Development of shell closures at $N=32,34$. II. Lowest yrast excitations in even-even Ti isotopes from deep-inelastic heavy-ion collisions

B. Fornal,[1] S. Zhu,[2] R. V. F. Janssens,[2] M. Honma,[3] R. Broda,[1] P. F. Mantica,[4,5] B. A. Brown,[4,6] M. P. Carpenter,[2] P. J. Daly,[7] S. J. Freeman,[2,8] Z. W. Grabowski,[7] N. J. Hammond,[2] F. G. Kondev,[9] W. Królas,[1] T. Lauritsen,[2] S. N. Liddick,[4,5] C. J. Lister,[2] E. F. Moore,[2] T. Otsuka,[10] T. Pawłat,[1] D. Seweryniak,[2] B. E. Tomlin,[4,5] and J. Wrzesiński[1]

[1]*Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Cracow, Poland*

[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[3]*Center for Mathematical Sciences, University of Aizu, Tsuruga, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan*

[4]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

[5]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*

[6]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

[7]*Chemistry and Physics Departments, Purdue University, West Lafayette, Indiana 47907, USA*

[8]*Department of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*

[9]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[10]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan and RIKEN, Hirosawa,Wako-shi, Saitama 351-0198, Japan*

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Gamma rays from neutron-rich nuclei in the vicinity of $Z=20$, $N=28$ have been studied at Gammasphere using deep-inelastic reactions induced by a 330-MeV ^{48}Ca beam on a thick ^{238}U target. The yrast γ-ray cascade of ^{56}Ti was identified for the first time and the location in energy of the 2^+, 4^+, and 6^+ states was determined. The low-spin ^{56}Ti yrast structure does not support the presence of a subshell closure at $N=34$ as suggested on the basis of other data on nuclei in the region as well as shell model calculations with a recently proposed interaction.

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I. INTRODUCTION

Recent investigations have shown that single-particle structure in exotic nuclei may significantly differ from that inferred from many years of studies of nuclei near the valley of stability. Drastic structural changes can occur over relatively small regions of the nuclear chart [1–4] and, as a result, some familiar magic numbers no longer apply while new ones appear. One example of such an unanticipated structural change in neutron-rich nuclei is the appearance of an $N=32$ subshell closure in nuclei located just above doubly magic ^{48}Ca. This phenomenon was first suggested by Huck *et al.* [5] who tentatively identified a candidate for the 2_1^+ level in ^{52}Ca at an excitation energy of 2563 keV, a value significantly higher than the corresponding 2_1^+ energy $[E(2_1^+)=1027$ keV$]$ in ^{50}Ca. However, the considerable uncertainty associated with the spin and parity assignments to this ^{52}Ca state did not give much emphasis to the issue at the time. Recently, this situation changed drastically when evidence for a subshell closure at $N=32$ came from a study of the systematic variation of the $E(2_1^+)$ energies for the chromium $(Z=24)$ [6] and titanium $(Z=22)$ [7] isotopes, where $E(2_1^+)$ was found to reach a maximum for ^{56}Cr$_{32}$ and ^{54}Ti$_{32}$, respectively. Beta-decay measurements of ^{56}V into ^{56}Cr can be found in Refs. [6,8], while the original in-beam work of Ref. [9] on the latter nucleus was extended further by Appelbe *et al.* [10].

The properties of ^{54}Ti were explored in our earlier study with a somewhat novel approach where β-decay data from fragmentation products were combined with prompt γ-ray spectroscopy following deep-inelastic reactions [7]. This study not only identified the first excited 2^+ state in ^{54}Ti, but also traced the higher-spin yrast structures in $^{52-54}$Ti up to $I^\pi \sim 10^+$. In doing so, it provided additional evidence for the $N=32$ subshell closure. For example, in ^{54}Ti, the significant energy spacing between the 6^+ level and the group of 8_1^+, 9_1^+, and 10_1^+ excitations involving the promotion of neutrons from the $\nu p_{3/2}$ state to the $\nu p_{1/2}$ or $\nu f_{5/2}$ orbitals signaled the presence of a significant energy gap between those single-particle states in the titanium isotopes, as predicted by theory.

