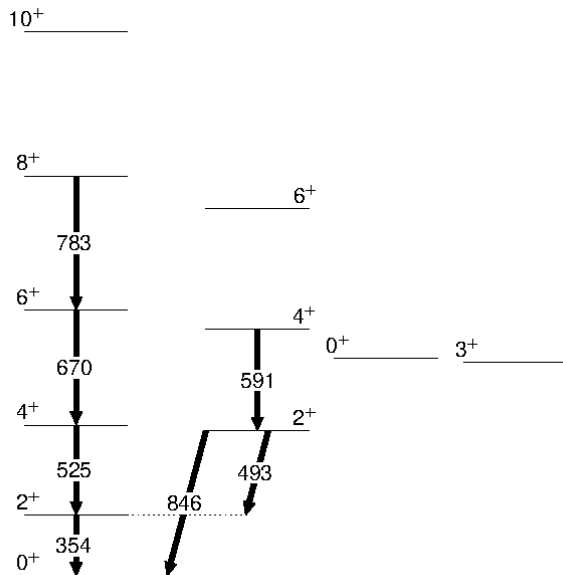


FIG. 4. Partial level scheme of  $^{124}\text{Xe}$  with observed transitions. Additional states included in the analysis are also shown.

TABLE II. Spectroscopic informations included in the minimization.

$I^\pi$	Lifetime $\tau$ (ps) [28]
$2_1^+$	67.51(1.73)
$g$ -factor = 0.23(2) [29]	
$4_1^+$	8.19(23)
$6_1^+$	1.86(15)
$8_1^+$	1.13(34)
$2_2^+$	17.74(3.03)
$4_2^+$	3.02(1.00)
$3_1^+$	8.94(1.00)
Transition	Branching ratio [28]
$2_2^+ \rightarrow 2_1^+/2_2^+ \rightarrow 0_1^+$	0.33(8)
$3_1^+ \rightarrow 4_1^+/3_1^+ \rightarrow 2_2^+$	0.13(3)
$3_1^+ \rightarrow 2_2^+/3_1^+ \rightarrow 2_1^+$	0.76(17)
$0_2^+ \rightarrow 2_2^+/0_2^+ \rightarrow 2_1^+$	0.10(5)
$4_2^+ \rightarrow 4_1^+/4_2^+ \rightarrow 2_2^+$	0.44(8)
$4_2^+ \rightarrow 2_2^+/4_2^+ \rightarrow 2_1^+$	0.02(1)
$6_2^+ \rightarrow 6_1^+/6_2^+ \rightarrow 4_2^+$	0.23(3)
$6_2^+ \rightarrow 4_2^+/6_2^+ \rightarrow 4_1^+$	0.10(2)
Transition	$\delta(E2/M1)$ mixing ratio [28]
$2_2^+ \rightarrow 2_1^+$	+8(7)
$3_1^+ \rightarrow 2_2^+$	+0.32(5)
$3_1^+ \rightarrow 2_1^+$	+0.73(6)
$4_2^+ \rightarrow 4_1^+$	+2.3(8)
$6_2^+ \rightarrow 6_1^+$	-0.54(18)

The partial level scheme of  $^{124}\text{Xe}$  included in the GOSIA minimization is presented in figure 4. To enhance the sensitivity, additional inputs such as the  $2_1^+$ ,  $4_1^+$ ,  $6_1^+$ ,  $8_1^+$ ,  $2_2^+$ ,  $4_2^+$  and  $3_1^+$  states lifetimes, the known decay branching ratios of the  $2_2^+$ ,  $4_2^+$ ,  $6_2^+$  and  $3_1^+$  states, the  $\delta(E2/M1)$  mixing ratio for the  $2_2^+ \rightarrow 2_1^+$ ,  $4_2^+ \rightarrow 4_1^+$ ,  $6_2^+ \rightarrow 6_1^+$ ,  $3_1^+ \rightarrow 2_2^+$  and  $3_1^+ \rightarrow 2_1^+$  transitions [28] and the known  $g$ -factor of the  $2_1^+$  state [29] were included in the minimization process (see table II). The kinematic lines in figure 1 are selected through the VAMOS++ acceptance. This effect is known for inelastic scattering in VAMOS++ [30] and was taken into account by a proper description of the  $(\theta - \phi)$  dependences of the scattering angles in GOSIA as described in [27]. The angular dependence of the setup was validated by the analysis of the differential Coulomb excitation cross section of the  $4_1^+$ ,  $6_1^+$  and  $8_1^+$  states in  $^{182}\text{W}$ . The agreement with the calculated cross sections using the matrix elements published in [31] is excellent demonstrating our control of the angular dependence.

