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Lifetime measurements in $^{52,54}$Ti to study shell evolution toward $N = 32$


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Lifetimes of the excited states in the neutron-rich $^{52,54}$Ti nuclei, produced in a multinucleon-transfer reaction, were measured by employing the Cologne plunger device and the recoil-distance Doppler-shift method. The experiment was performed at the Grand Accélérateur National d’Ions Lourds facility by using the Advanced Gamma Tracking Array for the $\gamma$-ray detection, coupled to the large-acceptance variable mode spectrometer for an event-by-event particle identification. A comparison between the transition probabilities obtained from the measured lifetimes of the $2^+_1$ to $8^+_1$ yrast states in $^{52,54}$Ti and that from the shell-model calculations based on the

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well-established GXPF1A, GXPF1B, and KB3G $fp$ shell interactions support the $N = 32$ subshell closure. The $B(E2)$ values for $^{52}$Ti determined in this work are in disagreement with the known data, but are consistent with the predictions of the shell-model calculations and reduce the previously observed pronounced staggering across the even-even titanium isotopes.

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I. INTRODUCTION

Understanding the evolution of shell structure toward the drip lines is one of the driving forces for many theoretical and experimental efforts, as investigations have shown that the shell structure often changes significantly as a result of the rearrangement of single-particle levels in exotic nuclear regions [1]. In this context, the $N = 40$ island of inversion represents a rich testing ground. For example, while $^{68}$Ni shows doubly shell-closure character, an increase in collectivity is apparent both from excitation energies and transition strengths in the neutron-rich $^{58-66}$Cr [2–5] and $^{62-70}$Fe [5–8] nuclei close to the $Z = 28$ shell closure. The experimental data assisted a comprehensive description of these nuclei with respect to the high collectivity predicted using the modern shell-model calculations [2,6].

Studies of neutron-rich Ti isotopes are also essential for an understanding of the shell structure in the Ti-Cr-Fe region beyond $N = 28$ and toward $Z = 20$. Known $B(E2; 2^+_1 \rightarrow 0^+_g)$ transition probabilities in $^{54}$Ti [9], $^{56}$Cr [10,11], $^{58}$Fe [12], and $^{60}$Ni [13] isotopes, which in a shell-model framework can be viewed as having a completely filled valence $\nu 2p_{3/2}$ orbital, suggest a phase transition. In particular, the collective structure in $^{58}$Fe evolves to a neutron-subshell closure along the isotonic chain with decreasing proton number, i.e., from $^{56}$Cr over $^{54}$Ti to $^{52}$Ca. This observation is supported by an increased staggering of the $2^+_1$ level energies for decreasing proton number as shown in Fig. 1. At the neutron shell closure $N = 28$, the isotopes show a local rise in the $2^+_1$ state energy but at $N = 32$ a different behavior is observed: only $^{52}$Ca, $^{54}$Ti, and $^{56}$Cr exhibit a local increase in the $2^+_1$ energy. The corresponding $B(E2; 2^+_1 \rightarrow 0^+_g)$ values suggest a weak and very localized subshell closure at $N = 32$ [14–16] for the Ca, Ti, and Cr isotopes, which collapses for Fe and Ni. This behavior was investigated in several recent experiments on $^{52,54,56}$Ti and $^{58}$Cr using deep-inelastic reactions [17,18], as well as Coulomb excitation at intermediate energies [9]. Essentially, all the experimental and theoretical works indicate the subshell closure at $N = 32$ is weaker compared to that at $N = 28$.

A possible explanation could be an effect similar to that for $N = 40$ isotopes described in works of Otsuka et al. [20–22], where the proton-neutron tensor force contribution to the monopole component of the residual interaction was proposed as one of the driving factors behind the shell evolution at $N = 40$. This ensures that the $N = 40$ gap is reduced by removing protons from the $\pi 1f_{7/2}$ subshell. For nuclei close to $N = 32$, a similar effect could result in a reverse order of the $\nu 1f_{5/2}$ and $\nu 2p_{1/2}$ orbitals and is assumed to open up the shell gap at $N = 32$, i.e., the energy difference between the $\nu 2p_{3/2}$ and $\nu 2p_{1/2}, \nu 1f_{5/2}$ orbitals with decreasing proton number from $Z = 28$ to $Z = 20$ [14].

For a better understanding of the shell evolution, data on $E2$ transition strengths between higher-spin states in $^{54}$Ti ($N = 32$) are essential, which are not available to date. Furthermore, the shell-model predictions so far do not agree with the $B(E2)$ data of the neighboring $^{52}$Ti that is only two neutron away but exhibits different $B(E2)$ behavior as a function of spin to that of $^{50}$Ti and $^{54}$Ti, e.g., $^{52}$Ti has relatively high $B(E2; 2^+_1 \rightarrow 0^+_g)$ and $B(E2; 6^+_2 \rightarrow 4^+_1)$ values but a low $B(E2; 4^+_1 \rightarrow 2^+_0)$ value. In contrast, experimental (theoretical) results for $^{50}$Ti ($^{54}$Ti) show relatively high $B(E2)$ values for the $2^+_1 \rightarrow 0^+_g$ and $4^+_1 \rightarrow 2^+_1$ transitions and a low $B(E2)$ value for the $6^+_2 \rightarrow 4^+_1$ transition. So far, no successful shell-model description could be reached for $^{52}$Ti, motivating a new detailed investigation of $^{52,54}$Ti in order to obtain a comprehensive picture of the evolving shell structure with regard to the emergence of a $N = 32$ subshell closure for $Z < 26$.