The presence of this $N=32$ subshell gap in neutron-rich nuclei located in the vicinity of doubly magic $^{48}_{20}$Ca$_{28}$ has been attributed to a decreased $\pi f_{7/2}$-$\nu f_{5/2}$ monopole interaction occurring when protons are removed from the $\pi f_{7/2}$ orbital. This reduced interaction results in a gradual migration of the $\nu f_{5/2}$ orbital towards higher energies. This feature, together with the large spin-orbit splitting for the $\nu p_{3/2}$-$\nu p_{1/2}$ states, then gives rise to a sizable energy gap at $N=32$ for nuclei with $Z \leqslant 24$ [11]. Recently, a new effective interaction for the full pf shell, labeled as GXPF1, was developed by Honma *et al.* [12], and full pf-shell model calculations with the GXPF1 Hamiltonian give a very good description of the $E(2_1^+)$ variations in the Cr, Ti, and Ca isotopic chains near $N=32$. In addition, the high-spin states in even-even Ti isotopes were also reproduced reasonably well by this GXPF1 interaction [7].

An intriguing feature of predictions based on the GXPF1 interaction is the development of a significant energy gap between the effective neutron single-particle energies associated with the $\nu p_{1/2}$ and $\nu f_{5/2}$ orbitals in neutron-rich nuclei. This would lead to a subshell closure at $N=34$ that should become apparent, for example, in the energy spacings observed for the low-lying levels in ^{56}Ti. In other words, the level structures of the $N=28$ ^{50}Ti, $N=32$ ^{54}Ti, and $N=34$ ^{56}Ti nuclei were calculated to closely mirror each other. However, the energy of the ^{56}Ti 2_1^+ state, measured very recently in the β decay of the ^{56}Sc parent produced in a fragmentation reaction, was reported to be only 1127 keV [13], almost 400 keV below the GXPF1 expectation. This observation seems to indicate that the degree of separation between the $\nu p_{1/2}$ and $\nu f_{5/2}$ states is not sufficient to create the anticipated $N=34$ subshell gap, at least in Ti isotopes. To explore the issue further, we performed γ-ray spectroscopic studies using a deep-inelastic reaction with the aim to delineate higher yrast excitations in ^{56}Ti.

In a series of earlier experiments, it has been shown that the yrast spectroscopy of hard-to-reach, neutron-rich nuclei, populated in heavy-ion-induced multinucleon transfer reactions, can be carried out successfully at energies 15–25% above the Coulomb barrier, when using γ-γ coincidence measurements and thick targets [14–16]. From a broader perspective, γ-ray intensity measurements from these reactions (as extracted from the γ-γ coincidence data) have provided a mapping of the A and Z distributions of product yields. In all cases, multinucleon transfers were shown to lead mostly to less neutron-rich nuclei in the region close in mass to the heavy colliding partner. Conversely, species on the neutron-rich side of the light reaction partner were found to be favored as well. It is possible to understand these yield distribution patterns in terms of a general tendency towards N/Z equilibration of the dinuclear systems formed in deep-inelastic reactions.

As already indicated above, valuable data on new yrast excitations in the $^{52-54}$Ti isotopes were obtained following deep-inelastic reactions between a thick ^{208}Pb target and a 305-MeV ^{48}Ca beam [7]. However, no information on ^{56}Ti could be derived from this data set. It was then decided to investigate the ^{48}Ca+^{238}U system instead, in order to take advantage of the larger neutron reservoir provided by the ^{238}U target. The larger N/Z ratio of 1.59 for the latter target compared to the corresponding value of 1.54 for ^{208}Pb should extend the product distribution significantly towards more neutron-rich nuclei, including the ^{56}Ti isotope of interest here.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS RESULTS