The minimization process was carried out in three steps. First, the  $4_2^+$ ,  $3_1^+$  and  $0_2^+$  states and their spectroscopic data were excluded from the minimization to obtain a first set of matrix elements reproducing the main transitions. The  $\gamma$ -ray yield of the  $4_2^+$  state, observed only in two data sets of table I corresponding to the

TABLE III. Reduced transition probabilities in  $^{124}\text{Xe}$  obtained in this work and compared to previous data

$I_1^\pi$	$I_2^\pi$	$B(E2; I_1 \rightarrow I_2) (e^2 b^2)$	$B(E2)$ (Wu)	Prev. [14]	IBM-1[14]
$2_1^+$	$0_1^+$	$0.212_{-0.006}^{+0.006}$	57.7(16)	57.7(15) <sup>a</sup>	57.7
$4_1^+$	$2_1^+$	$0.253_{-0.008}^{+0.008}$	68.8(21)	67.6(19) <sup>a</sup>	85.08
$6_1^+$	$4_1^+$	$0.339_{-0.030}^{+0.030}$	92.3(81)	90(18)	96.95
$8_1^+$	$6_1^+$	$0.35_{-0.27}^{+0.27}$	95(73)		
$2_2^+$	$0_1^+$	$0.0031_{-0.0005}^{+0.0008}$	$0.84_{-13}^{+21}$	1.45(12)	1.47
$2_2^+$	$2_1^+$	$0.135_{-0.017}^{+0.020}$	36.7(54)	64(5)	61.24
$4_1^+$	$2_2^+$	$1.0_{(-1,0)}^{(+0,1)} \times 10^{-3}$	$<0.30^b$	92(58)	0.06
$4_2^+$	$2_2^+$	$0.244_{-0.055}^{+0.055}$	66(15) <sup>b</sup>	66(12)	48.48
$4_2^+$	$4_1^+$	$0.004_{-0.020}^{+0.020}$	$<10^b$	35(6)	33.53
$4_2^+$	$2_1^+$	$0.0002_{-0.002}^{+0.001}$	$<0.5$	0.058(11)	0.33
$3_1^+$	$2_1^+$	$0.0029_{-0.0004}^{+0.0006}$	0.80(16)	2.33(38)	2.20
$3_1^+$	$2_2^+$	$0.033_{-0.010}^{+0.011}$	9(3)	95(19)	65.69
$3_1^+$	$4_1^+$	$0.09_{-0.02}^{+0.02}$	24(5)	26(12)	20.71
$0_2^+$	$2_1^+$	$0.11_{-0.06}^{+0.06}$	31(17)	13.2(31)	16.12
$0_2^+$	$2_2^+$	$0.33_{-0.21}^{+0.37}$	$90_{(-57)}^{(+100)}$	87(21)	76.45

<sup>a</sup> From Ref. [32].

<sup>b</sup> Influenced by the  $0_2^+$  and  $3_1^+$  states presence in the GOSIA minimization (see text).

TABLE IV. Spectroscopic quadrupole moments,  $Q_s$ (eb), in  $^{124}\text{Xe}$  obtained in this work and compared to  $^{126,128,130}\text{Xe}$ .

