Relativistic Coulomb excitation of neutron-rich $^{54,56,58}$Cr:
On the pathway of magicity from N=40 to N=32,34

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Abstract

The first excited $2^+$ states in $^{54,56,58}$Cr were populated by Coulomb excitation at relativistic energies and γ rays were measured using the RISING setup at GSI. For $^{56}$Cr and $^{58}$Cr the $B(E2, 2^+_1 \rightarrow 0^+)$ values relative to the previously known $B(E2)$ value for $^{54}$Cr are determined as 8.7(3.0) and 14.8(4.2) W.u., respectively. The results confirm a subshell closure at $N = 32$ which was already indicated by the higher energy of the $2^+_1$ state in $^{56}$Cr. Recent large-scale shell model calculations using effective interactions reproduce the trend in the excitation energies, but fail to account for the minimum in the $B(E2)$ values at $N = 32$.

Key words: Radioactive beams, Coulomb excitation, transition probabilities, shell model
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Nuclei far off the valley of stability have become more accessible in recent years through the use of radioactive ion beams. The investigation of shell structures of such nuclei is a key topic of nuclear structure studies. It has become evident that shell and subshell closures may differ significantly from those of nuclei near stability, in particular for very neutron-rich nuclei, since they are intimately related to the monopole part of the nucleon-nucleon (NN) residual interaction [1]. However, experimental data, needed to test and refine the interactions used in the shell model calculations [2–5], are still scarce. Modifications of the shell structure have far reaching consequences for nuclear properties and also beyond nuclear structure physics, e.g. for the rapid neutron-capture process (r-process) of stellar nucleosynthesis and the resulting isotopic abundances [6].

The experimental evidence of changing shell structures for very neutron-rich nuclei along the $N = 8, 20$ and 28 isotonic sequences can be explained in terms of the monopole part of the NN residual interaction. Schematically this is due to the $(\sigma\sigma)(\tau\tau)$ part of the interaction, which is strongly binding in the $S = 0$ (spin-flip), $\Delta l = 0$ (spin-orbit partners) and $T = 0$ (proton-neutron) channel of the two-body interaction. This causes large monopole shifts of neutron single-particle orbitals due to their missing $S = 0$ proton partners at large neutron excess, and thus may generate new shell gaps. The effect was first discussed for the (s,d) shell [2,3] and for the (p,f) shell [1,3]. For heavier nuclei the tensor part of the NN interaction creates a likewise strong monopole interaction between $S = 0$, $\Delta l = 1$ and $T = 0$ orbits of adjacent harmonic oscillator shells [7,8], which plays a key role in the evolution of the spin-orbit splitting. It has recently been shown, that both terms originate from the tensor force,

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which in a major shell with fixed parity reduces essentially to the \((\tau \tau)(\sigma \sigma)\) part [8]. To date the investigations concentrate, in the region of neutron-rich Ca, Ni and Sn isotopes, on the most significant matrix elements, the spectroscopic factors and the magnetic moments which are sensitive indicators of their structure.

The neutron-rich Cr isotopes are located at a key point on the pathway from the \(N = 40\) subshell closure via a deformed region to spherical nuclei at \(N = 28\). Two large-scale shell model calculations have been performed based on different realistic effective interactions with empirically tuned monopoles [9,10], which await experimental proof with respect to model space and evolution of subshells and deformation. Experimentally, a possible subshell closure at \(N = 32, 34\) seems to develop in the Ca isotopes beyond \(N = 28\) as indicated by a rise in the \(2^+_1\) energies. The Cr and Ti isotopes show a maximum of those energies at \(N = 32\) [4,11-14]. However, the Ni isotopes do not show such an effect. Within the \(N = 34\) isotones, \(E(2^+_1)\) is increasing from Fe to Cr in contrast to the expected trend towards mid-shell, which suggests an \(N = 34\) closure [4]. Besides the \(2^+_1\) energies, masses (which are difficult to measure due to short half lives) and \(B(E2)\) values are an important test of the evolution of the subshell structure. A recent determination of \(B(E2, 0^+ \rightarrow 2^+_1)\) values in \(^{52,54,56}\)Ti confirms the subshell closure at \(N = 32\), but provides no evidence for the predicted \(N = 34\) closure [15]. The measurement of \(B(E2)\) values of the \(N = 30-34\) isotopes of Cr, which is the subject of the present investigation, confirms the \(N = 32\) subshell closure for \(Z = 24\).