The experiment was performed at Argonne National Laboratory using Gammasphere [17], which consisted of 101 Compton-suppressed Ge spectrometers. A 330-MeV ^{48}Ca beam from the ATLAS superconducting linear accelerator was focused on a 50-mg/cm^2, isotopically enriched ^{238}U target placed in the center of the array. Gamma-ray coincidence events were collected with a trigger condition requiring three or more Compton-suppressed γ rays to be present in prompt coincidence. For each event, the energy and timing information was stored for all suppressed Ge detectors firing within 800 ns of the trigger signal. A total of 2.3×10^9 three- and higher-fold coincidence events were recorded for off-line analysis. The beam, with an intrinsic bunch width of ~0.3 ns, was pulsed with a ~420 ns repetition time, providing an opportunity for clean separation of prompt and isomeric decays. In the analysis, conditions placed on the time parameters were used to increment a number of prompt and delayed $\gamma\gamma$ coincidence matrices and $\gamma\gamma\gamma$ cubes covering a γ-ray energy range of up to ~4 MeV. Furthermore, a fourfold histogram (i.e., $\gamma\gamma\gamma\gamma$) was updated as well, but only for prompt γ rays, within a time window of ~40 ns.

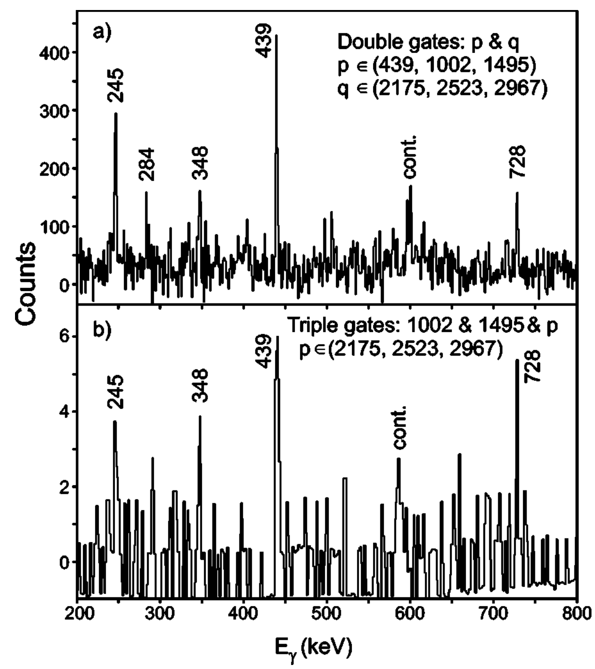

FIG. 1. Representative coincidence γ-ray spectra for ^{54}Ti illustrating the quality of data collected with Gammasphere for the reaction ^{48}Ca+^{238}U: (a) sum of double gates on selected ^{54}Ti γ transitions using the $\gamma\gamma\gamma$ coincidence cube, (b) sum of triple gates on selected γ rays using the $\gamma\gamma\gamma\gamma$ fourfold histogram. The ^{54}Ti transitions, labeled by their energy in keV, are given in the level scheme of Fig. 3.

At first, it should be recognized that, in the case of the ^{238}U target, the target-like products of deep-inelastic processes mostly undergo fission. Thus, an identification based on cross-coincidence relationships between γ rays from reaction partners, such as that performed for the ^{48}Ca+^{208}Pb system reported earlier [7], is very difficult, if not impossible. Instead, new transitions in neutron-rich pf nuclei identified by other means have to be taken as starting points for more detailed investigations of the associated level structures. In the case of the lighter $^{52-54}$Ti isotopes, coincidence spectra with gates placed on the known transitions confirmed the level structures established previously [7] or even expanded them in some instances [18]. The present data set turned out to be of sufficient statistical accuracy that it was readily possible, for example, to confirm the transitions located at the top of the ^{54}Ti level scheme in such an analysis. This is illustrated in Fig. 1 with double- and triple-gated coincidence spectra.

