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Short Note

Coulomb excitation of $^{72}_{30}$Zn$_{42}$

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Abstract. The reduced transition probability $B(E2\colon 0_1^+ \to 2^+)$ of ^{72}Zn has been measured for the first time by Coulomb excitation at intermediate energy. The result $B(E2\colon 0_1^+ \to 2^+) = 1740 \pm 210\ e^2\text{fm}^4$, corresponds to the deformation parameter β_2 of 0.23, in close agreement with expectations derived from the neighboring nucleus ^{73}Zn. A discussion of the evolution of the $N = 40$ sub-shell closure as a function of Z is presented.

PACS. 25.70.De Coulomb excitation – 23.20.-g Electromagnetic transitions

1 Introduction

The $N = 40$ spherical sub-shell closure is characterized by a change of parity between the $N = 3\ p_{1/2}p_{3/2}f_{5/2}$ orbitals and the intruder $N = 4\ g_{9/2}$ orbital. As a result of this parity change, quadrupole excitations $B(E2\colon 0_1^+ \to 2_1^+)$, which preserve the parity symmetry, are strongly reduced as observed in the case of $^{68}_{28}$Ni [1]. The spherical $N = 40$ gap may not be strong enough to stabilize the nuclei in a spherical shape when protons are added to the ^{68}Ni core. Indeed several even-even $N = 40$ isotones exhibit remarkable sequences of low-energy excited states, with the first excited 0^+ state lying very close or below the first 2^+ state. It has been suggested that deformed states co-exist with spherical ones; the 0_1^+ or 0_2^+ corresponding alternatively to spherical or deformed configuration depending on the proton number [2–5]. Even with a moderate deformation, $\beta_2 \sim 0.25$, the density of Nilsson orbitals is very high, thus providing many possibilities to generate 2^+ states via particle-hole excitations, as deformation smears out the distinction between the negative- and positive-parity states below and above the $N = 40$ spherical gap, respectively. The $B(E2\colon 0_1^+ \to 2_1^+)$ is therefore expected to be large if the spherical $N = 40$ gap is not strong enough to prevent the nuclei from deformation. Consequently, a maximum of collectivity is expected approximately at mid-distance between $N = 28$ and $N = 50$.

The present paper focuses on the development of collectivity in the $_{30}$Zn isotopic chain, which appears to be a transitional region between the spherical $_{28}$Ni isotopes and the deformed $_{32}$Ge nuclei. The $B(E2\colon 0_1^+ \to 2_1^+)$ of ^{72}Zn has been measured in order to investigate the evolution of the collectivity along the Zn isotope chain, up to $N = 42$. The nuclear structure in the vicinity of the $N = 40$ sub-shell closure is discussed in the light of the $B(E2)$ and $E(4^+)/E(2^+)$ systematics.

2 Experimental procedure and results

Secondary beams of ^{76}Ge and ^{72}Zn were produced via the reaction of a 50 AMeV ^{86}Kr beam furnished by the GANIL

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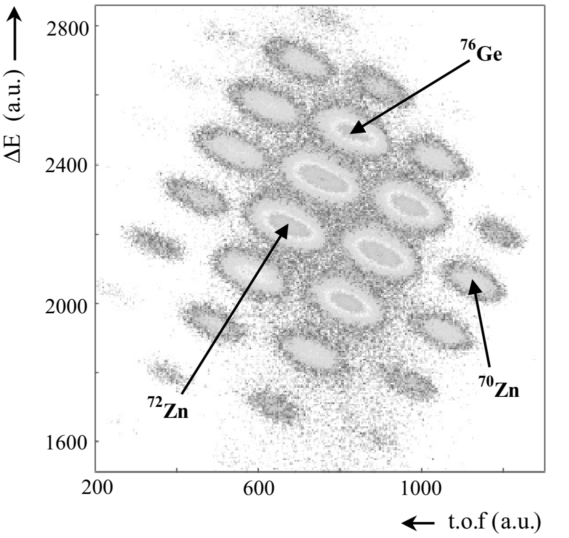

Fig. 1. Spectrum of energy loss (ΔE) *versus* time of flight (t.o.f.).