Three consecutive experiments were performed to measure Coulomb excitation of high-energy \(^{54}\)Cr, \(^{56}\)Cr and \(^{58}\)Cr beams using the FRS-RISING setup at GSI [16]. The setup is shown schematically in Fig. 1. Fully stripped Cr ions were produced by fragmentation of a \(^{86}\)Kr beam on a \(^9\)Be production target with a thickness of 2.5 g/cm\(^2\) placed in front of the fragment separator FRS.

Fig. 1. Schematic diagram of the RISING setup at the fragment separator, FRS, at GSI. The BaF\(_2\) scintillation spectrometers of the HECTOR array were used only in the setup phase. The first degrader, which was placed between the first two dipole magnets in the experiments, is not shown.
Table 1
Summary of beam times, beam intensities and beam compositions for the three experiments.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Beam Time [h]</th>
<th>Intensity [s⁻¹]</th>
<th>⁵⁴Cr abundance [%]</th>
<th>Other Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁵⁴Cr</td>
<td>22</td>
<td>2000</td>
<td>45</td>
<td>⁵⁵Mn, ⁵³V</td>
</tr>
<tr>
<td>⁵⁶Cr</td>
<td>20</td>
<td>1400</td>
<td>35</td>
<td>⁵⁷Mn, ⁵⁵V</td>
</tr>
<tr>
<td>⁵⁸Cr</td>
<td>55</td>
<td>600</td>
<td>25</td>
<td>⁵⁹Mn, ⁵⁷V</td>
</tr>
</tbody>
</table>

The ⁸⁶Kr beams with energies of ≈ 480 A MeV and an intensity of 3 to 10 · 10⁸ ions per second were provided by the heavy-ion synchrotron SIS. The nuclei of interest were selected in the FRS by their magnetic rigidity, Bρ, and their specific energy loss in the degraders, ΔE. The various detectors on the way to the reaction target, see Fig. 1, were used to perform A and Z identification as well as position tracking [16]. Table 1 summarises the beam times, beam intensities and beam compositions that were obtained in the three experiments.

The energies of the Cr beams were adjusted to ≈ 136 A MeV before the reaction target, a 7 × 7 cm² Au foil of 1 g/cm² thickness, in which the ions were slowed down to 100 A MeV in all three experiments. The identification of the nuclei behind the reaction target in Z and A is performed by the array of nine Si and CsI detectors of the calorimeter telescope CATE [16]. The Z resolution of CATE is good, but masses of neighbouring isotopes partly overlap.

Gamma rays emitted after Coulomb excitation were measured in the array of 15 Ge-Cluster detectors of the RISING setup [16]. Due to the high recoil velocities of v/c ≈ 0.43 the Doppler broadening of the γ-ray lines is appreciable. To maintain a good energy resolution, the Ge detectors were placed under forward angles with a small opening angle of 3°. The photopeak efficiency of the Cluster array was 1.13(1)% at 1.33 MeV, measured with a ⁶⁰Co source. However, the solid angle transformation increases the efficiency to 2.3% for γ rays emitted from the high-energy Cr ions. To reduce background contributions, the Cluster detectors were surrounded at the sides by lead shielding of 6 mm thickness. Thinner Pb absorbers were used in front of the detectors to suppress γ rays with energies below 500 keV in the laboratory frame.

