Enhanced collectivity along the $N = Z$ line: lifetime measurements in $^{44}$Ti, $^{48}$Cr, and $^{52}$Fe

To cite this article: K. Arnswald et al 2018 J. Phys.: Conf. Ser. 966 012029

View the article online for updates and enhancements.
Enhanced collectivity along the $N = Z$ line: lifetime measurements in $^{44}$Ti, $^{48}$Cr, and $^{52}$Fe

K. Arnswald$^1$, P. Reiter$^1$, L. Coraggio$^2$, B. Birkenbach$^1$, A. Blazhev$^1$, T. Braunroth$^1$, A. Dewald$^1$, C. Fransen$^1$, B. Fu$^1$, A. Gargano$^2$, H. Hess$^1$, R. Hirsch$^1$, N. Itaco$^{2,3}$, S. M. Lenzi$^4$, L. Lewandowski$^1$, J. Litzinger$^1$, C. Müller-Gatermann$^1$, M. Queiser$^1$, D. Rosiak$^1$, D. Schneider$^1$, M. Seidlitz$^1$, B. Siebeck$^1$, T. Steinbach$^1$, A. Vogt$^1$, K. Wolf$^1$, and K. O. Zell$^1$

$^1$ Institut für Kernphysik, Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany
$^2$ Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, I-80126 Napoli, Italy
$^3$ Dipartimento di Matematica e Fisica, Università degli Studi della Campania “Luigi Vanvitelli”, via A. Lincoln 5, I-8110 Caserta, Italy
$^4$ Dipartimento di Fisica dell’Università and INFN, Sezione di Padova, I-35141 Padova, Italy

E-mail: konrad.arnswald@ikp.uni-koeln.de

Abstract. Lifetimes of the $2^+_1$ states in $^{44}$Ti, $^{48,50}$Cr, and $^{52}$Fe were determined with high accuracy exploiting the recoil distance Doppler-shift method. The reduced E2 transition strengths of $^{44}$Ti and $^{52}$Fe differ considerably from previously known values. A systematic increase in collectivity is found for the $N = Z$ nuclei compared to neighboring isotopes. The $B$(E2) values along the Ti, Cr, and Fe isotopic chains are compared to shell-model calculations employing established interactions for the $0f1p$ shell, as well as a novel effective shell-model Hamiltonian starting from a realistic nucleon-nucleon potential. The theoretical approaches underestimate the $B$(E2) values for the lower-mass Ti isotopes. Strong indication is found for particle-hole cross-shell configurations, recently corroborated by similar results for the neighboring isotope $^{42}$Ca. A detailed manuscript has meanwhile been published in Physics Letters B [1].

1. Motivation

The $0f1p$ shell above the $^{40}$Ca core is a fertile region for shell-model studies. Several interactions like KB3G [2], FPD6 [3], and the GXPF1A [4] are available and well established, yielding good agreement with various experimental observables, such as energy spectra or – with the inclusion of Coulomb contributions – isospin-dependent effects like mirror-energy differences. In fact, a considerable number of nuclei near the $N = Z$ line is accessible via stable-beam fusion-evaporation reactions with reasonable production yields. This opens the door for high-precision measurements of lifetimes and transition strengths to be compared to theory. This work focuses on the $N = Z$ nuclei $^{44}$Ti, $^{48}$Cr, and $^{52}$Fe. Reduced transition strengths are sensitive signatures to describe collective excitations in this region of the Segrè chart. Along the isotopic chains, (sub-)shell closures can be identified by a drop of the $B$(E2; $2^+_1 \to 0^+_g.s.$) value which increases towards midshell. In the chain of titanium isotopes such a drop was previously observed at...
Figure 1. (a) Adopted $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ values of Ti (green squares), Cr (blue circles), and Fe (red triangles) isotopes. Data are taken from Refs. [5, 6]. Data points of the same element are connected and the Ti and Fe chains are slightly shifted horizontally with respect to the Cr data to guide the eyes. (b) Adopted $B_{4/2}$ ratios for even-even $N = Z$ nuclei between $^{40}$Ca and $^{56}$Ni. Limits for an ideal vibrator (long dashed purple line), an ideal rotor (dotted green line), and the limit for a non-collective behavior ($B_{4/2} = 1$) (black line) are indicated. See text for details.