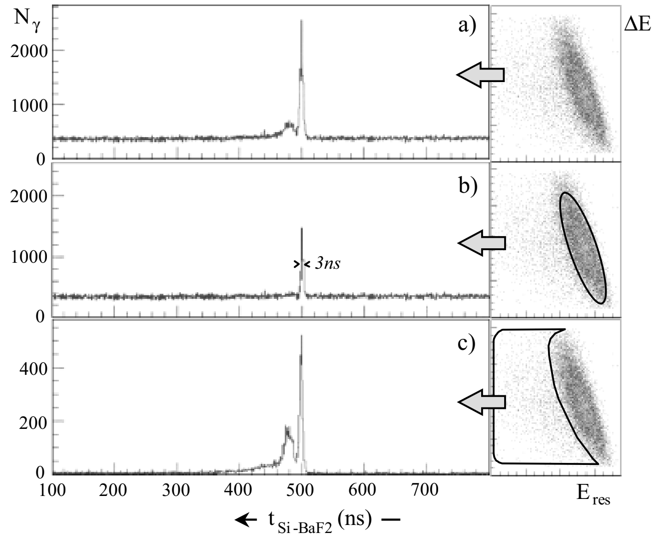

Fig. 2. Time difference between the detection of a ^{76}Ge ion in the first Si-detector (selected by means of ΔE-t.o.f. conditions) and a γ-ray in any BaF_2 crystal. The prompt peak has been placed approximately in the middle of the time spectrum. The right part shows the ΔE, $E_{\rm res}$ spectrum for ^{76}Ge in which the different reaction channels have been selected.

coupled cyclotrons on a ^{58}Ni target (100 μm). The reaction products of interest were selected and purified using the LISE3 spectrometer operated with an achromatic degrader (Be, 94 μm). The mean β of the ^{76}Ge and ^{72}Zn was 0.28. The intensities were some 100 and 120 pps, respectively.

A secondary Pb reaction target ($220\,{\rm mg}\cdot{\rm cm}^{-2}$) was employed to induce the Coulomb excitation. This was followed some 50 cm dowstream by a two-element large area (25 cm^2) Si-detector telescope. The first element (300 μm) was used to determine the energy loss (ΔE), which is proportional to Z^2. The second element (3.5 mm) provided a measure of the residual energy ($E_{\rm res}$). The time of flight (t.o.f.) was derived from the timing signal of the first Si-detector with respect to the cyclotron radiofrequency.

Figure 1 displays a ΔE *versus* t.o.f. spectrum showing the nuclei produced in the experiment. The identification was confirmed by the detection of the γ-decay of the well-known $13/2^+$ isomeric state in ^{69}Cu [6].

The Si-telescope provided an angular coverage up to 3 degrees in the projectile reference frame. This is well below the grazing angle of the system (6.5 degrees), ensuring that the excitation process was purely Coulomb in origin.

The target was surrounded by an array composed of 70 BaF_2-detectors of the "Chateau de Cristal" which were mounted in a 4π geometry at a distance of 32 cm from the target. Each BaF_2 crystal is an hexagonal cylinder of 9 cm diameter and 14 cm length. The photopeak efficiency of the array at 600 keV was 6.5%. The energy resolution, including both the intrinsic resolution of the detectors and the Doppler broadening arising from the in-flight emission, was about 15%.

