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Shape transitions far from stability: The nucleus ^{58}Cr

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Abstract

Excited states up to $I^\pi = 8^+$ in the neutron-rich nucleus ^{58}Cr have been identified by using a new experimental setup composed of the large acceptance magnetic spectrometer PRISMA and the highly efficient γ-detector array CLARA. Interestingly, the excitation energy sequence of the ground-state band follows the one expected by the $E(5)$ dynamical symmetry for a nucleus at the critical point of the shape phase transition from a spherical vibrator ($U(5)$) to a γ-soft rotor ($O(6)$). For the first time, in the same physical system, large scale shell-model calculations in the full fp shell are compared to the $E(5)$ analytical model results and to the Interacting Boson Model. The theoretical results are in excellent agreement with the present data.

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The study of neutron-rich nuclei, far from the stability line, is a subject of substantial current interest from both the experimental and the theoretical side. In the shell-model description of nuclei, the relative shell energies are expected to undergo significant changes with the increasing neutron excess, leading to the disappearance of some of the nuclear magic numbers known near stability, and to the appearance of new ones [1]. The development of new regions of deformation, together with the entire set of phenomena specific to the shape phase transition in nuclear systems, is also expected.

The structure of nuclei in the transitional region from spherical to deformed is rather difficult to understand. There are, however, some exceptions; for those species that lie on the critical point of the phase transition, analytical expressions of

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the different observables have been obtained by Iachello in a geometrical picture of the nucleus. These dynamical symmetries are the $E(5)$ [2], describing the phase transition between a spherical vibrator ($U(5)$) and a γ-soft rotor ($O(6)$), and the $X(5)$ [3] for the critical point of the spherical to axially deformed ($SU(3)$) transition. Only a few examples of nuclei close to the critical point have been proposed, all of them near stability with mass numbers larger than 100 [4,5].

Neutron-rich nuclei in the $A \approx 60$ mass region constitute an ideal ground for investigations of shape evolution. Recently, spherical shapes, due to the appearance of a sub-shell gap at $N = 32$, have been observed in Ca, Ti and Cr isotopes (see Ref. [6] and references therein). On the other hand, the onset of stable deformation is expected in heavy Cr and Fe isotopes when approaching $N = 40$ [7,8]. In this spherical-to-deformed path, a critical point for the phase transition could be encountered.

From the experimental side, the production of neutron-rich nuclei is quite difficult in reactions induced by stable beams. Most of the available information on the structure of these nuclei has been obtained in β-decay studies. Fusion-evaporation reactions, that are the standard tool for the spectroscopy of yrast high-spin excited states, mainly produce nuclei near to stability and/or proton-rich systems. Multi-nucleon transfer and deep-inelastic collisions have been shown to be appropriate reaction mechanisms to populate medium and high-spin states in neutron-rich nuclei. In these types of reactions a large number of both projectile-like and target-like isotopes are produced. Consequently, a device to perform the mass and atomic number identification, as well as to detect the γ rays following the de-excitation of the nuclei produced in the reaction, is needed.

In this Letter we report the first results on the ground state band in the nucleus ^{58}Cr ($Z = 24$, $N = 34$), following the observation of several γ-rays with the new CLARA–PRISMA experimental setup. Previous studies of ^{58}Cr, performed from the β decay of ^{58}V [9], associated several γ rays to ^{58}Cr, but only the transition from the 2_1^+ to the ground state was placed in the level scheme. We have populated the nucleus ^{58}Cr in the reaction ^{64}Ni + ^{238}U [10]. The ^{64}Ni beam, with an energy of 400 MeV was delivered by the Tandem-ALPI accelerator complex of the Legnaro National Laboratory. The thickness of the uranium target was 400 μg/cm^2.

Projectile-like nuclei, produced following multi-nucleon transfer, were detected with the PRISMA [11] spectrometer placed at 64° in the laboratory frame, corresponding to the grazing angle of the reaction. PRISMA is a large acceptance magnetic spectrometer, consisting of a quadrupole singlet followed by a dipole magnet. The (x, y) coordinates of an ion entering the spectrometer are measured using a position-sensitive microchannel plate detector placed at 25 cm from the target. After passing the magnetic elements, the (x', y') coordinates of the trajectory are measured again in the focal plane of the spectrometer using a 10-element, 100 cm long, multi-wire parallel-plate proportional counter. Finally, the ion is stopped in a (10×4)-elements ionization chamber used for Z and ion charge state identification. Consequently, for each ion detected in PRISMA, we obtain the atomic number Z, the mass number A, the initial direction of the ion flying from the target and the absolute value of its velocity. The mass resolution obtained in the present experiment is 1/170, which allows a very clean discrimination of all the detected projectile-like nuclei. More than 150 isotopes, ranging from Ca to Kr, were resolved with PRISMA in this experiment. The mass spectrum obtained for the Cr isotopes, covering ten mass units, can be seen in Fig. 1.