$N = 22$ (cf. Fig. 1 (a)) which is not expected with regard to the shell closure at $N = 20$. For $^{48}$Cr and $^{52}$Fe the $B(E2)$ values are only known with considerable errors.

Furthermore, reduced transition strengths in these nuclei are of high interest to investigate the systematics of $B_{4/2}$ ratios, as recently discussed in Ref. [7]. The $B_{4/2}$ ratio (sometimes also referred to as RE4) is defined as follows:

$$B_{4/2} = \frac{B(E2; 4^+_1 \rightarrow 2^+_1)}{B(E2; 2^+_1 \rightarrow 0^+_{g.s.})}$$  \hspace{1cm} (1)

In rotational and vibrational nuclear models as well as in shell-model calculations the value of $B_{4/2}$ is always larger than one. $B_{4/2}$ ratios deduced from previously adopted $B(E2)$ values evolve dramatically in the $0f_{7/2}$ shell along $N = Z$ from a vibrational behavior for $^{44}$Ti and $^{52}$Fe to a single-particle value at the $0f_{7/2}$ mid-shell for $^{48}$Cr (cf. Fig. 1(b)).

2. Experiment

Lifetime measurements of the $2^+_1$ states in $^{44}$Ti, $^{48,50}$Cr, and $^{52}$Fe were performed at the Institute for Nuclear Physics, University of Cologne employing the Cologne plunger device [8]. Ion beams were provided by the FN tandem accelerator at 62, 26, and 86 MeV inducing $^{nat}$Mg($^{23}$Na, xnp)$^{44}$Ti, $^{48}$Ca($^{10}$B, np)$^{48}$Cr, $^{27}$Al($^{28}$Si, $\alpha$p)$^{50}$Cr, and $^{27}$Al($^{28}$Si, 2np)$^{52}$Fe fusion-evaporation reactions, respectively. Excited recoil nuclei left the target with velocities of 1 to 3% of the speed of light and were finally stopped within a 9.6-mg/cm$^2$ thick Au foil. Emitted $\gamma$ rays were detected by a setup of twelve high-purity germanium (HPGe) detectors. The HPGe detectors were placed in rings centered at polar angles of $\theta_0 = 0^\circ$ (1 detector), $\theta_1 = 45^\circ$ (6 detectors), and $\theta_2 = 143^\circ$ (5 detectors) with respect to the beam axis. During the experiments, data were recorded for different target-to-stopper distances. For each target-to-stopper distance coincident $\gamma$ rays were sorted into $\gamma\gamma$ matrices correlating groups of the different detector rings.
3. Results
In the analysis lifetimes were determined using the recoil distance Doppler-shift (RDDS) technique in combination with the differential decay-curve method (DDCM) [8]. To reduce systematic uncertainties caused by unobserved side feeding, the DDCM was applied for $\gamma\gamma$-coincidence data. Lifetimes of the $2^+_{1s}$ states were obtained from the intensity ratios of shifted (SH) and unshifted (US) components (i) of the depopulating transition for gates on the shifted part of feeding transitions and (ii) of the direct feeding transitions for coincidence requirements on the unshifted component of the $2^+_1 \rightarrow 0^+_{gs}$ transition. Exemplary gated $\gamma$-ray spectra of the $2^+_1 \rightarrow 0^+_{gs}$ transition in $^{50}$Cr are shown in Figs. 2 (a, b). The lifetime $\tau$ is deduced from the weighted mean of each lifetime $\tau_i$ obtained at a distance $i$ in the sensitive range. The resulting plots for the $2^+_1$ lifetime of $^{50}$Cr are given in Figs. 2 (c, d). Corresponding spectra and lifetime curves of $^{44}$Ti, $^{48}$Cr, and $^{52}$Fe are published in Ref. [1]. Results of the determined lifetimes and corresponding $B(E2)$ values are summarized in Table 1.