γ-ray spectra could be constructed by applying appropriate conditions on the ΔE-t.o.f. spectrum of fig. 1 for each secondary beam transmitted by the spectrometer. This procedure could be achieved event by event, which made possible to study the Coulomb excitation of each isotope of fig. 1 for only one spectrometer setting. Figure 2a shows the time difference between the detection of a ^{76}Ge ion in the first Si-detector (selected by means of ΔE-t.o.f. conditions) and a γ-ray in any BaF_2 crystal. Moreover, by gating on ΔE and $E_{\rm res}$, two principal types of reactions could be selected, as displayed in figs. 2b,c. The middle spectrum (fig. 2b) is restricted to ^{76}Ge nuclei which have not undergone nucleon removal reaction of any sort. The narrow peak corresponds to events with γ-rays arising from the Coulomb excitation of both the projectile (^{76}Ge in this case) and the target nuclei. The width of the peak (FWHM = 3 ns) is a convolution between the resolution of the Si-detector and the BaF_2-detectors. Given this time resolution and the low rate of total nuclei which impinged onto the target (2000 per second), each photon detected could be attributed to a precursor nucleus unambiguously. The bottom spectrum (fig. 2c) is conditioned on nuclei detected at lower $E_{\rm res}$, which have lost at least one nucleon. In such cases of fragmentation or transfer reaction, the projectile and/or the target residues, having high excitation energy, de-excite by the emission of neutrons and γ-rays. The broader peak observed at longer times corresponds to the neutrons. The flat component in figs. 2a,b is the result of random coincidences between ions which triggered the Si-detectors and for which a signal generated by the γ background in the experimental area or the internal α radioactivity was detected in one of the BaF_2 crystals within 800 ns. Part of this bakground sits below the prompt peak. It is of importance to estimate its contribution and to subtract it to obtain the final γ energy spectra. We have, therefore, built an energy spectrum gated on a part of the background (flat) component in the time spectrum (fig. 3c) with a time width similar to that of the prompt peak of fig. 3a. Then, the background-

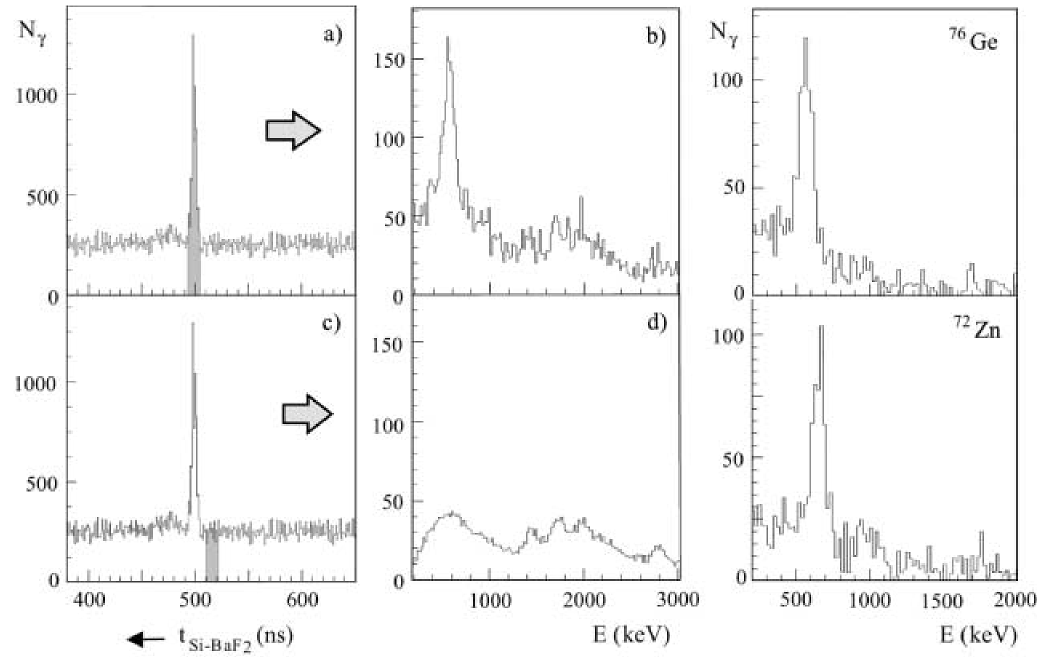

Fig. 3. Left: time spectra for ^{76}Ge on which different selections have been operated to build prompt and delayed γ energy spectra (spectrum b) and d), respectively). Right: background-subtracted and Doppler-corrected γ-ray spectra for ^{76}Ge (top) and ^{72}Zn (bottom).