The γ rays following the de-excitation of the reaction products were detected with the CLARA array [12]. CLARA is a high-granularity, Ge array, consisting of 25 EUROBALL Clover detectors, placed in the hemisphere opposite to the PRISMA spectrometer, 29.5 cm from the target, uniformly covering the azimuthal angles from 98° to 180°. The clover array CLARA was specially designed to obtain a relatively high absolute photopeak efficiency ($\approx$ 3.3% at 1.33 MeV) with the possibility to perform a good quality Doppler correction for the detected γ rays due to the high granularity of the array. The Doppler correction for the photons in coincidence with the ions detected in PRISMA was performed on an event-by-event basis, using the recoil velocity vector obtained after trajectory reconstruction in the spectrometer. The γ-ray energy resolution obtained was 0.8% FWHM over the whole broad velocity distribution of the projectile-like products, ranging from 4.5% to 10% of the speed of light.

The γ-ray spectra obtained in coincidence with the detection of different Cr isotopes are shown in Fig. 2. Similar spectra were observed not only for the lighter Cr isotopes, but also for

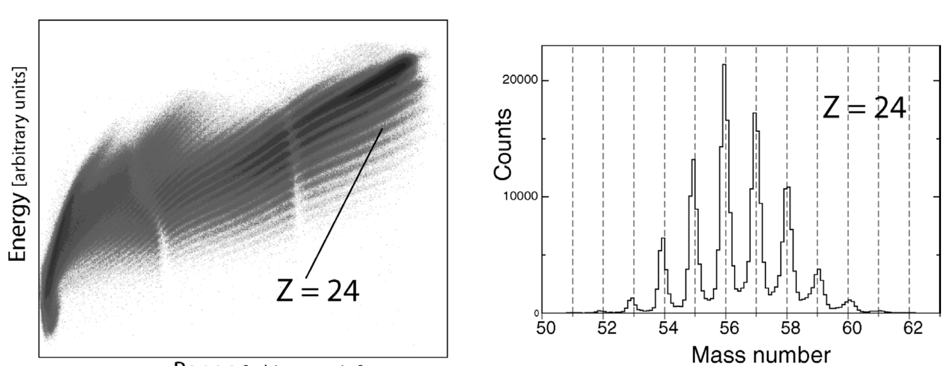

Fig. 1. Range–energy matrix from the ionization chamber of PRISMA, used for Z identification (left), and the mass spectrum obtained for chromium isotopes (right).