![Figure 2](image_url)

Figure 2. Exemplary $\gamma$-ray energy spectra of the $2^+_1 \rightarrow 0^+_{gs}$ decay at 783 keV in $^{50}$Cr, obtained by a cut on the shifted component of the $4^+_1 \rightarrow 2^+_1$ transition at $E_\gamma = 1098$ keV. Short (a) and large (b) target-to-stopper distances at backward angles are shown. (SH) and (US) label the Doppler-shifted as well as the unshifted components, respectively. $\tau$ curves of the $2^+_1$ state (c) for $^{50}$Cr are presented. The weighted mean value of the lifetime is represented by a black solid line; dashed lines mark the statistical uncertainty. (d) Shifted and unshifted intensities of the $2^+_1 \rightarrow 0^+_{gs}$ transition are marked with full black circles and open black circles, respectively. The polynomial fit function to the given intensities is presented in solid and dashed red. Lifetimes and $\gamma$-ray intensities are presented in dependence of the target-to-stopper distances. Note the logarithmic distance scale.

4. Discussion
The newly determined $B(E2; 2^+_1 \rightarrow 0^+_{gs})$ value for $^{44}$Ti yields $22.2^{+2.2}_{-1.8}$ W.u., which is significantly larger than the adopted value of $14.7^{+1.3}_{-0.6}$ W.u.. Specifically, it now gives a pronounced minimum for the $B(E2) = 19.8(37)$ W.u. value of its semi-magic neighboring isotope $^{42}$Ti. In $^{44}$Ti, the hitherto adopted value includes results deduced from lifetime experiments employing the Doppler-shift attenuation method (DSAM) following $\alpha$-capture and $\alpha$-transfer reactions on a
Table 1. $2^+_1$ lifetimes and corresponding $B(E2)$ values in $^{44}$Ti, $^{48,50}$Cr, and $^{52}$Fe from the present experiment as well as previously adopted values taken from Ref. [5]. The results are compared to four different shell-model calculations (for details see text).

| Nucleus | Lifetime [ps] | $B(E2)$ [W.u.] | $B(E2; 2^+_1 \to 0^+_{g.s.})$ [W.u.] |
|---------|--------------|----------------|----------------------------------|
|          | Present      | Previous       | Present                          | Previous             | GXPF1A | KB3G | FPD6 | Realistic |
| $^{44}$Ti | 2.7(2)       | 4.03$^{+0.18}_{-0.32}$ | $22.2^{+2.2}_{-1.8}$            | $14.7^{+1.3}_{-0.6}$ | 11.4   | 12.9 | 15.2 | 13.0      |
| $^{48}$Cr | 12.2(7)      | 12.4(14)       | $26.9^{+1.7}_{-1.4}$            | 26.4(29)             | 24.2   | 24.4 | 30.3 | 26.2      |
| $^{50}$Cr | 13.0(4)      | 13.15$^{+0.44}_{-0.29}$ | 19.6(6)                        | 19.23(58)            | 19.9   | 19.9 | 25.2 | 22.2      |
| $^{52}$Fe | 7.0(4)       | 11.3(14)       | $23.0^{+1.3}_{-1.1}$            | 14.2(18)             | 19.2   | 18.8 | 25.3 | 23.7      |

