Search for Isovector Valence-Shell Excitations in ^{140}Nd and ^{142}Sm via Coulomb excitation reactions of radioactive ion beams

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Abstract. Projectile Coulomb excitation experiments were performed at HIE-ISOLDE at CERN with the radioactive ion beams of ^{140}Nd and ^{142}Sm. Ions with an energy of 4.62 MeV/A were impinging on a 1.45 mg/cm^2 thick ^{208}Pb target. The γ-rays depopulating the Coulomb-excited states were recorded by the HPGe-array MINIBALL and scattered particles were detected by a double-sided silicon strip detector. Experimental intensities were used for the determination of electromagnetic transition matrix elements. A preliminary result of the $B(M1; 2^+_3 \to 2^+_1)$ of ^{140}Nd and an upper limit for the case of ^{142}Sm are revealing the main fragments of the proton-neutron mixed-symmetry $2^+_{1,\mathrm{ms}}$ states.

1 Introduction

The proton-neutron interaction is of particular interest in respect how collectivity emerges in nuclear many-body quantum systems. The quadrupole-quadrupole part of this interaction forms the lowest-lying collective states in heavy open-shell nuclei. These states have wave functions which are completely symmetric in respect to the exchange of any proton and neutron components. In the framework of the Interacting Boson Model (IBM) [1, 2] the states are dubbed fully symmetric states (FSSs). On the other hand, the distinction of protons and neutrons explicitly introduced in the IBM, the IBM-2 [1, 3], results in a class of states which can be partially asymmetric in respect to the proton-neutron exchange. These are the so-called proton-neutron mixed-symmetry states (MSS). Proton-neutron MSS are collective excitations where the protons and neutrons oscillate out of phase. This type of states exhibits information about the isovector part of the proton-neutron interaction which is not accessible via the study of FSSs [1, 2].

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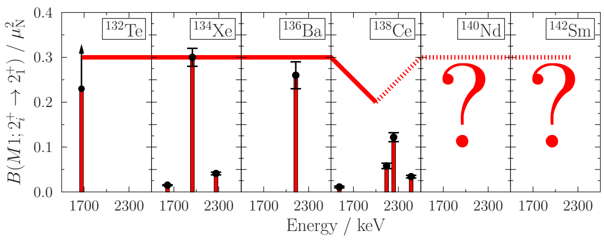

Figure 1. (Color online) The experimental $M1$-strength distributions of $2^+_i \to 2^+_1$ transitions of even-even N=80 isotones from ^{132}Te (Z=52) to ^{138}Ce (Z=58) show the evolution of fragmentation of the $2^+_{1,\mathrm{ms}}$ state along this isotonic chain. The question marks at ^{140}Nd and ^{142}Sm present the question which this experiment tries to answer. The graphic is taken from Ref. [4].

According to the IBM-2 the lowest-lying isovector valence-shell excitation in vibrational nuclei is the one-quadrupole-phonon $2^+_{1,\mathrm{ms}}$ state [2, 3], which exhibits some significant decay properties due to its isovector nature. The most indicative signature is a strong $M1$ transition to the symmetric one-quadrupole-phonon 2^+_1 state, as well as

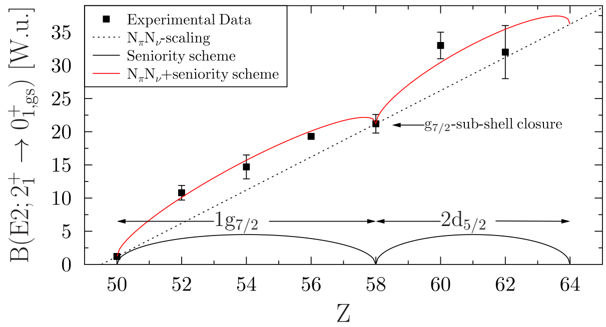

Figure 2. (Color online) The collectivity of the 2^+_1 of even-even N=80 isotones from the proton-shell closure at Z=50 to Z=62 is shown via experimental $B(E2; 2^+_1 \rightarrow 0^+_1)$ values. These values are described by a superposition of a simple $N_\pi N_\nu$ scaling and the seniority scheme [25]. The graphic is taken from Ref. [19].