In this work, the evolution of the shell structure in $^{52,54}$Ti is studied by measuring the lifetimes of the first $2^+_1$, $4^+_1$, $6^+_2$, and $8^+_3$ states in the yrast band by employing the recoil-distance Doppler-shift (RDDS) method [23]. The deduced $E2$ transition strengths are discussed together with the state-of-the-art shell-model calculations.

II. EXPERIMENTAL SETUP

The experiment was performed at the Grand Accélérateur National d’Ions Lourds (GANIL) in Caen, France using the Cologne plunger for deep-inelastic reactions [23]. The $^{52,54}$Ti nuclei were produced via two-neutron and four-neutron multinucleon-transfer reactions induced by a $^{238}$U beam at an energy of $E(^{238}\text{U}) = 1608.9$ MeV (6.76 MeV/u) impinging on a $^{50}$Ti target. The target was $\approx 1.5$ mg/cm$^2$ thick and had a $^{40}$Ca layer of $\approx 0.4$ mg/cm$^2$ in front of the target. The plunger device including target and degrader foils was

FIG. 1. Evolution of experimental excitation energies $E(2^+_1)$ in neutron-rich even-even Ca-Ni nuclei with $20 \leq Z \leq 28$ and $26 \leq N \leq 34$. 

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placed close to the grazing angle of the multinucleon-transfer reactions of interest at an angle of 45° with respect to the beam axis. Target and degrader foils were mounted orthogonal to the entrance axis of the magnetic spectrometer VAMOS++. The 50Ti target layer had an effective thickness of ≈2.1 mg/cm² resulting in an effective 238U beam energy of 6.16 MeV/u in the middle of the 50Ti layer, taking into account the energy loss in the Cu layer with an effective thickness of ≈0.57 mg/cm². A 99.9Mg degrader foil with a thickness of ≈3.2 mg/cm² was placed downstream the target. The targetlike recoils were thus slowed down before entering the VAMOS++ magnetic spectrometer, consisting of two quadrupoles, a dipole magnet, and an array of focal plane detectors, for an event-by-event particle identification. A schematic drawing of the experimental setup is shown in Fig. 1 of Ref. [27] (without the EXOGAM detectors). The focal plane detection system was used to identify the mass (A), charge (Q) and atomic number (Z) of the reaction products. It consisted of a multiwire proportional counter (MWPC), four drift chambers and a segmented ionization chamber. The dual position-sensitive multiwire proportional counter (DPS-MWPC) [26] placed at the entrance of the spectrometer provided the start signal for the time-of-flight (TOF) and the position (x, y) of the recoiling reaction products. Together with the MWPC at the focal plane, they provide the TOF and the direction of the velocity of the ions for Doppler correction. The drift chambers, which also detected the position (x, y) as well as the emission angles (θ, φ) of the recoiling reaction products, were used together with the DPS-MWPC to determine the trajectory of the ions after the dipole magnet. Finally, the ionization chamber was employed for measuring the total energy E and energy loss ΔE of the ions at the focal plane. In the present experiment, the magnetic field of the VAMOS++ dipole was set such that a magnetic rigidity of \( B\rho = 0.975 \) Tm was selected for the central trajectory in the spectrometer.

Prompt γ rays were detected by the Advanced Gamma Tracking Array (AGATA) [28,29]. At the time of this experiment, it consisted of 29 36-fold encapsulated germanium detectors in ten cryostats placed at a radial distance of ≈23.5 cm to the target center and covered angles from 120°−175° with respect to the optical axis of the spectrometer. Using the velocity vector reconstructed by VAMOS++ and the position of the first γ-ray interaction in AGATA, the observed γ rays were Doppler corrected on an event-by-event basis using the angle between the scattered particle and the direction of γ rays detected in AGATA. The γ-ray interaction points, determined by the pulse shape analysis (PSA) using GRID search algorithm techniques [30], were tracked by using the Orsay forward tracking (OFT) algorithm [31]. The particle velocity after passing through the degrader foil is used for the Doppler correction. Therefore, the slow component, corresponding to photon emissions after the degrader, occurs at the central γ-ray energy whereas the fast component is shifted toward lower energies, as AGATA was located at backward angles.

Data were taken at six different nominal target-to-degrader distances between 70 μm and 1000 μm for about 24 h per distance, which results in sensitivity to lifetimes ranging from a few ps to about 400 ps.

FIG. 2. Beam-induced changes observed for the 50Ti plunger target. The originally stretched target foil was severely damaged. Here, the side of the target with the copper layer that was facing the beam.