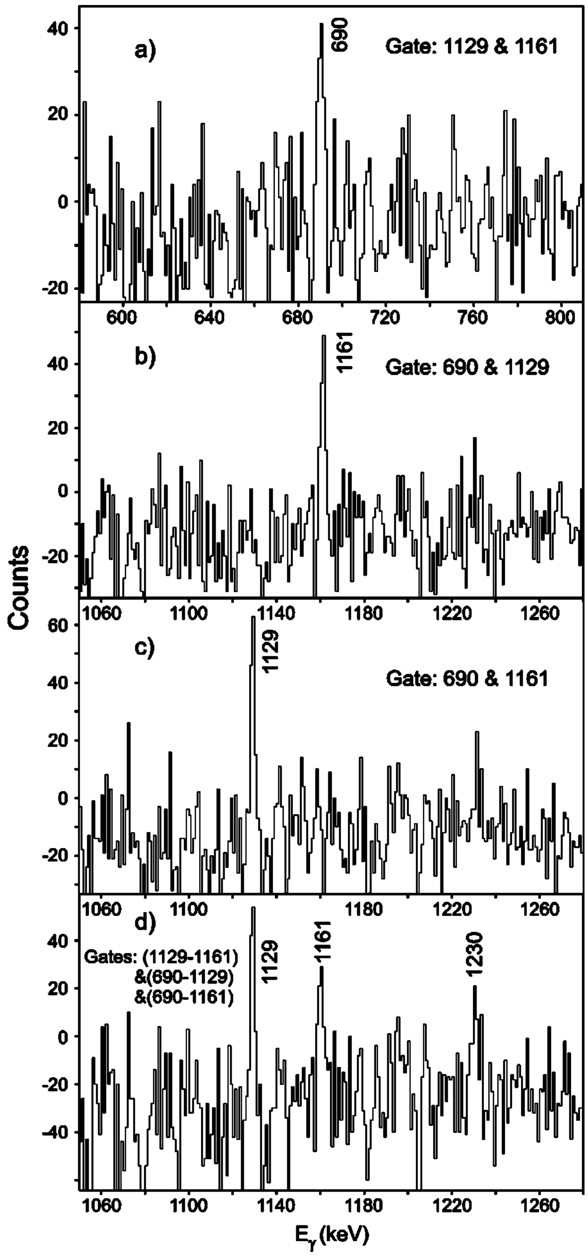

FIG. 2. Gamma-ray coincidence spectra for different double gates on specified transitions in ^{56}Ti.

In the case of ^{56}Ti, a starting point for the analysis has also recently become available. As outlined in Ref. [13] and in the preceding paper [19], a $2^+ \rightarrow 0^+$ γ ray with an energy $E_\gamma = 1127$ keV had been identified in a β-decay study of the ^{56}Ti parent, ^{56}Sc. As a first step towards identifying γ rays feeding this 2^+ excitation, a search was carried out aimed at finding a transition in coincidence with this 1127-keV line in the ^{48}Ca+^{238}U coincidence data set which was not present (or present with a very low yield) in the earlier ^{48}Ca+^{208}Pb γ-γ data. Only one γ ray, with an energy of 1161.0(5) keV, satisfied this criterion. The inspection of the double-coincidence gate placed on the newly found 1161-keV line together with the 1127-keV γ ray, shown in Fig. 2(a), revealed the presence of a 690.0(6)-keV transition. By double gating on the different combinations of the 1127-, 1161-, and 690-keV γ rays their mutual-coincidence relationships were confirmed. It is worth noting also that from these coincidence spectra the energy of the $2^+ \rightarrow 0^+$ transition was remeasured and determined to be 1128.8(5) keV, in fair agreement with the 1127(1) keV energy measured in the β-decay measurement [13].