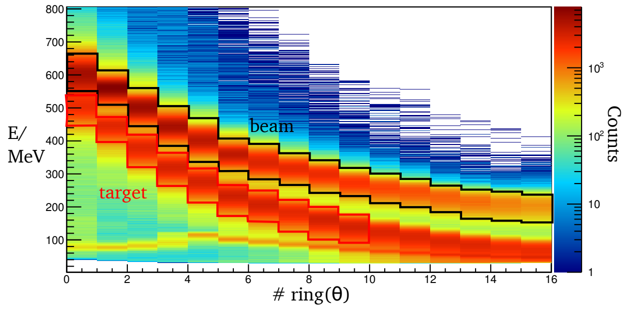

Figure 3. (Color online) The spectrum of the DSSD shows the particle energy of the ^{208}Pb(^{142}Sm,^{142}Sm*)^{208}Pb* reaction in dependence of the scattering angle, ring #1 corresponds to 21° and ring #16 to 60°. The used gates for the scattered projectile (black) and the recoiling target (red) particles are marked.

a weakly-collective $E2$ transition (≈1 W.u.) to the ground state; see, e.g., Refs. [5–9]. The strong $M1$ transition (≈0.2 μ_N^2) [9], which is strongly suppressed for isoscalar transitions [3], serves as the main experimental signature for the identification of the one-quadrupole-phonon MSS.

One-phonon MSSs are identified in many even-even vibrational nuclei in different mass regions [9]. Prominent examples are found in the mass A=90 region. Several cases are reported in the mass A=130 region and recently three cases are found in the mass A=208 region [10–12]. It is observed, that the even-even N=80 isotones form isolated proton-neutron mixed-symmetry $2^+_{1,ms}$ states from Z=52 to Z=56 [13–15]. For ^{136}Ba, it was shown that the one-phonon FSSs (2^+_1) and MSSs ($2^+_{1,ms}$) are formed by excitations in open orbitals – $\nu 1h_{11/2}$ and $\pi 1g_{7/2}$ [16]. This situation changes at ^{138}Ce (Z=58). In contrast to the Z<58, isotones ^{138}Ce shows a significant fragmentation of the $2^+_{1,ms}$ state as illustrated in Fig. 1. It was suggested that the fragmentation is caused by a fully filled $\pi 1g_{7/2}$ orbital [17], which leads to a breaking of this filled orbital structure to form nuclear excited states. So, the configuration of the $2^+_{1,ms}$ state gets more complex and it starts mixing with near-lying 2^+ states. This effect is called lack of valence-shell stabilization and leads to the suggestion of a proton sub-shell closure at ^{138}Ce (Z=58) [17] for the N=80 isotones.

An indirect manifestation of the Z=58 sub-shell closure is already observed in the evolution of the FSSs in the N=80 isotones. The properties of the one-phonon FSSs in N=80 isotones are measured from Z=50 to Z=62 [13, 18–24]. The evolution of the $B(E2; 2^+_1 \rightarrow 0^+_1)$ strength can be outlined as an almost smooth rise from the proton-shell closure Z=50 towards mid-shell, with a small decrease at Z=58 as illustrated in Fig. 2. This shallow minimum, in addition with a sudden increase of collectivity at Z=60 (cf. Fig. 2), is an indication, that the trend of the collectivity cannot be described solely by a simple proportionality to the product of the number of valence protons N_π and of valence neutrons N_ν [25]. Apparently sub-shell effects, stemming from seniority like behavior [19, 20], modulate the rise of collectivity in this isotonic chain. Applying the seniority scheme, one expects the highest contribution to the collectivity when an orbital is half filled and no contribution when it is fully filled with nucleons [19, 20]. A superposition of both models depicts the experimental data quite well (cf. Fig. 2).