The first of the three experiments to measure Coulomb excitation of ⁵⁴,⁵⁶,⁵⁸Cr at relativistic energies was devoted to stable ⁵⁴Cr. In this case, the reduced transition probability, B(E2; ²⁺ → ⁰⁺) = 14.6(6) W.u., is known from previous work [17]. This value may be used as a normalisation for the determination of the ²⁺ → ⁰⁺ reduced transition probabilities of ⁵⁶Cr and ⁵⁸Cr.
The information obtained from the detection systems shown in Fig. 1 was recorded for every 256th particle or if a γ ray was detected in one or more of the Ge detectors, with the condition that an incoming particle was detected in the scintillator SCI2 and an outgoing particle in one of the CsI detectors of CATE. In the off-line analysis an event-by-event tracking and identification of the incoming ions was performed. The irradiated target area, deduced from the multi-wire position information, had a diameter of ≈ 50 mm. For the correction of Doppler shifts of the γ-ray energies, the trajectory of every incoming Cr projectile, the position of the scattered particles measured in CATE and the position of the Ge crystal detecting a γ ray were used to calculate the γ-ray emission angle with respect to the direction of the scattered projectile. After Doppler correction, an energy resolution of 2 % was obtained. The accepted scattering angles of the Cr fragments were limited to the range of 0° ± 6° to 2° ± 8° to select Coulomb-excitation events. This range of scattering angles corresponds to impact parameters between 10 fm (below which nuclear reactions prevail) and 50 fm (above which atomic background becomes dominant).

![Figure 2: Examples of Doppler- and efficiency-corrected γ-ray spectra showing the 2°1+ → 0° transitions in 54,56,58Cr.](image)

The γ-ray spectra obtained for the three Cr isotopes are displayed in Fig. 2. These spectra were obtained with isotope identification before and after the Au target and with a prompt time gate to reduce the background from γ rays.
produced at various places along the beam line. Other peaks in the spectra originate from neighbouring Cr isotopes produced by transfer reactions which cannot be completely separated due to an insufficient mass resolution after the target. However, this contamination does not influence the result as they represent a negligible fraction of the total number of projectiles, $N_{\text{pro}}$.

Gamma-ray transition intensities, $I_\gamma$, were obtained from the measured counts in the Cr $2^+_1 \rightarrow 0^+$ peaks in the three spectra dividing event-by-event by the detection efficiencies of the individual detectors. Angular distribution effects, which should be identical for the three Cr isotopes, were not taken into account. In principle, $B(E2)$ values could be determined from the Coulomb-excitation cross sections. However, to avoid possible systematic errors, e.g. from the high-energy Coulomb excitation calculation, from possible excitations of higher-lying $2^+$ states or from unknown angular distribution effects, we prefer to give the $B(E2)$ values for $^{56}\text{Cr}$ and $^{58}\text{Cr}$ relative to the previous value of $^{54}\text{Cr}$, see Table 2.

The $B(E2)$ values show that the collectivity of the $2^+_1$ state in $^{56}\text{Cr}$ with $N = 32$ is significantly lower than that of the neighbouring isotopes, $^{54}\text{Cr}$ and $^{58}\text{Cr}$ with $N = 30$ and 34, respectively. In fact, it appears to be similar to that of $^{52}\text{Cr}$ with the $N = 28$ shell closure. In Fig. 3 the experimental $2^+_1$ excitation energies, $E(2^+_1)$, and the $B(E2, 2^+_1 \rightarrow 0^+)$ values for the Cr isotopes are compared to results of shell model calculations using two different approaches. In the calculations the effective interactions $\text{GXPF1}$ [9] and $\text{KB3G}$ [10], respectively, were used in the (p,f) model space. The $B(E2)$ values were calculated with equal polarisation charges for protons and neutrons, $\delta e = 0.5e$. For $N \geq 36$ the $\nu(g_{9/2}, d_{5/2})$ orbitals were included in ref. [10] to account for the onset of deformation which is expected near $N \sim 40$ due to the upward monopole drift of the $\nu f_{5/2}$ orbital which closes the $N = 40$ gap. Up to $N = 36$, however, little effect is predicted as compared to the (p,f) model-space values. The $\text{GXPF1}$ interaction was recently modified ($\text{GXPF1A}$) to better account for the $E(2^+_1)$ energies in Ti and Cr isotopes, however, with marginal effect for the $B(E2)$ values (see Fig. 3) [8]. Similarly, a tuned $\text{KB3G}$ interaction (named $\text{KB3GM}$ in