A. Target degradation and effective plunger distances

During the experiment, despite the low beam current of 0.1 pnA, beam-induced changes of the 50Ti target occurred, even though estimates of the beam spot temperature from the momentum transfer of the beam did not indicate any significant thermal load. A self-supporting 50Ti target with a thickness of ≈1.5 mg/cm² was used at first. This target developed wrinklelike structures with amplitudes of about 100 μm soon after being exposed to the 6.76 MeV/u 238U beam with a beam current of 0.1 pnA. To improve heat conductivity, this target was replaced by the aforementioned ≈1.5 mg/cm² 50Ti target with an additional ≈0.4 mg/cm² copper that was evaporated onto the 50Ti foil. The copper layer was facing the beam. This target experienced similar damages after being exposed to the beam (see Fig. 2). Nevertheless, as no other alternative was available, the 50Ti target with the additional copper layer was used. After a careful analysis, the observed degradation of the target can be explained as resulting from the sensitivity of the Ti material to the electronic stopping of heavy ions (see Ref. [32]). This effect leads to a drastic increment of the lattice temperature of Ti induced by the irradiation by the highly energetic 238U ions (so-called thermal spikes) and thus to structural damages of the Ti target foil. Titanium is very sensitive to this effect due to its large Debye temperature on the one hand and its low thermal conductivity on the other hand. This observation can be reproduced within the thermal-spike model (see, e.g., Ref. [33]). The degrader, on the other hand, showed no such effects since magnesium has a much lower Debye temperature and a higher thermal conductivity.

For this reason, a direct and precise determination of the distances between the plunger target and the degrader was not possible. Instead, average absolute distances for each distance setting need to be specified as the structural changes to target continue to take place during the 238U beam exposure. These distances are referred to as the effective distances and can be extracted from γ-ray spectra related to nuclear states whose lifetimes are known with high precision. A strongly populated reaction channel produced 46Ti (see Fig. 3 for the corresponding spectrum), for which a high-precision RDDS
measurement was performed only recently with results published in Ref. [34]. Since $^{46}$Ti isotopes were produced via multinucleon-transfer reactions, only the low-lying states $2^+_1$, $4^+_1$, and $6^+_1$ were populated, so that other feeding can be excluded. Feeding corrections for the observed transitions from the $4^+_1$ and $6^+_1$ states were taken into account in the analysis.

For the determination of effective distances, $\gamma$-ray spectra for $^{46}$Ti were created through a versatile GEANT4-based Monte Carlo simulation tool [35] using a precise experimental geometry including that for the target chamber and the AGATA detectors. For the distance determination, distance assumptions were provided to the simulation toolkit and their values were varied in discrete steps. For illustration, Fig. 3 shows a representative comparison of the experimental spectra showing the $2^+_1 \rightarrow 0^+_{gs}$ transition in $^{46}$Ti at a nominal distance of 240 $\mu$m with the best-fitting simulation, assuming a separation following the described approach. For each comparison between the simulated and the experimental spectrum, a $\chi^2$ value was calculated according to the following modified version of the least-squares method:

$$\chi^2 = \sum_i \left( \frac{i_{\text{exp}} - i_{\text{sim}}}{\Delta i_{\text{exp}}} \right)^2,$$

where $i_{\text{exp}}$ ($i_{\text{sim}}$) is the number of counts in bin $i$ in the experimental (simulated) spectrum. The chosen range was restricted to both the fast and slow components of the considered transition. An example of this approach with the $\chi^2$ method is depicted in Fig. 4 for the nominal distance of 300 $\mu$m. As indicated, the errors of the $\chi^2$ method are deduced from lifetimes with $\chi^2_{\text{min}} + 1$. See text for details.

III. DATA ANALYSIS AND RESULTS

Figure 5(a) shows the energy loss $\Delta E$ versus the total energy $E$ spectra, using which the recoils with specific atomic number $Z$ can be identified. The mass-over-charge $A/Q$ ratio and the mass $A$ are determined from the TOF, the path through the spectrometer, and the magnetic rigidity. The mass resolution for the isotopic chains, shown in Fig. 5(b), was $\Delta M/M \approx 1.4\%$, so that an unambiguous identification of the reaction residues in the mass region around $A = 50$ was possible.

Figure 6 shows the $\gamma$-ray spectra after Doppler correction with $\beta_D = 11.68\%$ for the slow component detected with AGATA in coincidence with $^{54}$Ti and $^{52}$Ti ions identified in VAMOS++, summed over all six distances. Therefore, the slow component appears at nominal $\gamma$-ray energy while the fast component has lower energy. It can be clearly seen that the statistics for $^{52}$Ti is $\approx 13$ times higher than that for $^{54}$Ti.

<table>
<thead>
<tr>
<th>$d_{\text{exp}}$ ($\mu$m)</th>
<th>$d$ ($\mu$m)</th>
</tr>
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<tbody>
<tr>
<td>70</td>
<td>102(8)</td>
</tr>
<tr>
<td>150</td>
<td>198(9)</td>
</tr>
<tr>
<td>180</td>
<td>200(6)</td>
</tr>
<tr>
<td>240</td>
<td>277(10)</td>
</tr>
<tr>
<td>300</td>
<td>328(9)</td>
</tr>
</tbody>
</table>

TABLE I. Effective distances $d$ resulting from a comparison with the simulations and corresponding nominal distances $d_{\text{exp}}$ used for the measurement (i.e., relative to electrical contact at the start of the experiment).