$I^\pi$	$^{124}\text{Xe}$	$^{126}\text{Xe}$ [33]	$^{128}\text{Xe}$ [33]	$^{130}\text{Xe}$ [10]
$2_1^+$	$-1.60_{-0.36}^{+0.22}$	-0.76(15)	$-0.44_{-0.12}^{+0.09}$	$-0.38_{-0.14}^{+0.17}$
$4_1^+$	$-1.43_{-0.20}^{+0.30}$	-0.59(12)	-1.04(10)	-0.41(12)
$6_1^+$	$-0.67_{-0.20}^{+0.60}$			

largest scattering angles, and its additional spectroscopic constrains were added in a second step of the minimization. In Ref.[14], the  $0_2^+$  and  $3_1^+$  states were observed and the measured  $B(E2)$  were found to be large. Decays from both states were not observed in the present data. Their spectroscopic data were well determined [14, 28] and allowed us to investigate the effect of un-observed states in our minimization process. Therefore, in a third step of the minimization, the  $0_2^+$  and  $3_1^+$  states with their spectroscopic information were included in the minimization process. As a result, a minimum in  $\chi^2$  was obtained for a set of E2 and M1 matrix elements, including their relative signs, reproducing best the  $\gamma$ -ray intensities for all data sets and known spectroscopic information. Particular care was taken in verifying the uniqueness of the best solution after varying the relative signs of the matrix elements.

The transitional matrix elements allow to calculate the reduced transition probabilities and the spectroscopic quadrupole moments  $Q_s$  were deduced from diagonal matrix elements. The results are presented in table III and table IV. The experimental  $B(E2)$  values in table III labelled with the  $b$ -symbol are influenced by the

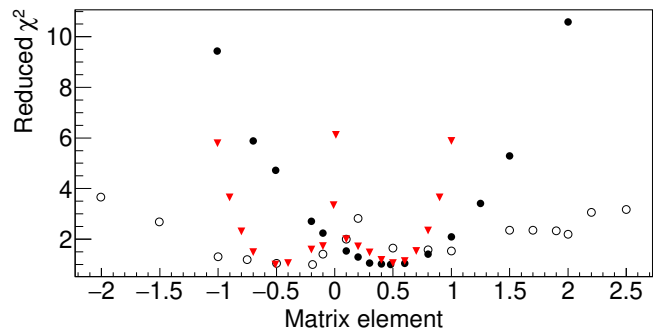


FIG. 5. (Color online)  $\chi^2$  scans for the E2 the  $3^+ \rightarrow 2_2^+$  (full circles) and  $4_2^+ \rightarrow 4_1^+$  (open circles)(eb) and M1  $4_2^+ \rightarrow 4_1^+$  (red triangle)( $\mu_N$ ) matrix elements.

$0_2^+$  and  $3_1^+$  states present in the GOSIA minimization. The final error bars include the statistical effects of observed transitions and the systematic effects from the un-observed  $0_2^+$  and  $3^+$  states. All the known branching ratio are reproduced within  $1\sigma$ . The  $\delta(E2/M1)$  mixing ratio for the  $2_2^+ \rightarrow 2_1^+$  and  $4_2^+ \rightarrow 4_1^+$  transitions are reproduced at 1.5 and 2.6  $\sigma$  respectively. All lifetimes are reproduced below  $1\sigma$ . All  $\gamma$ -ray intensities are reproduced below  $2\sigma$  except for the  $4_1^+ \rightarrow 2_1^+$  transition, in the last data set, with a deviation at 3.4  $\sigma$ .