gated γ energy spectrum of fig. 3d was subtracted to the prompt-gated γ energy spectrum of fig. 3b. This leads to the spectra of the right part of fig. 3 from which the numbers of γ-rays emitted in the Coulomb excitation of ^{76}Ge and ^{72}Zn were subsequently extracted. The Doppler shifts, which depend on the detection angles, were corrected in order to retrieve the energy of the emitted γ-rays.

The collective behaviour of ^{76}Ge at low excitation energy is well known: the first 2^+ state is located at low energy (563 keV) and the reduced transition probability is large, $B(E2\colon 0^+_1 \to 2^+_1) = 2680(80)\ e^2\mathrm{fm}^4$ [7]. It has thus been used here as a reference nucleus to determine the $B(E2)$ value of ^{72}Zn. From the number of incident nuclei and γ-rays detected, the $B(E2)$ of ^{72}Zn was determined from that of ^{76}Ge after having corrected for the efficiency of the BaF_2 array at the energy of the $2^+ \to 0^+$ transition in each nucleus. Given that the Coulomb excitation of both nuclei occured under the same geometrical conditions, at similar velocities, and with the emission of photons in the same energy range, further corrections to the $B(E2)$ are consequently negligible. $B(E2)\!\uparrow = 1740(210)$ $e^2\mathrm{fm}^4$ was deduced for ^{72}Zn. The error bar on the $B(E2)$ value mainly corresponds to the uncertainty on the counting of the photons in the spectra of fig. 3 and on the determination of the γ-ray efficiencies at 563 keV and 652 keV. From the $B(E2)$ value, a deformation parameter of $\beta_2 = 0.233(14)$ is derived using the relations $B(E2)\!\uparrow = 5/(16\pi)Q_0^2$ and $Q_0 = 0.757\ ZR^2\beta_2$, where Q_0, Z, R are the intrinsic quadrupole moment, atomic number and radius of the nucleus, respectively. This value may be compared with that obtained for the neighbouring isotope ^{73}Zn ($\beta_2 \sim 0.2$) in order to reproduce the energy and the spin of the $5/2^+$ isomer ($t_{1/2} = 13$ ms), populated in the β-decay of ^{73}Cu [8].

3 Discussion

Information on the nature of the $N = 40$ sub-shell closure for the $_{28}$Ni, $_{30}$Zn and $_{32}$Ge isotopic chains can be derived from the systematics of the $B(E2)\!\uparrow$ values (fig. 4). Part of this systematics is known for a long time ($^{70\text{-}76}$Ge, $^{62\text{-}70}$Zn)

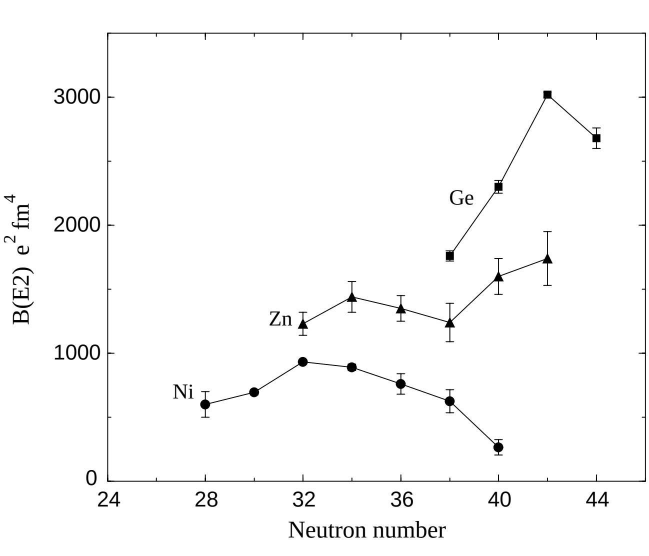

Fig. 4. Experimental $B(E2)\!\uparrow$ values as a function of the neutron number N for Ni (filled circles, [1,7,9]), Zn (triangles, [7] and this work) and Ge (squares, [2,7,10]) isotopic chains.

