Evidence for Possible E(5) Critical-Point Symmetry in the Neutron-Rich ^{58}Cr Nucleus

N. Mărginean[1,5], S.M. Lenzi[2], E. Farnea[2], A.Gadea[1], S.J. Freeman[3], D.R. Napoli[1], D. Bazzacco[2], S. Beghini[2], B.R. Behera[1], P.G. Bizzeti[4], A.M. Bizzeti-Sona[4], D. Bucurescu[5], R. Chapman[6], L. Corradi[1], A.N. Deacon[3], F. Della Vedova[2], G. de Angelis[1], E. Fioretto[1], M. Ionescu-Bujor[5], A. Iordachescu[5], Th. Kröll[7], A. Latina[1], X. Liang[6], S. Lunardi[2], R. Mărginean[2], R. Menegazzo[2], G. Montagnoli[2], M. Nespolo[2], G. Pollarolo[8], C. Rusu[1], F. Scarlassara[2], J.F. Smith[3], K. Spohr[6], A.M. Stefanini[1], S. Szilner[9], M. Trotta[10], C.A. Ur[2,5], B.J. Varley[3], W. Zhimin[1]

1 INFN, Laboratori Nazionali di Legnaro, Italy, 2 Dipartimento di Fisica and INFN, Padova, Italy, 3 University of Manchester, Manchester,UK, 4 Dipartimento di Fisica and INFN, Firenze, Italy, 5 NIPNE, Bucharest, Romania, 6 University of Paisley, Paisley, Scotland, UK, 7 Physik-Department E12, TUM, Garching, Germany, 8 Dipartimento di Fisica and INFN, Torino, Italy, 9 Ruder Bŏscović Institute, NR- 10002, Zagreb, Croatia, 10 INFN, Napoli, Italy

For many decades, the theoretical modeling of nuclear structure was constructed relying on the experimental information obtained for nuclear systems not very far from the stability line. The continuous experimental developments in the field of nuclear spectroscopy gradually drive us toward the unique way to reveal the power of modern nuclear structure models: to compare the theoretical predictions with the experimental data obtained for the most exotic nuclei we can reach in the present days. That is why the study of neutron-rich nuclei is one of the most interesting fields in the present research of nuclear structure. The single-particle energies are expected to undergo significant changes with increasing neutron excess, leading to the disappearance of some of the nuclear magic numbers known from the stability line, together with the appearance of new ones. The developments of new regions of deformation, together with the entire phenomena specific to the spherical-to-deformed transition in nuclear systems, are also expected.

Proper reaction mechanisms to populate medium and high spin states in neutron-rich nuclei are multi-nucleon transfer and deep inelastic collisions. 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 the gamma rays following the de-excitation of the nuclei produced in the reaction, is needed. The PRISMA/CLARA setup at LNL constitutes a proper tool to perform these studies.

The A ≈ 60 mass region of neutron-rich nuclei, where protons are partially filling the $f_{7/2}$ shell and neutrons are filling the other *pf* orbits, are predicted to develop deformation. In particular, recent shell-model calculations predict large B(E2) values for Cr and Fe isotopes with N ≈ 40 (which at stability is a magic number) [1]. In the present work we present recent experimental results obtained with the PRISMA/CLARA setup on the high spin spectroscopy of ^{58}Cr (Z=24, N=34). From a previous study of the β-decay of ^{58}V [2] several gamma rays were associated to ^{58}Cr. Except the $2^+_1 \rightarrow 0^+_1$ transition of 880 keV, no other gamma ray was placed in the level scheme of ^{58}Cr.

The nucleus ^{58}Cr has been populated in the reaction ^{64}Ni + ^{238}U. The ^{64}Ni beam accelerated to 400 MeV was delivered by the Tandem-Alpi accelerator complex. The thickness of the Uranium target was 400 μg/cm^2. Projectile-like nuclei produced following multi-nucleon transfer were detected with the PRISMA spectrometer placed at 64°, which corresponds to the grazing angle of the reaction. The trajectory inside PRISMA was reconstructed for every ion which arrived in the ionization chamber placed on the final side of the spectrometer. Consequently, for every ion completely detected in PRISMA we obtained the atomic number Z, the mass

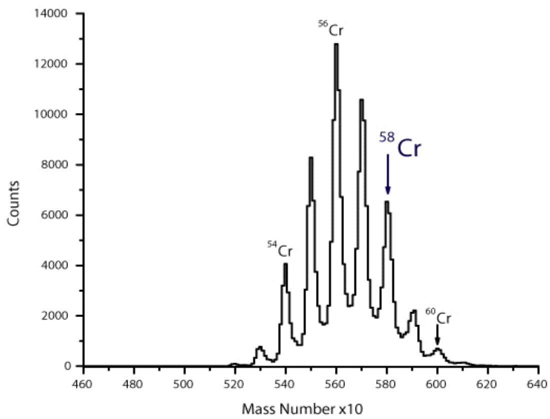

FIG. 1: Mass spectrum of Cr isotopes obtained with the PRISMA spectrometer

number A, the initial direction of the ion flying from the target and the absolute value of the velocity vector. The mass resolution obtained after trajectory reconstruction is 1/150, sufficient to have a very clean discrimination of all the projectile-like isotopes detected (see Fig. 1). Gamma rays following the de-excitation of the reaction products were detected with the CLARA array, consisting of 22 clovers covering the backward (considering PRISMA direction as forward) 2π of the total solid angle. Using the recoil direction and recoil velocity obtained after trajectory reconstruction in PRISMA, we performed event-by-event Doppler correction of gamma rays detected in coincidence. The energy resolution obtained after Doppler correction is 0.7% FWHM all over the broad velocity distribution of the

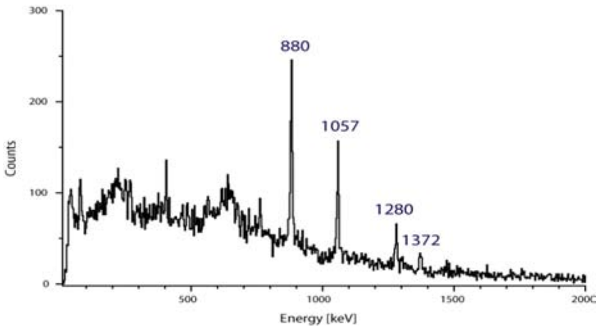

FIG. 2: Gamma-ray spectrum of ^{58}Cr

projectile-like products, ranging from 4.5% to 10% of the light velocity.