$^{40}$Ca target [9, 10]. Challenging aspects of these experiments were the lack of precise knowledge of the stopping power, unknown feeding contributions, and the decreasing sensitivity of the DSAM for lifetimes longer than 1 ps. The present value provides a solution of the puzzling question of the robustness of the $N = 20$ shell closure (see Fig. 3(a)). The $B(E2; 2^+_1 \to 0^+_{g.s.}) = 26.9^{+1.3}_{-1.4}$ W.u. of $^{48}$Cr and $B(E2; 2^+_1 \to 0^+_{g.s.}) = 19.6(6)$ W.u. of $^{50}$Cr are in good agreement with previously known values. In the case of $^{48}$Cr the relative uncertainty was further reduced and amounts to 5.8%. Both values follow the overall trend along the $Z = 24$ isotopes (cf. Fig. 3(b)). Similar to $^{44}$Ti, also the $B(E2; 2^+_1 \to 0^+_{g.s.})$ value of 23.0$^{+1.3}_{-1.1}$ W.u. in $^{52}$Fe exceeds the previously known value of 14.2(18) W.u. [11] and suggests a stronger collectivity at $N = Z = 26$. Both $B(E2)$ values, the previously known as well as the present one, are consistent with the expectation of an increased collectivity with respect to the $N = 28$ shell closure, however, the present slope is more pronounced (see Fig. 3(c)). To sum up, the $B(E2; 2^+_1 \to 0^+_{g.s.})$ values in $^{44}$Ti and $^{52}$Fe are considerably larger than the previously measured ones. Thus, an enhanced collectivity close to the doubly-magic nuclei $^{40}$Ca and $^{50}$Ni at $N = Z$ is found.

Furthermore, shell-model calculations were performed to compare the experimental results with theory. Shell-model calculations were performed using the NuShellX@MSU code [12]. For comparison three established interactions were employed, namely the KB3G [2], FPD6 [3], and GXPF1A [4]. Single-particle excitations are limited to the full 0f1p valence space. For the calculation of the matrix elements, effective charges $e_\alpha = 1.5 e$ and $e_\nu = 0.5 e$ were employed. Furthermore, realistic shell-model calculations, using the shell-model code Antoine [13], have been performed [14]. The calculated $B(E2; 2^+_1 \to 0^+_{g.s.})$ values are reported in Table 1. An overview on the evolution of the $B(E2)$ values for Ti, Cr, and Fe isotopes is shown in Fig. 3.

For each interaction the theoretical $B(E2)$ values along the chain of titanium isotopes are in poor agreement with the experimental ones close to $N = Z$ (see Fig. 3(a)). A large deviation is observed for $N = 20$ where the theoretical values are considerably smaller than the experimentally determined values. This discrepancy decreases with an increasing number of valence neutrons toward $N = 26$. However, the sub-shell closure at $N = 28$ is also not reproduced by the calculations. In the neighboring even-even isotope $^{42}$Ca a recent investigation revealed a similar result [15]. Shell-model results underpredict the enhanced experimental $B(E2)$ values. It was suggested that the reduced theoretical values arise from $2\hbar \omega$ sd-shell excitations, which are not included in the 0f1p model space [16]. Evidence for the importance of core excitations is also found in the study of the schematic $\alpha$-cluster model where excitation energies of all rotational bands in $^{44}$Ti are reproduced using an $\alpha + ^{40}$Ca($\Gamma$) system [17]. Moreover, their calculated $B(E2; 2^+_1 \to 0^+_{g.s.}) = 18$ W.u. value [17] is in a better agreement with the present experimental results.
Figure 3. Experimental and theoretical $B(E2; 2^+ \rightarrow 0^+)$ values in dependence of the neutron number for (a) titanium, (b) chromium, and (c) iron isotopes. $B(E2)$ values from this work are marked with red squares. Black triangles mark the previously adopted $B(E2)$ values [5, 6]. Shell-model calculations based on the GXPF1A (orange open diamonds), KB3G (blue open triangles), and FPD6 (green stars) interactions, as well as a shell-model calculation using an effective Hamiltonian starting from a realistic potential (purple open circles) are shown.

In the chain of chromium isotopes the different shell-model calculations reproduce the trend of the measured $B(E2)$ values for $N < 28$, whereas the measured values are overestimated for $N \geq 28$ (cf. Fig. 3(b)).

Only partial agreement between experiment and theory is found for the iron isotopes (see Fig. 3(c)). For light isotopes at $N = 24, 26$ results from the realistic calculation and the FPD6 interaction are consistent with the present experimental data. However, nice agreement is achieved between the KB3G interaction and experiment for $N \geq 28$. It is noteworthy, that no calculation describes the huge experimentally observed drop in $B(E2)$ values between $N = Z = 26$ and the shell closure at $N = 28$; it is underestimated by each interaction.