but only these two isotopic series have been compared (see for instance [11,12]). Thanks to the new experimental $B(E2)$ values of ^{72}Zn and ^{66,68}Ni [1], the drastic change of structural effect at $N = 40$ between the Ni and Ge isotopic chains can now be discussed.

The qualitative behaviour of the $B(E2)$ values along the Ni isotopic chain can be interpreted in terms of neutron excitations in the restricted $p_{3/2}f_{5/2}p_{1/2}$ (or "fpr") valence space, as already discussed in ref. [1]. The $B(E2)$ values reach a maximum at mid-distance between $N = 28$ and $N = 40$, when the number of active neutrons in the fpr is maximum. While filling the fpr orbits up to $N = 40$, the possibilities to generate quadrupole excitations are drastically reduced. Indeed, positive-parity excitations are hindered across the $N = 40$ gap, *e.g.*, from the negative-parity fpr orbits to the positive-parity $g_{9/2}$ orbit. Nevertheless, the neutron pair scattering across $N = 40$ induces a polarization of the proton core. The importance of pair scattering around ^{68}Ni has already been pointed out in several papers [1,13].

In the Zn isotopic chain, the $B(E2)$ values also exhibit a maximum around $N = 34$ and subsequently decrease with the same slope as the Ni chain up to $N = 38$. Between $N = 32$ and $N = 38$, the values for the Zn curve are larger than those for Ni, owing to the fact that the $B(E2)$ values of Zn also contain the contribution arising from the two extra protons in the fp shell. At $N = 38$, the Zn curve strongly deviates from that of the Ni isotopes, reaching a maximum value for ^{72}Zn. This can be qualitatively interpreted in terms of the onset of deformation, which could result from the combination of three effects: the addition of two protons out of the Ni core, the maximum in neutron pairing correlations at $N = 40$ [1], and the presence of the strongly downsloping $l = 4$ Nilsson neutron orbitals close to the Fermi surface. In fact, even with a modest deformation value, such as $\beta_2 \sim 0.23$ extracted from the $B(E2)$ values of ^{70}Zn or ^{72}Zn, positive-parity single-particle levels penetrate into the region of negative-parity states due to the splitting of the orbitals as a function of deformation. For instance, in ^{71}Zn, at least two positive- and three negative-parity states exist below 500 keV excitation energy [14]. Since there is no longer clear separation between positive- and negative-parity states as in ^{68}Ni, a large $B(E2)$ value can be generated in ^{70,72}Zn, as a lot of excitations involving both neutrons and protons are activated. The experimental $B(E2)$ value for ^{72}Zn ($B(E2)\!\uparrow = 1740(210)\ e^2\mathrm{fm}^4$) is in excellent agreement with the value obtained in shell model calculations ($B(E2)\!\uparrow = 1740\ e^2\mathrm{fm}^4$) [15]. The interaction and valence space used to describe ^{72}Zn are the same as those used for the study of ^{68}Ni [1].

The $B(E2)$ values for the Ge isotopes display[1] a steep and constant increase between $N = 38$ and $N = 42$, with a maximum at $N = 42$ (fig. 4). As in the Zn isotopic chain,

[1] We have not reported in fig. 4 the values which can be calculated for ^{66,68}Ge from the half-lives of the 2_1^+ states [16] as they seem too low as compared to expectations from the 2_1^+ energies. It would consequently be very important to measure directly the $B(E2)$ values of ^{66,68}Ge.