It was soon realized that the 1160- and 689-keV lines observed in the γ-ray spectrum obtained following the β decay of ^{56}Sc [13] may be identical with the 1161- and 690-keV transitions found in coincidence with the 1129-keV γ ray seen in the present experiment. An updated energy calibration for transitions in ^{56}Ti populated following the β decay of ^{56}Sc is reported in the preceding paper [19]. The revised energies of 690.2(0.4), 1128.2(0.4), and 1160.0(0.5) keV compare favorably with those of 690.0(0.5), 1128.8(0.5), and 1161.0(0.5) keV deduced in the present work. Energy values of 690.1(0.4), 1128.5(0.4), and 1160.5(0.5) keV, which correspond to weighted averages of the results from the independent β-decay and in-beam measurements, have been adopted for these three γ-ray transitions in ^{56}Ti.

As in the known even-even titanium isotopes ^{50,52,54}Ti, the 4^+ and 6^+ levels in ^{56}Ti are expected to correspond to proton excitations of $\pi f_{7/2}^2$ character with energy spacings $E(4^+ - 2^+) > E(6^+ - 4^+)$. Keeping in mind that deep-inelastic reactions preferentially populate yrast states, an assignment of the 1161- and 690-keV γ rays to the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions is then straightforward. These two transitions locate the 4^+ and 6^+ levels at excitation energies of 2290 and 2980 keV, respectively, as indicated in the level scheme of Fig. 3.

The coincidence relationships between the three main transitions in ^{56}Ti were first observed in the deep-inelastic experiment under discussion here. In turn, these observations actually lead to the suggestion that the presence of the 1161- and 690-keV lines in the ^{56}Sc β-decay spectrum, with an intensity lower by a factor of 2 than the yield of the $2^+ \rightarrow 0^+$ transition [13], might be due to the presence of two β-decaying isomers in ^{56}Sc: one of low spin feeding mostly the 2^+ excitation and a second of higher angular momentum feeding primarily the 6^+ state. This hypothesis has been since fully confirmed by the more detailed analysis of the ^{56}Sc β-decay data presented in the preceding paper [19]; different half-lives have now been associated with the 1129-keV γ-gated decay curve and with that derived for the 690- and 1161-keV γ rays.

As shown in Fig. 2, one additional weak transition has been assigned to the level scheme of ^{56}Ti. A careful examination of all the coincidence spectra revealed the presence of a 1230(1)-keV γ ray with an intensity of ~25% of the 690-1161-1129 keV cascade intensity. Because of its weak nature, this transition is given in the level scheme without proposing a spin assignment (Fig. 3).

III. DISCUSSION

As shown in Refs. [7,13], the full pf-shell model calculations employing the GXPF1 [12] Hamiltonian proved to be very successful in describing the 2^+ energy systematics and