$\chi^2$  scans were performed for the E2 and M1 matrix elements connecting the non-yrast states to the ground state band for which no  $\gamma$  transition is observed. The results are presented in figure 5. The  $\chi^2$  dependence on the E2 matrix element between the  $4^+$  states is weak as revealed by the large error bar. The M1 dependence is however very strong. Similarly, the  $\chi^2$  dependence on the E2 matrix element between the  $3_1^+$  and  $2_2^+$  states is strong excluding previously measured values. The  $\chi^2$  analysis shows that the dependence comes from agreement with the spectroscopic data such as the lifetime and the branching ratio for the  $3_1^+$  and  $2_2^+$  states. In the present analysis, the mixing and branching ratio used in the minimization were taken from the evaluated values in [28] as in [14], the experimental values from [12] were used having a significant deviation for the mixing ratio of the  $3_1^+ \rightarrow 2_2^+$  transition. A  $\chi^2$  scan for the  $2_1^+$  state diagonal matrix element is shown in figure 6. In the figure, only this matrix element was permitted to vary, keeping the others at their nominal values. This  $\chi^2$  scan is shown for illustration and cannot be used for the final error evaluation. The later shown in table III and table IV is obtained using the full GOSIA procedure [27].

The stability of the solution was investigated under different assumptions as shown in figure 7. The diagonal matrix element of the first  $2^+$  state was found very stable under these different constraints. In table III, three reduced transition probabilities are significantly different from the previous measurement. The  $B(E2, 4_1^+ \rightarrow 2_2^+)$  was found much smaller than the previous experimental value but becomes compatible

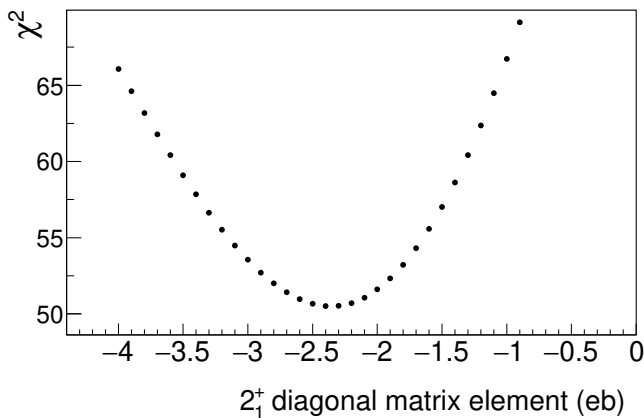


FIG. 6.  $\chi^2$  scan on the  $2_1^+$  diagonal matrix element. Only this matrix element was permitted to vary, others remain fixed.

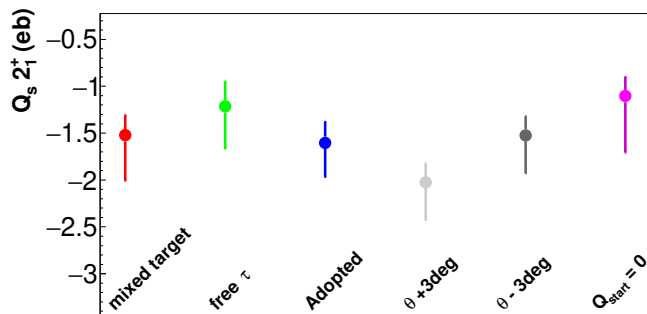


FIG. 7. Stability of the solution under different assumptions. In red,  $^{nat}W$  is considered as mixed in Fe, i.e. cross sections are integrated over the full Fe thickness. In blue, the W is facing VAMOS, i.e. cross sections are calculated at the lowest beam energy (table III). The light (dark) gray assumes a misalignment in scattering angle of  $\pm 3$  degrees in the laboratory frame respectively. In violet, the minimization is forced to low  $Q_s$  and constrained released for final solution. In green, all lifetimes are a free parameter of the minimization.

with the IBM-1 calculations having a remarkable agreement with the experimental data. The  $B(E2, 3_1^+ \rightarrow 2_2^+)$  and  $B(E2, 4_2^+ \rightarrow 4_1^+)$  were also found much smaller with large error bars and deviate from the IBM-1 calculations.