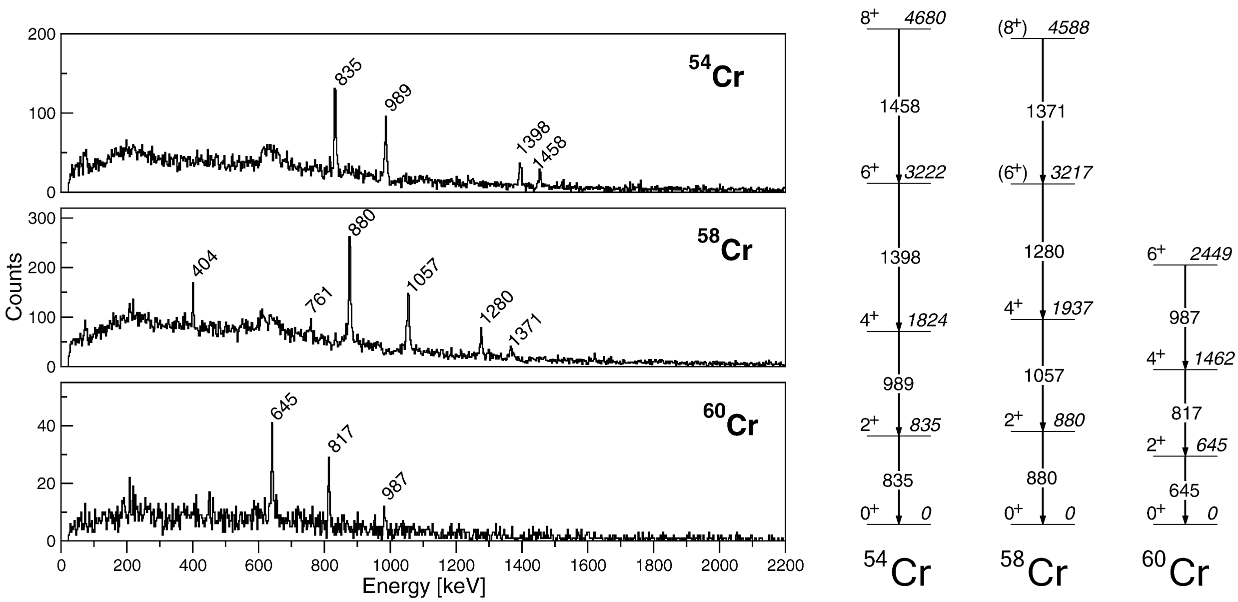

Fig. 2. Gamma spectra obtained for ^{54,58,60}Cr from the present experiment. The corresponding level schemes are reported on the right side.

the Ti, Fe and Ni even–even isotopes populated in the reaction. For all these nuclei we observed a very intense population of the yrast levels compared with a weak population of non-yrast states. One example is the spectrum obtained for the well-known stable isotopes, ^{54}Cr [13], where the four γ rays observed correspond to the E2 cascade of the yrast ground-state band shown on the right of Fig. 2. The heaviest even chromium isotope populated was ^{60}Cr, where three γ rays were identified. These three peaks were very recently observed also in a fusion-evaporation reaction [14] and were assigned to the ground state band, as shown in Fig. 2.

The γ-ray spectrum for ^{58}Cr is shown in Fig. 2; the γ rays with energies of 880.1(6), 1056.9(7), 1279.7(8) and 1371(1) keV are clearly evident. From γ–γ coincidences, we observed that the 880-, 1057- and 1280-keV transitions are in mutual coincidence. The statistics was, however, insufficient to prove coincidence relationships for the 1371-keV transition. The 880- and 1057-keV γ rays were previously observed following the β decay of ^{58}V [9]. In that work the 880-keV γ ray was assigned to the $2^+_1 \to 0^+_{\mathrm{gs}}$ transition. Based on the assumption that ^{58}V β decays from a state of spin 0^+ or 1^+, it was suggested that the 1057-keV γ ray could be a candidate for the $0^+_2 \to 2^+_1$ transition in ^{58}Cr. From the present data we were able to estimate the anisotropy of the angular distributions of the 880- and 1057-keV γ rays. For CLARA we define the anisotropy of the angular distribution as being the ratio between the efficiency-corrected intensity of a given transition seen in the clovers covering the $\theta = 150°$–$180°$ region, and the intensity of the same γ ray seen in the ring placed at 100°. We obtained the ratio 1.28(17) for the 880-keV, and 1.18(17) for the 1057-keV transitions, respectively. In both cases the anisotropy is consistent with the value of ~ 1.2 expected for a stretched quadrupole transition. As a γ ray following the decay of a 0^+ state must have an isotropic angular distribution, the observed anisotropy rules out the hypothesis that the 1057-keV γ ray could be originated in a 0^+ state. We assign this γ ray to the $4^+_1 \to 2^+_1$ transition. (As a consequence, this indicates that the β decay of ^{58}V originates, at least partially, in a 3^+ state.) Other two minor peaks of 404(1) and 760(1) keV appear in the spectrum of ^{58}Cr but the intensities do not allow their placement in the level scheme. Based on the above observations and considering that for all known even–even nuclei produced in this reaction we observed mainly transitions along the yrast line, we propose for ^{58}Cr the level scheme shown in Fig. 2.

Interestingly, we note that the ratios between the experimental excitation energies of ^{58}Cr follow the expectations of the dynamical symmetry $E(5)$ for a nucleus at the critical point of the phase transition from spherical to γ-soft rotor. This dynamical symmetry predicts, in a parameter-free, analytical way, the following energy ratios for a nucleus at the critical point: $E(4^+_1)/E(2^+_1) = 2.20$, $E(6^+_1)/E(2^+_1) = 3.59$ and, $E(8^+_1)/E(2^+_1) = 5.17$ [2]. The present experimental values in ^{58}Cr are 2.20, 3.66 and 5.22, respectively.