To test directly the hypothesis of shell stabilization of MSSs in the N=80 isotones, these states have to be identified in the isotones with Z>58, i.e. in ^{140}Nd and ^{142}Sm. The main goal of the present work is to address this task by measuring the Coulomb-excitation yields of ^{140}Nd and ^{142}Sm radioactive ion beams.

2 Experiment

The projectile Coulomb-excitation experiments were performed at the radioactive ion beam facility HIE-ISOLDE at CERN [26]. The radioactive ^{140}Nd and ^{142}Sm were produced by irradiating a thick tantalum target with 1.4 GeV protons, which were provided by the CERN PS Booster. An identical primary target has been used in previous measurements [19, 20]. The hot surface ion source was combined with the laser ionization system RILIS [27] to maximize the rate of the desired isotope. The mass selection is done with GPS following a post acceleration through HIE and REX cavities up to 4.62 MeV/A leading to an ion velocity of about 9% of the speed of light. The radioactive ion beam was impinging on a 1.45 mg/cm^2 thick ^{208}Pb target. The chosen beam energy is equivalent to about 76% of the Coulomb barrier for the ^{140}Nd/^{142}Sm+^{208}Pb reaction and can be considered as "safe" Coulomb excitation [28] at all relevant scattering angles. The MINIBALL spectrometer [29] consisting of 24 six-fold segmented HPGe-detectors was used for the γ-ray detection. Additional a double-sided silicon strip detector (DSSD) was placed in forward direction, 21°÷60° in the lab frame with respect to the beam axis. It is used for detection and identification of scattered charged particles as illustrated in Fig. 3. A total of 1.2×10^6 and 4.3×10^6 events were collected over a period of one day and five days of beam time using the

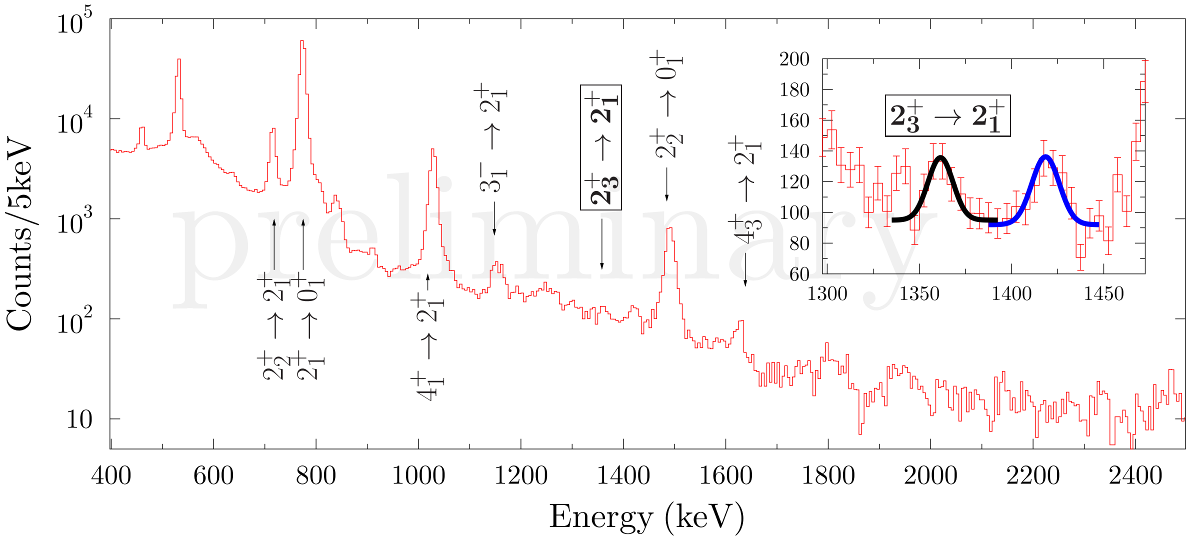

Figure 4. (Color online) The time-background subtracted, particle-gated and Doppler-corrected spectrum of ^{140}Nd is shown and the most prominent transitions of Coulomb-excited ^{140}Nd are marked. Transitions of the main beam contaminant ^{140}Sm are also prominent in the spectrum. The energy region of the $2^+_3 \rightarrow 2^+_1$ transition is zoomed in and gaussians are fitted to the $2^+_3 \rightarrow 2^+_1$ transition of ^{140}Nd (black) and on a ground-state transition of ^{140}Sm at 1420 keV (blue).