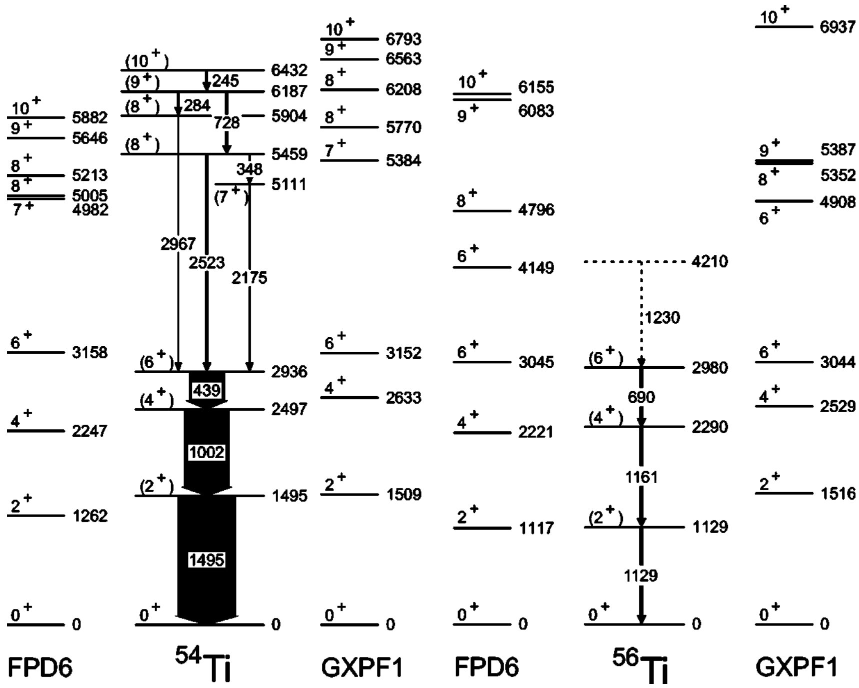

FIG. 3. The proposed level scheme for ^{56}Ti with the results of the full pf-shell model calculations using the GXPF1 and FPD6 Hamiltonians. The experimental findings for ^{54}Ti from Ref. [7], together with the calculated levels for the two interactions, are shown for comparison.

the higher-spin yrast structure in the even-even ^{50,52,54}Ti isotopes, including features associated with the $\nu p_{3/2}$ subshell closure at $N=32$. The GXPF1 calculations fail, however, in the case of ^{56}Ti: the excitation energy of 1516 keV predicted for the 2^+ state is significantly higher than the actual experimental value of 1129 keV. The calculated high excitation energy reflects the prediction of a $N=34$ subshell closure that is clearly not borne out by the data.

The interaction labeled FPD6 is another empirical Hamiltonian constructed for nuclei in the pf shell [20]. Calculations with this Hamiltonian are not performing as well as those with the GXPF1 interaction when it comes to reproducing the 2^+ energy systematics in ^{50,52,54}Ti nuclei. For example, the FPD6 results underestimate this 2^+ energy in ^{54}Ti by roughly 250 keV. However, in the ^{56}Ti case, the situation is reversed: with the FPD6 Hamiltonian, the predicted 2^+ energy is 1117 keV, only 12 keV below the data. These features are illustrated further in Fig. 3, where the results of the two shell model calculations are displayed together with the experimental data for both ^{54}Ti and ^{56}Ti.

Differences in the predictions of the two Hamiltonians regarding the 2^+ energy in the ^{54}Ti and ^{56}Ti nuclei can be associated with differences in the effective single-particle energies of the $\nu p_{1/2}$ and $\nu f_{5/2}$ orbitals with respect to the $\nu p_{3/2}$ state in neutron-rich nuclei. In the FPD6 calculations around ^{56}Ti, the effective single-particle energy of the $\nu f_{5/2}$ state lies between these of the $\nu p_{3/2}$ and $\nu p_{1/2}$ orbitals whereas, in the GXPF1 Hamiltonian, the ordering is reversed; i.e., the $\nu f_{5/2}$ level is located above the $\nu p_{3/2}$ and $\nu p_{1/2}$ single-particle states and, in addition, there also is sizable splitting between these two p states. From this point of view, the results for ^{54}Ti then suggest that the separation between the $\nu p_{3/2}$ and the pair of the $\nu p_{1/2}$ and $\nu f_{5/2}$ orbitals is well accounted for by the GXPF1 Hamiltonian and that, in contrast, this gap is too small in the FPD6 case. On the other hand, comparisons between theory and experiment for ^{56}Ti then suggest that the $\nu p_{1/2}$ and $\nu f_{5/2}$ levels are not separated to the degree implied by the GXPF1 interaction and, as a result, the wave functions of excitations involving either of these two orbitals may well be characterized by considerable admixtures with components from the companion state.

As discussed in Ref. [7], another measure of the energy spacing between the $\nu p_{3/2}$ and $\nu f_{5/2}$ orbitals is the location of the $I^{\pi}=9^+$ and 10^+ states in ^{54}Ti, since these levels involve the excitation of a neutron in the $\nu f_{5/2}$ orbital. Indeed, the energies of those two states, as predicted by the FPD6 Hamiltonian, are on average lower than the values from the GXPF1 calculations by 900 keV; i.e., they are also $\sim$550 keV too low with respect to the data (Fig. 3), an observation in line with the discussion above.