The velocities of the recoil ions were determined as follows: the velocity after the degrader was measured directly by VAMOS++, whereas the velocity between target and degrader was deduced from the experimentally observed Doppler shift between the two components of the transitions. The mean recoil velocity behind the target (degrader) is $\beta_T = 12.70(21)\% \ [\beta_D = 11.68(23)\%]$ of the speed of light.
The clearly visible variations of the intensities of the fast and slow components with the distance \( d \) in the Doppler-corrected energy spectra for the \( 2^+_1 \rightarrow 0^+_g \) transition in \( ^{54}\text{Ti} \) at three different distances are shown in Fig. 7. During the fitting procedure, the peak positions and widths were fixed. The latter were determined by calibrating the line width using the \( \gamma \)-ray spectra of \( ^{50},^{52},^{53}\text{Ti} \), which have a significantly higher level of statistics than that of \( ^{54}\text{Ti} \). Due to the relatively small difference in the velocity of \( \Delta v = 0.0102 \, c \), the fast and slow components of the \( \gamma \)-ray lines are not well separated from each other.

Lifetimes of the excited states in \( ^{52,54}\text{Ti} \) were extracted from the \( \gamma \)-ray intensities for each distance in the sensitive range (see Eq. (20) in Ref. [23]) using the differential decay curve method (DDCM) [36]. The lifetime of an excited state should not depend on the target-to-degrader distances at which it has been determined, therefore, \( \tau \) values are expected to remain unchanged with plunger distance. In \( ^{54}\text{Ti} \) it is possible to identify five transitions: \( 2^+_1 \rightarrow 0^+_g \) (1495 keV), \( 4^+_1 \rightarrow 2^+_1 \) (1002 keV), \( 6^+_1 \rightarrow 4^+_1 \) (439 keV), \( 8^+_1 \rightarrow 6^+_1 \) (2523 keV), and a transition at 840 keV from a state with unknown spin and parity \( J^\pi \) deexciting to the \( 4^+_1 \) state. Only for the \( 2^+_1 \rightarrow 0^+_g \) transition, in the Doppler-corrected energy spectra for the \( 4^+_1 \rightarrow 2^+_1 \) transition, both components are visible for all distances. For the 439 keV \( 6^+_1 \rightarrow 4^+_1 \) transition, only the fast component is visible, while the slow component is visible at all distances. Therefore, only a lower limit of the \( 6^+_1 \) lifetime could be determined. In contrast, for the \( 8^+_1 \rightarrow 6^+_1 \) transition at 2523 keV only the fast component is visible, and as a consequence only an upper limit of the \( 8^+_1 \) lifetime was deduced. In \( ^{52}\text{Ti} \) it is possible to identify ten transitions: \( 2^+_1 \rightarrow 0^+_g \) (1050 keV), \( 4^+_1 \rightarrow 2^+_1 \) (1268 keV), \( 6^+_1 \rightarrow 4^+_1 \) (711 keV), \( 8^+_1 \rightarrow 6^+_1 \) (1258 keV), \( 2^+_2 \rightarrow 2^+_1 \) (1214 keV), \( 2^+_1 \rightarrow 4^+_1 \) (1382 keV), \( 3^+_1 \rightarrow 4^+_1 \) (1135 keV), \( 10^+_1 \rightarrow 8^+_1 \) (2406 keV), \( 10^+_2 \rightarrow 8^+_1 \) (3232 keV), and \( J^\pi \rightarrow 3^+_1 \) (1025 keV). It should be noted that the \( \gamma \)-ray spectra are particle-gated singles spectra. For the lifetime determination of the \( 2^+_1, 4^+_1, 6^+_1, \) and \( 8^+_1 \) states, a feeding correction was carried out by subtracting the intensities of the slow component of a direct feeder from the intensity of the slow component of \( \gamma \) decay of the state to be analyzed. All contributions from states outside the yrast band have been neglected due to nonobserved slow components, which means that these states are characterized by a rather small lifetime. It should be
mentioned that the fast component of the $4^+_1 \rightarrow 2^+_1$ transition is equal in energy to the slow component of the $8^+_1 \rightarrow 6^+_1$ transition. In order to account for this, an intensity function depending on the spin was first established by determining the intensities of the fast and slow components of the $2^+_1 \rightarrow 0^+_g$, $6^+_1 \rightarrow 4^+_1$, and $10^+_2 \rightarrow 8^+_2$ transitions in $^{52}$Ti in the spectrum summed up over all distances. This intensity function was compared to the corresponding one in $^{48}$Ti, this is possible due to similarity of the level schemes. Using the intensity function, in the sum spectrum the added intensities ($I_{\text{fs.sum}}(J^+_1 \rightarrow (J-2)^+_1)$) of the fast and slow components of the $4^+_1 \rightarrow 2^+_1$ and $8^+_1 \rightarrow 6^+_1$ transitions in $^{52}$Ti were calculated. Then the intensities of the $2^+_1 \rightarrow 0^+_g$ transitions were determined for each distance ($I_{\text{fs.dist}}(2^+_1 \rightarrow 0^+_g)$) and the unknown intensities of the $4^+_1 \rightarrow 2^+_1$ and $8^+_1 \rightarrow 6^+_1$ were calculated according to $I_{\text{fs.dist}}(2^+_1 \rightarrow (J-2)^+_1) = \alpha_l \cdot I_{\text{fs.dist}}(2^+_1 \rightarrow 0^+_g)$ with