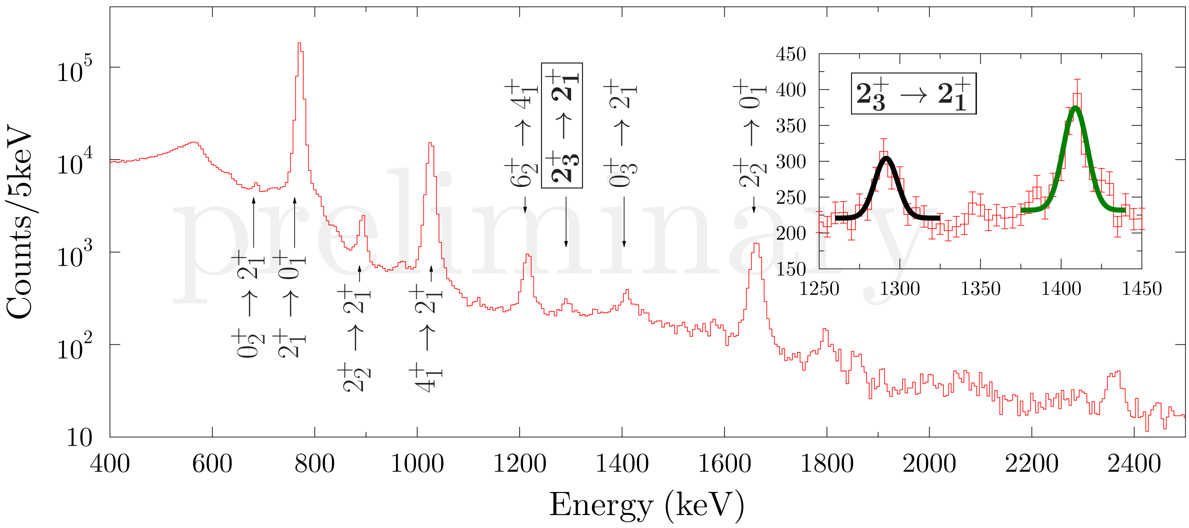

Figure 5. (Color online) The time-background subtracted, particle-gated and Doppler-corrected spectrum of ^{142}Sm is shown and the most prominent transitions of Coulomb-excited ^{142}Sm are marked. The energy region of the $2^+_3 \rightarrow 2^+_1$ transition is zoomed in and gaussians are fitted to the $2^+_3 \rightarrow 2^+_1$ (black) and $0^+_3 \rightarrow 2^+_1$ (green) transitions of ^{142}Sm.

condition of a detected target- or beam-like particle with an A=140 and A=142 beam, respectively. Events with a γ-ray multiplicity of 2 or greater are sorted in the E_γ–E_γ matrix.

3 Analysis and preliminary results

The advantage of an experiment in the "safe" Coulomb-excitation regime is that the population of the excited states is proportional to the Coulomb-excitation cross sections. Experimental yields of the excited states of ^{140}Nd and ^{142}Sm are determined through the observed γ-ray transition intensities, known branching ratios [30, 31], and theoretical electron-conversion coefficients [32]. These measured excited states' populations are used to calculate the ground-state transition matrix elements to excited states via Coulomb-excitation code `CLX` [33] relative to the known $B(E2; 2^+_1 \rightarrow 0^+_1)$ [19, 20]. The $E2$ and $M1$ strengths of non-ground-state transitions are derived with complementary information about branching ratios and multipole mixing ratios. The focus of the experiment lies on the analysis of $2^+_i \rightarrow 2^+_1$ transitions.