The gamma-ray spectrum obtained in coincidence with the detection at PRISMA of ^{58}Cr isotopes is shown in Fig. 2. Similar spectra are observed also for the lighter even-even Cr isotopes, $^{54-56}$Cr, where the four gamma rays observed correspond to the E2 cascade of the yrast ground-state band. Following the systematics of the decay pattern

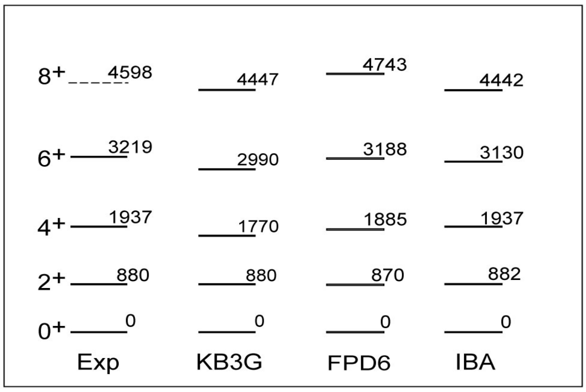

FIG. 3: Ground-state band in ^{58}Cr, compared with shell model calculations with the KB3G and FPD6 interactions and the IBM results for n=5 bosons.

in these isotopes, we propose for ^{58}Cr the level scheme shown on the left side of Fig. 3.

It is interesting to note that the ratios between the experimental excitation energies of ^{58}Cr follow those expected by the dynamical symmetry E(5) for a nucleus in the critical point of the shape phase transition from spherical anharmonic vibrator (U(5)) to γ-soft rotor (O(6)). The E(5) dynamical symmetry, introduced by F. Iachello [3], predicts, in a parameter-free manner, for a nucleus at the critical point the energy ratios: E_{4+}/E_{2+}=2.2 and E_{6+}/E_{2+}=3.59; experimentally we find 2.20 and 3.66, respectively. The relative excitation energies for the E(5) dynamical symmetry can be calculated in the framework of the IBA [4]. The results obtained for N=5 bosons are reported on right side of Fig. 3, where a scale parameter has been used to compare with the experiment.

One of the advantages of medium-light mass nuclei is that large scale shell-model calculations can be performed in the full *pf* shell for both protons and neutrons. For ^{58}Cr we have used two different residual interactions, KB3G [5] and FPD6 [6]; the results are shown in Fig. 3. All calculations compare well with experiment.

A more stringent test of the E(5) critical point in ^{58}Cr would be the comparison with the transitions probabilities. Although the measurement of the lifetimes has not yet been done, we can compare the results of the different models for the yrast states of Fig. 3. The B(E2) values, normalized to the B(E2: $2^+ \rightarrow 0^+$), are shown in Table I, where for the IBA calculations five bosons have been considered. All theoretical predictions agree quite well in the description of the transition probabilities, in particular, the FPD6 interaction seems to give a description closer to the E(5) solution than KB3G for both the excitation energies and B(E2) values. Further investigations devoted to the measurement of the lifetimes are absolutely needed to confirm the E(5) symmetry in ^{58}Cr. One should note that the amazing convergence of the results coming from a very simple, parameter-free model and large scale shell-model calculations give strong hint to suppose the realization of the E(5) in ^{58}Cr.

Table I *: Theoretical B(E2) values for the yrast sequence in ^{58}Cr, normalized to the B(E2: $2^+ \rightarrow 0^+$).*

^{58}Cr	$B(E2)_{KB3G}$	$B(E2)_{FPD6}$	$B(E2)_{IBA}$
$2^+ \rightarrow 0^+$	1	1	1
$4^+ \rightarrow 2^+$	1.15	1.38	1.39
$6^+ \rightarrow 4^+$	1.13	1.24	1.41
$8^+ \rightarrow 6^+$	0.90	1.16	1.16

The E(5) dynamical symmetry has been so far observed only in few nuclei of medium-large mass [4,5]. No medium-light mass nucleus was proposed until now as candidate for critical-point symmetry. ^{58}Cr is the first one, and the resemblance of its yrast line with the one predicted by the E(5) is really striking. Therefore, the nucleus ^{58}Cr constitutes a very interesting physical benchmark where very different models can be compared. Moreover, the shell model could provide a microscopic basis for further studies of the E(5) critical-point symmetry.

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[1] E. Caurier et al., Eur. Phys. J. A **15** (2002) 145.
[2] P.F. Mantica et al., Phys. Rev. C **67** (2003) 014311.
[3] F. Iachello, Phys. Rev. Lett. **85** (2000) 3580.
[4] A. Arima and F. Iachello, Phys. Rev. Lett. **35** (1975) 1079.
[5] A. Poves at al., Nucl. Phys. **A694** (2001) 157.
[6] W.A. Richter et al., Nucl. Phys. **A523** (1991) 325.