\[
\alpha_l = \frac{I_{\text{fs.sum}}(J^+_1 \rightarrow (J-2)^+_1)}{I_{\text{fs.sum}}(2^+_1 \rightarrow 0^+_g)},
\]

with $I_{\text{fs.sum}}(2^+_1 \rightarrow 0^+_g)$ is the added intensity of the fast and slow components of the $2^+_1 \rightarrow 0^+_g$ transition in the sum spectrum. The relevant plots for the lifetime analysis for the decay of the $2^+_1$ and $4^+_1$ states in $^{54}$Ti ($^{52}$Ti) are shown in Fig. 8 (Fig. 9). Fits of the intensities of the two components were performed with the NAPATAU code [39]. Here a feeding correction was carried out so that the summed intensity of $I_f$ and $I_s$ does not have to be constant. The different plot curves of the intensity of the slow components of Figs. 8 and 9 result from the different slopes in the intensities of the fast components. The weighted average lifetime is calculated using the points inside the region of sensitivity, i.e., from the maximum of the slope of the decay curve to its half value. The weighted averages of the mean lifetimes in $^{52,54}$Ti are summarized along with the corresponding $E2$ transition strengths in Table II. The statistical uncertainty of each lifetime value is dominated by the distribution of the individual $\tau$ values. The uncertainty of the recoil velocity and the uncertainty of the relative target-to-degrader distances have dominant contributions to the systematic errors of the lifetime. The final experimental error of the lifetime results from the root sum squared of the statistical and the systematic uncertainties.

In addition, the lifetimes determined according to DDCM were verified with the GEANT4-based Monte Carlo tool. Figure 7 shows a comparison between the experimental and simulated $\gamma$-ray spectra for $^{52}$Ti at three different distances. The lifetime $\tau(2^+_1) = 1.3(5)$ ps of the $2^+_1$ state in $^{54}$Ti determined in this work corresponds to a reduced transition probability $B(E2; 2^+_1 \rightarrow 0^+_g) = 84_{-25}^{+53} e^2$fm$^4$ and agrees with the adopted lifetime $\tau(2^+_1) = 1.53(27)$ ps with corresponding $B(E2; 2^+_1 \rightarrow 0^+_g) = 72_{-11}^{+13} e^2$fm$^4$ [9] within their error limits.

In $^{52}$Ti there is a considerable discrepancy between the new $B(E2; 2^+_1 \rightarrow (J-2)^+_1)$ values in this work for $2^+_1$, $4^+_1$, $6^+_1$ yrast states and the previously measured $B(E2)$ values [37,38] (see Fig. 13). The lifetime values of the $2^+_1$ and $4^+_1$ states from Ref. [37] and this measurement differ by a factor of approximately 2.

IV. DISCUSSION

A. Systematics

The results of this work yield new insights into the shell evolution for neutron-rich Ti, Cr, and Fe isotopes. Figure 10 illustrates the systematics of excitation energies and the evolution of $B(E2; 2^+_1 \rightarrow 0^+_g)$ values for even-even nuclei with $20 \leq Z \leq 28$ and $26 \leq N \leq 34$. The $B(E2; 2^+_1 \rightarrow 0^+_g)$ value in $^{52}$Ti has been obtained in the present work, that for $^{54}$Ti is taken from Ref. [9] (being consistent with the present result but subject to a smaller uncertainty), and the remaining values are adopted ones [40]. At the neutron shell closure $N = 28$, all depicted isotopes are characterized by high excitation energies of the first $2^+_1$ state and relatively small $B(E2; 2^+_1 \rightarrow 0^+_g)$ values (see Fig. 10). At $N = 30$ all isotopes show a reduction of the $2^+_1$ energies, but the $B(E2; 2^+_1 \rightarrow 0^+_g)$ values exhibit a
FIG. 8. Lifetime curves (a), (d) for the $2^+_1$ (left) and $4^+_1$ (middle) states in $^{54}$Ti. Black solid lines in (a), (d) represent the weighted mean value of the lifetime; dashed lines mark the statistical uncertainty. In addition, the intensities of the fast (b), (e) and slow (c), (f) components are shown, where the latter are corrected for delayed observed feeding. The polynomial fit function to the intensities is presented in solid black in (b), (e) and (c), (f). Note the logarithmic distance scale. Right: Partial level scheme with the relevant $\gamma$-ray transitions in the yrast band in $^{54}$Ti.