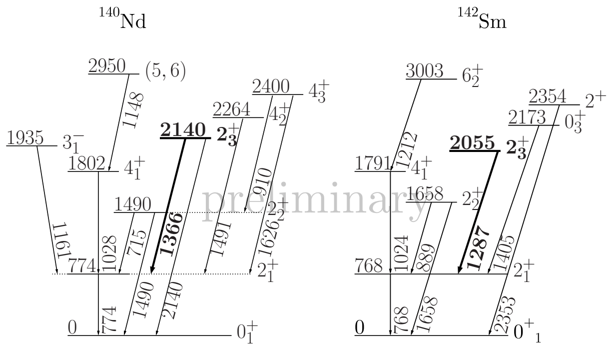

Figure 6. (Color online) The preliminary partial level schemes of ^{140}Nd and ^{142}Sm include all transitions, which were observed in this Coulomb-excitation experiment. The 2_3^+ state, the most promising candidate for the $2^+_{1,\mathrm{ms}}$ and its decay is highlighted with a thicker line.

3.1 ^{140}Nd

Via Coulomb excitation of ^{140}Nd three 2^+ states are populated. In addition to the 2^+ states, three 4^+ states, one 0^+ state, one 3^- state and one state with uncertain spin and parity (J^π=5, 6) were also populated. This results in an observation of 12 γ-ray transitions of ^{140}Nd. The assignment to known transitions was done by checking coincidences in the E_γ–E_γ matrix. The decay behaviors of the excited low-lying 2^+ states were already measured via β-decay [30], especially the multipole mixing ratios δ of transitions to the 2_1^+ state. Therefore, the dominant $M1$ decay of the 2_3^+ state at 2140 keV to the 2_1^+ state with a multipole mixing ratio of $\delta = -0.08(8)$ is known. This leads to the assumption that this state is the most promising candidate for the $2^+_{1,\mathrm{ms}}$ state. The 2_3^+ state is also the only populated quadrupole excitation in the energy region of ≈2 MeV (cf. Fig. 4). Combining the measured yield of the 2_3^+ state, determined via the γ-ray intensity of the $2_3^+ \to 2_1^+$ transition (cf. Fig. 4) and the known branching ratio Ref. [30], with the previously known multipole mixing ratio a $B(M1, 2_3^+ \to 2_1^+)$ strength of approximately 0.25 μ_N^2 can be derived at this point of the analysis.

3.2 ^{142}Sm

A similar level scheme is observed for the ^{208}Pb(^{142}Sm,^{142}Sm*)^{208}Pb* Coulomb-excitation reaction. In total four 2^+, one 0^+, one 4^+ and one 6^+ states are populated. The analysis was done analogously to ^{140}Nd and, as in ^{140}Nd, the 2_3^+ state is the only populated quadrupole excitation in the energy region of ≈2 MeV (cf. Fig. 5). The character of the $2_3^+ \to 2_1^+$ transition of ^{142}Sm is unknown, but an analogy to the level scheme of ^{140}Nd is apparent. That leads to an assumption of a $M1$-dominated $2_3^+ \to 2_1^+$ transition. Therefore, the 2_3^+ state is the most promising candidate for the $2^+_{1,\mathrm{ms}}$ state and an upper limit for the $B(M1; 2_3^+ \to 2_1^+)$ strength around 0.3 μ_N^2 can be determined at this point of the analysis. Preliminary level schemes of ^{140}Nd and ^{142}Sm were made as presented in Fig. 6.