The deduced spectroscopic quadrupole moments for the  $2_1^+$ ,  $4_1^+$  and  $6_1^+$  states are shown in table III. They are large and negative underlining the prolate axial deformation of the ground state band with an axial deformation parameter  $\langle \beta_2 \rangle \approx 0.3$ . The matrix elements were further analyzed using the quadrupole sum rules approach [25]. This method relates experimentally determined E2 matrix elements to deformation parameters, defined in the intrinsic frame of the nucleus, by constructing quadrupole invariants  $\langle Q^2 \rangle$  and  $\langle Q^3 \cos(3\delta) \rangle$ . The  $Q$  parameter describes the magnitude of the deformation, while the  $\delta$  parameter measures triaxiality. To determine

the  $\langle Q^2 \rangle$  invariant for a  $0^+$  state, it is necessary to measure absolute values of all E2 matrix elements that couple the state in question with low-lying  $2^+$  states. To obtain the triaxiality parameter,  $\langle \cos(3\delta) \rangle$ , more experimental information is needed, namely transitional matrix elements, along with their relative signs, between the state in question and  $2^+$  states, those coupling the  $2^+$  states one to another, as well as diagonal E2 matrix elements of the  $2^+$  states. As shown in [34], the  $\langle Q^2 \rangle$  invariant for the ground state in even-even nuclei is dominated by the contribution of the  $\langle 0_1^+ || E2 || 2_1^+ \rangle$  matrix element. The  $\langle 0_1^+ || E2 || 2_2^+ \rangle$  and  $\langle 0_1^+ || E2 || 2_3^+ \rangle$  matrix elements contributed less to the final  $Q^2$  value for the ground state. The situation is more complex for the higher-order quadrupole invariant  $\langle Q^3 \cos(3\delta) \rangle$ . Ref. [35] demonstrates that this invariant can be derived with a good accuracy using only four matrix elements:  $\langle 0_1^+ || E2 || 2_1^+ \rangle$ ,  $\langle 2_1^+ || E2 || 2_1^+ \rangle$ ,  $\langle 2_1^+ || E2 || 2_2^+ \rangle$  and  $\langle 2_2^+ || E2 || 0_1^+ \rangle$ . In the particular case of  $\gamma$  unstable deformed nuclei, the contribution of both  $2_2^+$  and  $2_3^+$  must be included. For  $^{124}\text{Xe}$ , matrix elements between the  $2_1^+$  and  $2_2^+$  states and the ground state were determined. All reduced transition probabilities between the  $2_3^+$  and  $0_2^+$  states and the observed states are known from Ref.[14] and can be translated in E2 matrix elements with unknown sign. All combinations of signs were tested giving rise to systematic errors in our calculations. The sum rules yield for the  $0_1^+$  state  $\langle Q^2 \rangle = 1.07(\pm 2 \text{ stat.}) (\pm 1 \text{ sys.}) e^2 b^2$  and  $\langle \cos(3\delta) \rangle = 1.7 (\pm 5 \text{ stat.}) (\pm 3 \text{ sys.})$ . The  $\langle Q^2 \rangle$  was found large as expected for a rotational ground state band. Its value is similar to the one measured for the  $0_1^+$  state in  $^{126}\text{Xe}$  and  $^{128}\text{Xe}$  [33]. However, the  $\langle \cos(3\delta) \rangle$  parameter is found two times larger than the corresponding value in  $^{126}\text{Xe}$  and  $^{128}\text{Xe}$  [33] supporting the fast increase of axiality toward mid-shell. The second invariant can also be translated in the deformation parameter  $\gamma \approx 1/3 \cdot \arccos(\langle \cos(3\delta) \rangle)$ . With  $\langle \cos(3\delta) \rangle = 1.7(5)(3)$ , the deformation parameter  $\gamma$  is null underlining the pure axial symmetry of the  $0_1^+$  state and thus supporting a significant breaking of the  $O(6)$  symmetry.