Considering the new $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ values, the $B_{4/2}$ values can be reevaluated using the new $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ values from Table 1 and the $B(E2; 4^+_1 \rightarrow 2^+_1)$ values from Refs. [18, 19, 20] (labeled Present) as well as the adopted $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ values from Ref. [5] and those of the $4^+_1 \rightarrow 2^+_1$ transition from Refs. [18, 19, 20] (labeled Previous). The $B_{4/2}$ values are shown in Fig. 4. The present evaluation of the $B_{4/2}$ ratios shows considerable differences for $^{44}$Ti and $^{52}$Fe with respect to the previous results. The observed strong variations of the $B_{4/2}$ ratios along the chain of isodiapheres, which were discussed in Ref. [7], are not confirmed. Moreover, the evaluated vibrator-like behavior for $^{44}$Ti and $^{52}$Fe is now suggested to be more rotor-like. The puzzle of the minimum value for mid-shell $^{48}$Cr close to unity could not be resolved and remains subject of future studies.

5. Summary
These proceedings report on lifetime measurements in $N = Z$ nuclei $^{44}$Ti, $^{48}$Cr, and $^{52}$Fe. RDDS experiments yield an increased $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ value in $^{44}$Ti and $^{52}$Fe. Enhanced collectivity is indicated for all investigated $N = Z$ nuclei. Results from state-of-the-art shell-model calculations are ambiguous; none of the four shell-model interactions reproduces the $B(E2; 2^+_1 \rightarrow 0^+_{g.s.})$ values for the investigated Ti, Cr, and Fe isotopes in a consistent way. The observed discrepancy between experimental and theoretical $B(E2)$ values for $^{44}$Ti can
Figure 4. $B_{4/2}$ ratios for even-even $N = Z$ nuclei between $^{40}$Ca and $^{56}$Ni. Results from this work are given in red squares and the adopted values are shown in black triangles. Same color code as in Fig. 1 (b) is used. See text for details.

be traced back to the importance of multi-particle multi-hole cross-shell configurations similar to recent observations in the neighboring isotone $^{42}$Ca. The different calculations reproduce the experimental $B(E2)$ values for $^{48}$Cr well, whereas for $^{52}$Fe the experimental value is only favored by the realistic and the FPD6 interaction. An extended description of these results was submitted for publication after the conference and can be found in Ref. [1].

References

[1] Arnswald K et al. 2017 Phys. Lett. B 772 599 – 606
[2] Poves A et al. 2001 Nucl. Phys. A 694 157 – 198
[3] Richter W A et al. 1991 Nucl. Phys. A 523 325 – 353
[4] Homma et al. 2005 Eur. Phys. J. A 25 499–502
[5] Pritychenko B et al. 2016 At. Data Nucl. Data 107 1 – 139
[6] Seidlitz M et al. 2011 Phys. Rev. C 84(3) 034318
[7] Hertz-Kintish D et al. 2014 Phys. Rev. C 90(3) 034307
[8] Dewald A et al. 2012 Prog. Part. Nucl. Phys. 67 786 – 839
[9] Dixon W R et al. 1973 Nucl. Phys. A 202 579 – 592
[10] Schielke S et al. 2003 Phys. Lett. B 567 153 – 158
[11] Yurkewicz K L et al. 2004 Phys. Rev. C 70(3) 034301
[12] Brown B A et al. 2014 Nucl. Data Sheets 120 115 – 118
[13] Caurier E et al. 2005 Rev. Mod. Phys. 77(2) 427–488
[14] Coraggio L et al. 2012 Ann. Phys. 327 2125 – 2151
[15] Hadyńska-Kłęk K et al. 2016 Phys. Rev. Lett. 117(6) 062501
[16] Brown B A 2001 Prog. Part. Nucl. Phys. 47 517 – 599
[17] Ohkubo S et al. 1998 Phys. Rev. C 57(5) 2760–2762
[18] Chen J et al. 2011 Nucl. Data Sheets 112 2357 – 2495
[19] Burrows T W 2006 Nucl. Data Sheets 107 1747 – 1922
[20] Dong Y and Junde H 2015 Nucl. Data Sheets 128 185 – 314