Increasing the neutron number by two and four, the behavior of the $2^+_1$ energies of Ca isotopes at $N = 32, 34$ is attributed to the local $\nu 2p_{3/2}$ and $\nu 2p_{1/2}$ subshell closures as discussed in Refs. [14,20]. Figure 11 shows the relevant...
TABLE II. Lifetime values for the first four yrast states in $^{52,54}$Ti obtained in the present experiment compared to previous experimental values taken from Refs. [9,37,38]. The corresponding experimental $B(E2; J_1^+ \rightarrow (J - 2)_1^+)$ values are presented as well.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$^{52}$Ti</th>
<th>$^{54}$Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1^+$</td>
<td>Lifetime (ps)</td>
<td>$B(E2)$ ($e^2f_m^2$)</td>
</tr>
<tr>
<td></td>
<td>This work</td>
<td>Previous</td>
</tr>
<tr>
<td>$2^+_1$</td>
<td>7.5(4)</td>
<td>5.19(20) [37]</td>
</tr>
<tr>
<td>$4^+_1$</td>
<td>2.3(3)</td>
<td>4.76(58) [37]</td>
</tr>
<tr>
<td>$6^+_1$</td>
<td>45.0(31)</td>
<td>36.7(63) [38]</td>
</tr>
<tr>
<td>$8^+_1$</td>
<td>29.4(21)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1.3(5)</td>
<td>1.53(27) [9]</td>
</tr>
</tbody>
</table>

from predominantly collective structures in $^{60}$Ni to a neutron subshell closure at $^{52}$Ca can be attributed to the weakening of the attractive proton-neutron interaction between the $\pi f_{7/2}$ and $\nu f_{5/2}$ orbitals with decreasing number of protons in the $\pi f_{7/2}$ orbital [14,20].

Figure 10 shows that in the case of the Ti isotopes, a similar peaking of $2^+_1$ energy is observed at $N = 32$ as for the Ca isotopes, although with a reduced amplitude, while for Cr this effect is much weaker and for Fe and Ni completely disappears. This speaks for the existence of a reduced $N = 32$ subshell closure in the Ti isotopes, which has recently been confirmed in mass measurements [42]. The systematics of $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in Ti isotopes obtained in earlier experiments showed a staggering anticorrelated with the subshell closures at $N = 28$ and $N = 32$. The revised $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in $^{52}$Ti reduces the amplitude of this staggering. The underlying nuclear structure of the lowest yrast states and $E2$ strengths can be addressed in the framework of the nuclear shell model.

B. Comparison with shell-model calculations

In the present work, shell-model calculations were performed with the code NUSHELLX@MSU [43] using three interactions, namely, KB3G [44], GXPF1A [45], and GXPF1B [46]. The model space comprises the full $pf$ main shell, coupled to a $^{40}$Ca core. Effective charges $e_\pi = 1.31$ e and $e_\nu = 0.46$ e were used for protons and neutrons, respectively, for all interactions [47]. The choice of the neutron effective

FIG. 10. Systematics of excitation energies for the $2^+_1$ state (top) and the evolution of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ (bottom) values in even-even nuclei with $20 \leq Z \leq 28$ and $26 \leq N \leq 34$ including the result for $^{52}$Ti obtained in the present work. For $^{54}$Ti the result from Ref. [9] is shown due to its smaller uncertainty.

FIG. 11. Schematic illustration of shell evolution from Ni to Ca for neutron orbits. The wavy line represents the interaction between the proton in the $1f_{7/2}$ orbit and the neutron in the $1f_{5/2}$ orbit. See text for more details. Adopted from Ref. [41].
calculations using GXPF1A, GXPF1B, GXPF1B-nf7, and KB3G interactions. For a better comparison the root-mean-square deviation (RMSD) for each interaction is provided.

Shell-model calculations using the KB3G, GXPF1A, GXPF1B, and GXPF1B-nf7 interactions are present in the 0

As seen in Fig. 12 the previously adopted values displayed a staggering in the \( B(E2; 2_1^+ \rightarrow 0_2^+ \) values, which has been a topic of several works. Although the established interactions were able to describe the excitations energies in these Ti isotopes and the structure of the neighboring nuclei, they were generally unable to exactly reproduce the staggering in the experimental \( B(E2; 2_1^+ \rightarrow 0_2^+ \) values in neutron-rich Ti isotopes using isoscalar proton and neutron effective charges [9,48,50]. As can be seen from Fig. 12, the new \( B(E2; 2_1^+ \rightarrow 0_2^+ \) systematics for \( ^{50-56}\text{Ti} \) exhibits a clearly weaker staggering with a rather flat behavior around \( N = 30 \) and similar values. A splitting in the \( B(E2; 2_1^+ \rightarrow 0_2^+ \) trends becomes apparent for \( ^{56}\text{Ti} \), where the values obtained using GXPF1A and GXPF1B interactions differ clearly from each other, with the latter one showing an increased value closer to the experimental result. Since the GXPF1B interaction was optimized to describe the local subshell closure at \( N = 34 \) in \( ^{54}\text{Ca} \) [46], it is not surprising that it also reproduces the isotope \( ^{50}\text{Ti} \) better than GXPF1A. The KB3G interaction yields a similar good description for \( ^{52-56}\text{Ti} \). Regarding \( ^{50}\text{Ti} (N = 28) \), there is clear overprediction of the \( B(E2; 2_1^+ \rightarrow 0_2^+ \) values by all shell-model interactions. One possible explanation is that proton particle-hole excitations across the \( Z = 20 \) \( ^{40}\text{Ca} \) core are present in the 0