#### IV. DISCUSSION

The presented result can be placed within a wider systematics. In figure 8, the systematic of the reduced transition probabilities for the first  $2^+$ ,  $B(E2, 2_1^+ \rightarrow 0_1^+)$ , is shown as a function of the neutron number for the even-mass isotopes of Sn, Te, Xe and Ba. The  $N=82$  shell closure is well marked with a minimum of  $B(E2)$ . When removing neutrons, the collectivity follow a smooth increase toward mid-shell having a maximum at  $N=66-68$  and an amplitude proportional to the number of proton pairs outside of the  $Z=50$  shell closure. The spectroscopic quadrupole moment obtained for  $^{124}\text{Xe}$  (blue square) is compared to the spectroscopic quadrupole moments of odd-mass Xe (full squares), Ba, Te and Sn ground states and  $2_1^+$  states for the even-mass

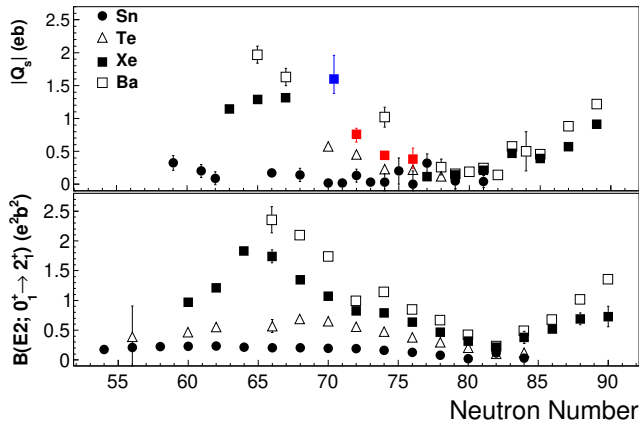


FIG. 8. (Color online) Top : Spectroscopic quadrupole moment systematics as a function of the neutron number for Sn, Te, Xe and Ba elements. The present work is highlighted in blue for  $^{124}\text{Xe}$ . The recent measurements in  $^{126-130}\text{Xe}$  [10, 33] are shown in red. Bottom: Reduced transition probability systematics as a function of the neutron number for Sn, Te, Xe and Ba elements.

isotopes, where known. The recent measurement in  $^{126-130}\text{Xe}$  [10, 33] are shown in red squares. The newly presented data points fit both the systematics of the  $^{117-121}\text{Xe}$  isotopes with large values reaching a maximum at  $N=70$ , indicating large deformation, followed by the decrease as function of the neutron number, in line with the systematic of  $^{126-130}\text{Xe}$ . From  $^{131}\text{Xe}$ , approaching the  $N=82$  neutron shell closure, the spectroscopic quadrupole moments are reduced. The systematics suggests a fast decrease of the  $\beta$  deformation in the Xe chain, probably associated to an increase of triaxiality as suggested in [10]. The spectroscopic quadrupole moment for the  $2_1^+$  and  $4_1^+$  states are compared for  $^{124-130}\text{Xe}$  in table III; The continuous increase of the  $Q_s$  of the  $2_1^+$  state from  $^{130}\text{Xe}$  to  $^{124}\text{Xe}$  is clearly visible. The analysis for the  $4_1^+$  is less evident. The value for  $^{124}\text{Xe}$  is significantly larger than the one reported for the heavier isotopes suggesting an axially deformed state.

The large values of the spectroscopic quadrupole moments support the breaking of the  $O(6)$  symmetry in  $^{124}\text{Xe}$  as suggested by [14] and favor the  $SU(3)$  symmetry for the ground state band. The exact  $O(6)$  symmetry is an ideal case of  $\gamma$ -unstable rotor for which  $\langle \cos(3\delta) \rangle$  equals zero. Any small admixture of other symmetries will lead to  $\langle \cos(3\delta) \rangle \neq 0$ .  $^{124}\text{Xe}$  has drawn some attention since its level scheme is in remarkable agreement with the IBM-1 model calculations having a large triaxial degree of freedom and with the typical spectrum for a nucleus exhibiting the  $O(6)$  symmetry [12, 36]. Even if the agreement with the level scheme is very good, the comparison with the transition probabilities has shown that the  $O(6)$  symmetry is substantially broken [14] and it is confirmed by the present spectroscopic quadrupole moments.