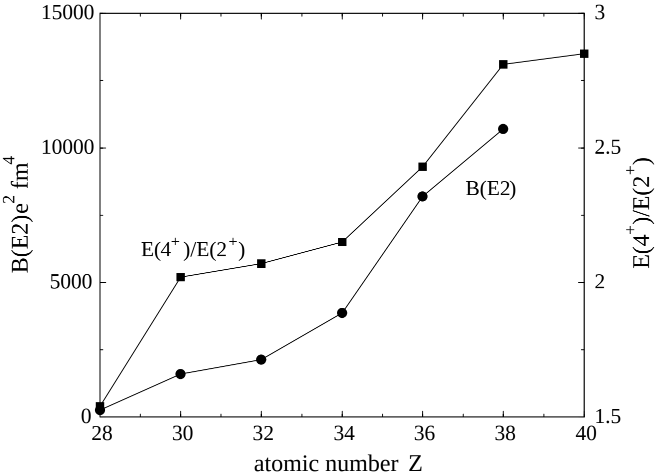

Fig. 5. Experimental $B(E2)$ values (filled circles) and $E(4^+)/E(2^+)$ ratios (filled squares) for the $N = 40$ isotones as a function of the atomic number.

the $N = 40$ spherical sub-shell closure is not "seen". The nucleus ^{74}Ge$_{42}$ exhibits a typical mid-shell behaviour, with a maximum $B(E2)$ value. The sharp decrease in $B(E2)$ after $N = 42$ indicates the effectiveness of the $N = 50$ shell closure which is confirmed by the high excitation energy of the 2_1^+ in ^{82}Ge$_{50}$ [16].

Having investigated the $N = 40$ sub-shell closure in the Ni, Zn and Ge isotopes, we will now extend it up to $_{40}$Zr. Figure 5 shows the evolutions of the $B(E2)\!\uparrow$ and the ratio $E(4^+)/E(2^+)$ for the $N = 40$ isotones as a function of the atomic number Z. The trend in $B(E2)$ is reasonably well correlated with that of the $E(4^+)/E(2^+)$ one. For a spherical shell closure at $Z = 40$, the $B(E2)$ curve would have started to decrease at $Z = 34$, which is at mid-shell between $Z = 28$ and $Z = 40$. The opposite trend is in fact observed, with a continuous increase of both collectivity and the ratio $E(4^+)/E(2^+)$. This ratio reaches a value of 2.85 for $^{80}_{40}$Zr$_{40}$, close to the value for a rigid rotor. Even though the $B(E2)$ of ^{80}Zr has not been measured so far, the $E(4^+)/E(2^+)$ systematics suggest that the deformation will be maximum at $Z = 40$. It is worth pointing out that the $B(E2)$ for ^{80}Zr is expected to be larger than that of its neighbours, as it lies very close to the drip line where additional contributions from excitations to the continuum should occur. In addition, it is a self-conjugate ($N = Z$) nucleus and proton-neutron quadrupole excitations should add to the collectivity as in the case of $^{56}_{28}$Ni$_{28}$ [9].

To summarize, the ground states of $N = 40$ isotones progressively evolve from spherical to well-deformed shapes. It is found that the *deformed* $N = 40$ shell gap dominates over the *spherical* one when the proton number is $Z = 40$.

4 Conclusion

The Coulomb excitation of ^{72}Zn has been measured for the first time. The $B(E2)\!\uparrow$ value of 1740(210) $e^2\mathrm{fm}^4$ corresponds to a moderate deformation of $\beta_2 = 0.233(14)$. It has been shown that the behaviour of $B(E2)$ around the $N = 40$ sub-shell closure is very different in the Ni and Zn isotopic chains. In the Ni isotopes, a minimum of collectivity is found at $N = 40$, whereas in the Zn isotopic chain, collectivity increases at least up to $N = 42$. It is concluded that the Zn isotopes reside in a transitional region between the spherical Ni and deformed Ge nuclei.

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