This interaction has only a qualitative value, but may be relevant for \( ^{50-52}\text{Ti} \) and generally provides the best results for the \( ^{50-56}\text{Ti} \) \( B(E2; 2_1^+ \rightarrow 0_2^+ \) systematics. This interaction has only a qualitative value, but may be relevant for \( ^{50-52}\text{Ti} \) and generally provides the best results for the \( ^{50-56}\text{Ti} \) \( B(E2; 2_1^+ \rightarrow 0_2^+ \) systematics. A splitting in the \( B(E2; 2_1^+ \rightarrow 0_2^+ \) trends becomes apparent for \( ^{56}\text{Ti} \), where the values obtained using GXPF1A and GXPF1B interactions differ clearly from each other, with the latter one showing an increased value closer to the experimental result. Since the GXPF1B interaction was optimized to describe the local subshell closure at \( N = 34 \) in \( ^{54}\text{Ca} \) [46], it is not surprising that it also reproduces the isotope \( ^{50}\text{Ti} \) better than GXPF1A. The KB3G interaction yields a similar good description for \( ^{52-56}\text{Ti} \). Regarding \( ^{50}\text{Ti} (N = 28) \), there is clear overprediction of the \( B(E2; 2_1^+ \rightarrow 0_2^+ \) values by all shell-model interactions. One possible explanation is that proton particle-hole excitations across the \( Z = 20 \) \( ^{40}\text{Ca} \) core are present in the 0

Figure 12 shows a comparison of experimental and shell-model systematics of the 2

\( ^{50,54,56}\text{Ti} \). The excitation energies are listed in Table III. All used interactions describe the experimental excitation energies reasonably well.

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strengths in the calculations are computed as $B(E2; J^+_1 \rightarrow (J - 2)^+_1) = (A_p e_p^2 + A_n e_n^2)/(2J_1 + 1)$ [51]. Here, $A_p$ and $A_n$ (in units of fm$^2$) are the proton and neutron amplitudes and are summarized in Table IV for the $2^+_1 \rightarrow 0^+_g$ transitions in 50–56Ti for four different interactions. Small $A_n$ are characteristic of shell gaps at $N = 28$ and $N = 32$, as discussed in Ref. [9].

In conclusion, the general flat trends in the $B(E2; J^+_1 \rightarrow 0^+_g)$ values of the shell model can be understood as resulting from a fine balance of proton and neutron amplitudes. Specifically, the variation in the $B(E2; 2^+_1 \rightarrow 0^+_g)$ values due to $A_n$ is nearly canceled by that due to $A_p$, leading to constant $B(E2; 2^+_1 \rightarrow 0^+_g)$ values calculated using these effective charges. Thus, regarding the systematics of the lowest transition strengths, a consistent picture between experimental and theoretical results emerges.

In the following, the properties of the higher-spin states in the even 50–56Ti are discussed. As the trends between GXPF1A and GXPF1B for these isotopes are similar, only the results using the GXPF1B interaction are discussed below. Figure 13 shows a comparison between the experimental results and the shell-model calculations for the $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values.

For 50Ti, the experimental $B(E2; 2^+_1 \rightarrow 0^+_g)$ value from Ref. [52] is slightly lower than that estimated by the present calculations, independent of the interaction. As already mentioned above, this could be attributed to either the proton particle-hole excitations across the $Z = 20$ 40Ca core present in the $0^+_g$ state, which are not accounted for in this model space, or, as discussed above, the $B(E2)$ value could be overestimated due to the degree of neutron particle-hole excitation across $N = 28$ as qualitatively demonstrated by the calculation using the GXPF1B-nf7 interaction. The adopted $B(E2; 4^+_1 \rightarrow 2^+_1)$ and $B(E2; 6^+_1 \rightarrow 4^+_1)$ values agree well (within 2σ) with the theoretical predictions for all interactions. The shell-model calculations predict that the $2^+_1$, $4^+_1$, $6^+_1$ states in 50Ti have a proton character dominated in $\geq 70\%$ by configurations of the type $\pi J^+ \otimes \nu 0^+$. For the neighboring nucleus 52Ti, the predictions generally agree well with the new $B(E2)$ values (see Fig. 13). Only the $B(E2; 2^+_1 \rightarrow 0^+_g)$ value is slightly overestimated or underestimated. In contrast to 50Ti, the wave function of the $2^+_1$ state has a dominant neutron character with $\approx 50\%$ $\pi 0^+ \otimes \nu 2^+$ and $\approx 30\%$ $\pi 2^+ \otimes \nu 0^+$ configuration. The two neutrons above $N = 28$ occupy predominantly the $2p_{3/2}$ orbital in which they can couple to a maximum angular momentum of 2$\hbar$. Therefore, the higher-spin $4^+_1$, $6^+_1$ yrast states cannot be of pure neutron character. For the $4^+_1$ state, mixed proton-neutron configurations $\approx 30\%$ $\pi 2^+ \otimes \nu 2^+$ and $\approx 40\%$ $\pi 4^+ \otimes \nu 0^+$ prevail for KB3G and GXPF1B. The wave functions of the three interactions are similar for the case of the $6^+_1$ state. The configuration $\pi 6^+ \otimes \nu 0^+$ has the largest contribution to the wave function ($\leq 50\%$), followed by the mixed configurations of type $\pi 2^+ \otimes \nu 2^+$ and $\pi 6^+ \otimes \nu 2^+$ ($\leq 12\%$). We note the very good agreement between the new experimental $B(E2)$ values from the present work and the theory both having the opposite trend as a function of spin to the adopted data from Refs. [37,38]. The new results are free of the longstanding contradiction between the shell model and

### Table IV. Proton and neutron amplitudes for the $2^+_1 \rightarrow 0^+_g$ of four different interactions for even-even 50–56Ti. See text for more details.