$^{124}\text{Xe}$  is collective but with a  $R_{42}=E(4_1^+)/E(2_1^+)$  ratio equal to 2.48, it cannot be considered as a rotational nucleus at the limit of  $SU(3)$ . In [37], a large survey of the correlation between experimental spectroscopic quadrupole moments  $Q_s$ ,  $B(E2)$  and  $R_{42}$  ratio is presented.  $X(5)$  symmetry like nuclei such as  $^{148-150}\text{Nd}$ ,  $^{152}\text{Sm}$  and  $^{154}\text{Gd}$  present large spectroscopic quadrupole moments with respect to their respective  $R_{42}$  and  $B(E2, 2_1^+ \rightarrow 0_1^+)$  values. In this survey a  $R_{QB}$  parameter was defined from the  $2_1^+$  spectroscopic quadrupole moments and  $B(E2)$  to the ground state. The  $^{124}\text{Xe}$  value is  $R_{QB} = 1.46(^{+21}_{-46})$ . It lies at the extreme of the  $R_{QB}$  systematics along the nuclear chart with the  $^{148-150}\text{Nd}$  or  $^{200-202}\text{Hg}$  which are just below and above the rotational region where  $R_{QB} \approx 1$ . The systematic in [37] shows that these large  $R_{QB}$  are between Nd and Os elements. The present results suggest that it could be extended up to Xe and such cases remain to be understood.  $^{124}\text{Xe}$  has extraordinary similarities with the  $X(5)$ -like nucleus  $^{148}\text{Nd}$ . The  $^{124}\text{Xe}$  ( $^{148}\text{Nd}$ )  $Q_s$  equals  $-1.51^{+21}_{-48}$  ( $-1.46(13)$ ) (eb),  $B(E2, 2_1^+ \rightarrow 0_1^+)$  equals  $57.7(16)$  ( $57.5(13)$ ) (Wu). and  $R_{42}$  equals 2.48 (2.49), respectively.  $^{148}\text{Nd}$  was investigated in detail by safe Coulomb excitation [38]. Similarly to  $^{124}\text{Xe}$ ,  $^{148}\text{Nd}$  presents a coexistence below 1.5 MeV excitation energy of a rotational ground state band, an octupole collective band, a  $\beta$ -band and a  $\gamma$ -band. The fair similarities between the in-band E2 matrix elements for the ground states bands and for  $\gamma$ -bands and inter-band E2 matrix elements between the two collective bands suggest that both nuclei can be described as deformed axial nuclei and deviation from the rotational behavior can be accounted for by including the coupling between rotational and vibrational modes [38]. The detailed coupling between the quadrupole rotation and the octupole vibration requires further experimental verification in  $^{124}\text{Xe}$ .

## V. CONCLUSION

The spectroscopic quadrupole moments for the  $2_1^+$ ,  $4_1^+$  and  $6_1^+$  states have been determined for the first time in  $^{124}\text{Xe}$  using the safe Coulomb excitation technique using a target with high-Z. The values found are large and negative underlining a large prolate axial deformation. These large spectroscopic quadrupole moments support that the  $O(6)$  symmetry is substantially broken. A more microscopical approach would be necessary to fully understand the collective behavior at low angular momentum in the mid-shell Xe isotopes. The large measured spectroscopic quadrupole moments lie at the limits of the nuclear collective models. We acknowledge the GANIL facility for provision of heavy-ion beams and we would like to thank J. Goupil, G. Fremont, L. Ménager, J. Ropert, C. Spitaels for assistance in using the G1 beam line and its instrumentation. This work was sup-

ported by STFC(UK). This research was also supported by the OASIS Project No. ANR-17-CE31-0026, by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC02-06CH11357, by the European Regional Development Fund with Contract No. GINOP-2.3.3-15-2016-00034 and by the Spanish Ministerio de Ciencia e Innovación

under contract PID2020-118265GB-C41. Work partially supported by Grants FPA2017-84756-C4, PID2020-118265GB-C4 by MCIN/ AEI /10.13039/501100011033, PROMETEO/2019/005 by Generalitat Valenciana and by the FEDER EU funds.

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