4 Summary and Outlook

In the reported experiment the states of interest of ^{140}Nd and ^{142}Sm, 2^+ states in the 2 MeV energy region, were successfully populated via Coulomb excitation. A preliminary result and an upper limit for the $B(M1; 2_3^+ \to 2_1^+)$ strengths of radioactive ^{140}Nd and ^{142}Sm could be determined, respectively. The prelimary results of $B(M1; 2_3^+ \to 2_1^+)$ strengths indicate that the one-phonon MSSs in both isotones are single isolated states. The lack of fragmentation supports the hypothesis of the isovector valence-shell re-stabilization after the proton sub-shell closure of ^{138}Ce. In particular the measured $M1$-transition strength of ^{140}Nd reinforces this suggestion. If the transition character of the $2_3^+ \to 2_1^+$ transition of ^{142}Sm is assumed as dominantly $M1$, similar to the neighbouring ^{140}Nd, the 2_3^+ state could be identified as an isolated $2^+_{1,\mathrm{ms}}$ state, too.

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References

[1] A. Arima *et al.*, Phys. Lett. B **66**, 205 (1977)
[2] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984)
[3] F. Iachello, A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, 1987)
[4] R. Stegmann, *One-Quadrupole-Phonon States of Heavy Vibrational Nuclei Studied in Coulomb Excitation* (Ph.D. Thesis, Technische Universität Darmstadt, Darmstadt, 2017)
[5] W. D. Hamilton *et al.*, Phys. Rev. Lett. **53**, 2469 (1984)
[6] N. Pietralla *et al.*, Phys. Rev. Lett. **83**, 1303 (1999)
[7] N. Pietralla *et al.*, Phys. Rev. Lett. **84**, 3775 (2000)
[8] U. Kneissl *et al.*, J. Phys. G: Nucl. Part. Phys. **32**, R217 (2006)
[9] N. Pietralla *et al.*, Prog. Part. Nucl. Phys. **60**, 225 (2008)
[10] D. Kocheva *et al.*, Phys. Rev. C **93**, 011303(R) (2016)
[11] R. Stegmann *et al.*, Phys. Lett. B **770**, 77 (2017)
[12] R. Kern *et al.*, to be published
[13] M. Danchev *et al.*, Phys. Rev. C **84**, 061306(R) (2011)
[14] T. Ahn *et al.*, Phys. Lett. B **679**, 19 (2009)
[15] N. Pietralla *et al.*, Phys. Rev. C **58**, 796 (1998)
[16] N. Lo Iudice *et al.*, Phys. Rev. C **65**, 064304 (2002)
[17] G. Rainovski *et al.*, Phys. Rev. Lett. **69**, 122501 (2006)
[18] B. Pritychenko *et al.*, Atom. Data Nucl. Data Tables **107**, 1 (2016)
[19] R. Stegmann *et al.*, Phys. Rev. C **91**, 054326 (2015)
[20] C. Bauer *et al.*, Phys. Rev. C **88**, 021302(R) (2013)
[21] W. F. Müller *et al.*, Phys. Rev. C **73**, 014316 (2006)
[22] D. C. Radford *et al.*, Nucl. Phys. A **764**, 83c (2004)

[23] S. Raman *et al.*, Atom. Data Nucl. Data Tables **78**, 1 (2001)
[24] G. Lo Bianco *et al.*, Z. Phys. A **332**, 103 (1989)
[25] R. F. Casten, N. V. Zamfir, J. Phys. G: Nucl. Part. Phys. **22**, 1521 (1996)
[26] M. Lindroos *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **266**, 4687 (2008)
[27] V. N. Fedosseev *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **266**, 4378 (2008)
[28] D. Cline, Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986)
[29] N. Warr *et al.*, Eur. Phys. J. A **49**, 40 (2013)
[30] E. Williams *et al.*, Phys. Rev. C **80**, 054309 (2009)
[31] T. D. Johnson *et al.*, Nucl. Data Sheets **112**, 1949 (2011)
[32] T. Kibédi *et al.*, Nucl. Instrum. Methods Phys. Res. A **589**, 202 (2008)
[33] H. Ower, *Coulombanregung von Hochspinzuständen in* ^{232}Th, ^{234}U *und* ^{236}U (Ph.D. Thesis, Johann Wolfgang Goethe-Universität Frankfurt am Main, Frankfurt am Main, 1980)