### Table 2

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$E(2^+_1)$ [keV]</th>
<th>$I_\gamma$</th>
<th>$N_{\text{pro}}$</th>
<th>$B(E2; 2^+_1 \rightarrow 0^+)$ [W.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{54}\text{Cr}$</td>
<td>835$^a$</td>
<td>21140(2747)</td>
<td>3.7 · 10$^7$ (norm.)</td>
<td>14.6(0.6)$^a$</td>
</tr>
<tr>
<td>$^{56}\text{Cr}$</td>
<td>1007$^a$</td>
<td>6164(1971)</td>
<td>1.8 · 10$^7$</td>
<td>8.7(3.0)</td>
</tr>
<tr>
<td>$^{58}\text{Cr}$</td>
<td>880$^b$</td>
<td>7282(1881)</td>
<td>1.2 · 10$^7$</td>
<td>14.8(4.2)</td>
</tr>
</tbody>
</table>

$^a$ from ref. [17] $^b$ from ref. [4]
Fig. 3. Calculated and experimental values for $E(2^+)$ and $B(E2; 2^+_1 \rightarrow 0^+_1)$ for $^{54,56,58}$Cr isotopes. The calculated values are from [9,10], the experimental values from previous work from [4,17]. The filled squares show the values obtained in this experiment.

Fig. 3) using effective polarisation charges as recently inferred from (p,f) shell mirror nuclei close to $^{56}$Ni [18], yielding good agreement with the Ti $B(E2)$ values [15], does not improve the Cr predictions. The two interactions differ mainly in the prediction of an $N = 34$ subshell in $^{54}$Ca, which is only produced by GXPF1. The difference can be traced back to the $\nu (p_{1/2})^2 T = 1$, $J = 0$ two-body matrix element which is strongly binding in GXPF1A [8] and opens another gap after filling the $\nu p_{1/2}$ orbital between $N = 32$ and 34. The situation is analogous to the (s,d) shell for $N = 14, 16$ in $^{22,24}$O and $Z = 14, 16$ in $^{34}$Si, $^{36}$S and to the proton (p,f) shell in the $N = 50$ isotones $^{88}$Sr, $^{90}$Zr at $Z = 38, 40$ [7]. Despite the variations in the $E(2^+_1)$ energies, the $B(E2)$ values are virtually unchanged in the various shell model approaches and show a constant trend from $N = 30$ to 34 (see Fig. 3). The experimental value for $^{56}$Cr lies clearly below the shell model predictions which is evidence for the $N = 32$ subshell closure already indicated by the higher $2^+_1$ energy. This result is in agreement with a recent measurement of $B(E2)$ values in $^{52,54,56}$Ti which also show a decrease in collectivity at $^{54}$Ti with $N = 32$. Further inspection of the shell model results reveals that the effective gap between $p_{3/2}$ and $p_{1/2}$ neutrons stays constant at a value of about 2 MeV for both interactions when going from Ca to Cr in agreement with the experimental $B(E2)$ trend. The $f_{5/2} - p_{1/2}$ gap decreases from 3.5 MeV in Ca to 1.5 MeV in Cr for GXPF1A while it disappears for KB3G [8]. This explains the fact that the $N = 34$ gap has not developed in Cr and Ti, which makes Ca the crucial experimental benchmark,
and on the other hand, accounts for the agreement within the two theoretical approaches. The experimental trend of the $B(E2)$ values implies that the $p_{3/2} - p_{1/2}$ gap is larger than predicted while the $f_{5/2} - p_{1/2}$ gap is smaller than inferred from the GXPF1 interactions. The $B(E2)$ values in the $N = 32, 34$ Cr isotopes must also be seen in the light of a comparison to the shell model values for the Fe and Ni isotopes [10] which show the normal peaking in the $(p,f_{5/2})$ mid-shell at $N = 32–34$. A further test of the model predictions would be a study of the heavier Cr isotopes which should show a steep increase in the $B(E2)$ values towards deformation.

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