The relative excitation energies of the levels for the $E(5)$ dynamical symmetry can be also calculated in the framework of the Interacting Boson Model (IBM) [15]. Considering the IBM Hamiltonian $H = \epsilon n_d - AP^\dagger P$, the critical point on the $U(5)$ to the $O(6)$ path is obtained for $\epsilon/A = 2(N-1)$ [4]. The results obtained for $N = 5$ bosons are shown in Fig. 3, where only the scale parameter has been adjusted ($\epsilon = 1.415$) to describe the data.

Moreover, ^{58}Cr gives the unique opportunity to compare the analytical $E(5)$ results with large scale shell-model calculations in the full fp shell. Several residual interactions have been developed to describe fp-shell nuclei; the most reliable ones, near the stability line, are KB3G [16] and FPD6 [17]. Recently, another interaction, GXPF1 [18], has been introduced to account for the whole fp shell. The results obtained with the shell-model code ANTOINE [19], using these interactions are shown in Fig. 3. Calculations with the KB3G and FPD6 interactions

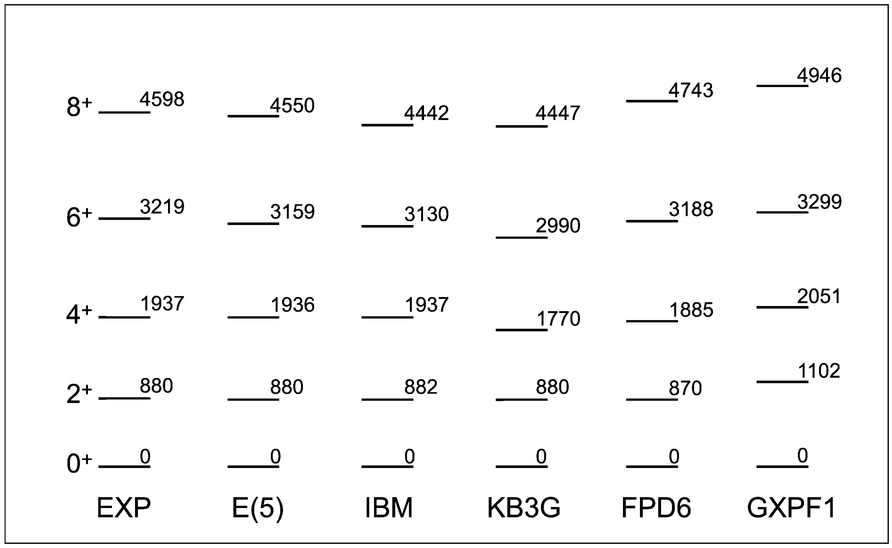

Fig. 3. Level scheme of ^{58}Cr as deduced from the present experiment compared to different theoretical calculations (see text for details).

Table 1
Ratios of the excitation energies and E2 transition probabilities for ^{58}Cr

	Exp	IBM	KB3G	FPD6	GXPF1
$E_{4_1^+}/E_{2_1^+}$	2.20	2.20	2.01	2.17	1.86
$E_{6_1^+}/E_{2_1^+}$	3.59	3.55	3.40	3.66	2.99
$E_{8_1^+}/E_{2_1^+}$	5.17	5.04	5.05	5.45	4.49
$\frac{B(\mathrm{E2};\ 4_1^+\to 2_1^+)}{B(\mathrm{E2};\ 2_1^+\to 0_1^+)}$		1.39	1.15	1.38	1.13
$\frac{B(\mathrm{E2};\ 6_1^+\to 4_1^+)}{B(\mathrm{E2};\ 2_1^+\to 0_1^+)}$		1.41	1.13	1.24	0.93
$\frac{B(\mathrm{E2};\ 8_1^+\to 6_1^+)}{B(\mathrm{E2};\ 2_1^+\to 0_1^+)}$		1.16	1.18	1.16	1.01

are in very good agreement with the present experimental data. In particular, the solutions of the FPD6 interaction are nearer to the $E(5)$ solutions and the experimental energies. On the other hand, the GXPF1 interaction does not give a good description of the data (see Table 1).