<table>
<thead>
<tr>
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<th>56Ti</th>
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<tr>
<td>GXPF1B-nf7</td>
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<td>10.06</td>
<td>9.96</td>
<td>15.17</td>
</tr>
</tbody>
</table>

FIG. 13. Comparison of experimental $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values in 50,52,54Ti with the results of the shell-model calculations with different effective interactions. See text for details.
adopted $B(E2; 2^+_1 \rightarrow 0^+)$ in $^{52}$Ti, thus putting in doubt the previous experimental results.

For $^{54}$Ti, i.e., four neutrons above $N = 28$, all interactions reproduce fairly accurately the $B(E2; 2^+_1 \rightarrow 0^+_{gs})$ value from Ref. [9] and yield very similar $B(E2; 4^+_1 \rightarrow 2^+)$ values. However, the predicted values are clearly lower than $B(E2; 4^+_1 \rightarrow 2^+_0) = 139^{+25}_{-28}$ cm$^2$ determined in the present work. For the $6^+_1 \rightarrow 4^+_1$ transition, the calculations yield $B(E2)$ values half the size of those for the $4^+_1 \rightarrow 2^+_1$ and $2^+_1 \rightarrow 0^+_{gs}$ transitions. From our data, we have an upper limit of $B(E2; 6^+_1 \rightarrow 4^+_1) \leq 132$ cm$^2$, which agrees with the calculations. In addition, the experimental lower limit of $B(E2; 8^+_1 \rightarrow 6^+_1) \geq 5.7$ cm$^2$ agrees with $7.0$ cm$^2$ calculated using the GXPF1B interaction. The wave functions calculated using the KB3G and GXPF1B interactions show a distinct proton occupation as found in the case of $^{50}$Ti. For the $2^+_1$ state, the proton occupation yields $\approx 50\% \ \pi_{3/2} \otimes \nu_{3/2}$ corresponding to a subshell closure of $\nu 2p_{3/2}$. This confirms that the $p_{3/2}$ and $f_{5/2}$ orbitals are not close to each other. Also the other higher-lying states $J = 4^+_1$, $6^+_1$ show a clear proton character ($\approx 60\% \ \pi_{4/2} \otimes \nu_{5/2}$ and $\geq 70\% \ \pi_{6/2} \otimes \nu_{5/2}$ for both KB3G and GXPF1B interactions). The trend in the predicted $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values resembles with that for $^{50}$Ti, which is another signature of the $N = 32$ subshell closure.

V. SUMMARY

The structure of the neutron-rich nuclei $^{52,54}$Ti produced via multinucleon-transfer reactions in inverse kinematics was investigated. The lifetime of the $2^+_1$ state in $^{54}$Ti was remeasured. The transition probability obtained from the measured lifetime of the $2^+_1$ state is in agreement with that from an earlier Coulomb-excitation work [9]. The lifetime of the $4^+_1$ state in $^{54}$Ti, a lower limit for the $6^+_1$ state, and an upper limit for the $8^+_1$ state were determined for the first time.

The comparison with shell-model calculations shows the following outcome: In $^{54}$Ti the trend of the $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values agrees well with the results of shell-model calculations using various interactions, only the experimental result of the $B(E2; 4^+_1 \rightarrow 2^+_0)$ value is underestimated.

In $^{52}$Ti, the lifetimes of the $2^+_1$, $4^+_1$, and $6^+_1$ states were remeasured with a surprising result. The transition probabilities obtained from the lifetimes determined in this work show an opposite trend with spin to the literature $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values [37,38]. The $B(E2; 2^+_1 \rightarrow 0^+_{gs})$ value obtained in the present work is smaller than the adopted value. A similar behavior was noted for the $6^+_1 \rightarrow 4^+_1$ transition strength. While, the new $B(E2; 4^+_1 \rightarrow 2^+_0)$ value is larger than the adopted value. In contrast to the previously adopted results for $^{52}$Ti, the new results on $B(E2; J^+_1 \rightarrow (J - 2)^+_1)$ values are well reproduced within the shell model. Compared to those for the neighboring isotopes, the new $B(E2; 2^+_1 \rightarrow 0^+_{gs})$ results reduce the amplitude of the staggering along the titanium isotope chain $^{50-54}$Ti. The experimental and theoretical results confirm a subshell closure at $N = 32$ in $^{54}$Ti that is somewhat weaker compared to that at $N = 28$.

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