As for the excitation energies, the $E(5)$ framework provides well-defined values for the ratios between the E2 transition probabilities. The measurement of the lifetimes of the states is a very difficult task with the present experimental techniques. For the time being, we can compare the $B(\mathrm{E2})$ predictions of the different models for the yrast states of ^{58}Cr. The analytical $E(5)$ solution gives $B(\mathrm{E2})$ values that increase with the increasing spin. This differs from the other theoretical models due to the finite number of active nucleons in ^{58}Cr, which makes the $B(\mathrm{E2})$ values decrease when approaching band termination. The IBM and shell-model $B(\mathrm{E2})$ values, normalized to the $B(\mathrm{E2};\ 2_1^+ \to 0_1^+)$, are reported in Table 1. The theoretical predictions agree quite well in the description of the transition probabilities for the yrast states. Also for the $B(\mathrm{E2})$ values the FPD6 interaction seems to give a description closer to the IBM solution than the other interactions. Recently, the $B(\mathrm{E2};\ 2_1^+ \to 0_1^+) = 14.8(4.2)$ W.u. has been measured at the RISING facility in GSI [20] in a Coulomb excitation reaction. This value is in good agreement with all the present theoretical results. Further challenging investigations devoted to the measurement of lifetimes in ^{58}Cr will provide the additional information to confirm the $E(5)$ symmetry in this nucleus.

The heaviest even isotope ^{60}Cr shows a more collective level scheme. This development of deformation has been predicted in Ref. [8] due to the lowering of the $g_{9/2}$ and $d_{5/2}$ orbits with increasing neutron number. The further decrease of the 2_1^+ excitation energy (446 keV) in the heavier ^{62}Cr [21] points to the evolution of even–even Cr isotopes towards the deformed regime near $N = 40$.

In conclusion, excited states up to $I^\pi = 8^+$ have been observed for the first time in the neutron-rich nucleus ^{58}Cr, following a multinucleon transfer reaction between stable ions at the new spectrometer complex CLARA + PRISMA. The striking resemblance of the ^{58}Cr yrast band with the predictions of the $E(5)$ dynamical symmetry suggests the possibility that ^{58}Cr sits at the critical point of the shape phase transition, a symmetry observed so far only in a few stable, heavier nuclei. Moreover, ^{58}Cr constitutes a very interesting benchmark where the analytical $E(5)$ predictions and shell model calculations can be compared for the first time. The amazing convergence of the results, not only for the observed level energies but also for the transition probabilities, gives a further hint for the realization of the $E(5)$ critical point in ^{58}Cr. However, the excitation energy of key non-yrast states and their decay pattern play a very important role in the $E(5)$ dynamical symmetry. Further, challenging experiments for the identification of non-yrast states and for lifetime measurements are therefore necessary. Interestingly, the present study opens the possibility of theoretical investigations on the underlying microscopic structure of the $E(5)$ dynamical symmetry.

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References

[1] T. Otsuka, et al., Phys. Rev. Lett. 87 (2001) 082502.
[2] F. Iachello, Phys. Rev. Lett. 85 (2000) 3580.
[3] F. Iachello, Phys. Rev. Lett. 87 (2001) 052502.
[4] R.F. Casten, N.V. Zamfir, Phys. Rev. Lett. 85 (2000) 3584.
[5] R.M. Clark, et al., Phys. Rev. C 69 (2004) 064322.
[6] R.V.F. Janssens, et al., Phys. Lett. B 546 (2002) 55.
[7] M. Hannawald, et al., Phys. Rev. Lett. 82 (1999) 1391.
[8] E. Caurier, F. Nowacki, A. Poves, Eur. Phys. J. A 15 (2002) 145.
[9] P.F. Mantica, et al., Phys. Rev. C 67 (2003) 014311.
[10] L. Corradi, et al., Phys. Rev. C 59 (1999) 261.
[11] A.M. Stefanini, et al., Nucl. Phys. A 701 (2002) 217c.
[12] A. Gadea, et al., Eur. Phys. J. A 20 (2004) 193.
[13] M. Devlin, et al., Phys. Rev. C 61 (1999) 017301.
[14] S.J. Freeman, et al., AIP Conf. Proc. 764 (2005) 142.
[15] F. Iachello, A. Arima, The Interaction Boson Model, Cambridge Univ. Press, Cambridge, 1987.
[16] A. Poves, et al., Nucl. Phys. A 694 (2001) 157.
[17] W.A. Richter, et al., Nucl. Phys. A 523 (1991) 325.
[18] M. Honma, et al., Phys. Rev. C 65 (2002) 061301.
[19] E. Caurier, Shell Model Code ANTOINE, IRES, Strasbourg, 1989–2004; E. Caurier, F. Nowacki, Acta Phys. Pol. B 30 (1999) 705.
[20] A. Bürger, et al., Phys. Lett. B 622 (2005) 29.
[21] O. Sorlin, et al., Eur. Phys. J. A 16 (2003) 55.