The other low-lying yrast excitations in ^{56}Ti identified in the present work offer an additional test of the shell model calculations. Using the GXPF1 interaction, the computed energy of the 6^+ level is 3044 keV, in reasonable agreement with the experimental value of 2980 keV. However, this observation is somewhat misleading as the energy spacings between the 2^+, 4^+, and 6^+ levels (calculated to be located at 1516, 2529, and 3044 keV, respectively) are quite different from those of the experimental sequence: 1129, 2290, and 2980 keV. This can be seen by considering, for example, that the experimental energy ratios $E(4^+)/E(2^+)=2.03$ and $E(6^+)/E(2^+)=2.64$ are much higher than the corresponding calculated GXPF1 values of 1.67 and 2.01. In contrast, the FPD6 Hamiltonian predicts the 2^+, 4^+, and 6^+ excitation energies to be 1117, 2221, and 3045 keV, respectively, and these values agree rather well with the data. In this case, the energy ratios are reproduced satisfactorily: $E(4^+)/E(2^+)=1.99$ and $E(6^+)/E(2^+)=2.72$. The main difference between the results with the two Hamiltonians regarding the energy sequence of the three lowest yrast states in ^{56}Ti arises again from differences in the location of the $\nu f_{5/2}$ orbital with respect to the $\nu p_{1/2}$ state. It is worth noticing that the calculations with the GXPF1 Hamiltonian predict that the wave functions of the 2^+, 4^+, and 6^+ states are dominated by the $\pi f_{7/2}^2 \nu p_{3/2}^4 p_{1/2}^2$ configuration, which is a closed neutron subshell configuration. In turn, in the FPD6 calculations, the main component of those wave functions are of the $\pi f_{7/2}^2 \nu p_{3/2}^4 f_{5/2}^2$ type—i.e., with two neutrons occupying the $\nu f_{5/2}$ orbital. The experimental data on ^{56}Ti favor the results of the FPD6 interaction and may indicate that the $\nu f_{5/2}$ state is not separated from the $\nu p_{1/2}$ level to the degree assumed by the GXPF1 Hamiltonian. Instead, these two single-particle states might lie close to each other or, as implied by the FPD6 Hamiltonian, their ordering might be reversed. In any event, the wave functions of the ^{56}Ti states can be expected to be characterized by considerable mixing between the components of the $\nu p_{1/2}$ and $\nu f_{5/2}$ orbitals.

As shown in Fig. 3, in ^{56}Ti both calculations predict above the 6^+ level a sequence of states with $J^\pi = 6^+$, 8^+, 9^+, and 10^+. The states with $J \geqslant 8$ are expected to be separated from the 6^+ yrast excitation by more than 1.7 MeV for the FPD6 Hamiltonian and by more than 2.3 MeV for the GXPF1 interaction. Assuming an intensity scenario in which the feeding of the 6^+ yrast state from the higher-lying yrast levels accounts for $\sim 15\%$ of the 6^+ decay intensity, as observed in the case of ^{54}Ti, leads to the natural conclusion that the identification of the corresponding transitions in ^{56}Ti using the present data set is rather difficult due to the low production yield for this nucleus. Indeed, only one weak transition with an energy of 1230 keV was found in the data. It was tentatively assigned as feeding this 6^+ state. It likely corresponds to one of the yrast transitions from a level with $J > 6$ or to a deexcitation from the second 6^+ state predicted at an energy of either 4149 keV or 4908 keV by the FPD6 and GXPF1 Hamiltonians, respectively. We note that with this transition added to the scheme, the level sequences in ^{52}Ti and ^{56}Ti are quite similar; i.e., the first excitations above the respective 6^+ yrast states are not located at an energy of 2 MeV or more, as is the case in ^{50}Ti ($N=28$) and ^{54}Ti ($N=32$). The level schemes above the 6^+ level would then reflect the absence of any subshell closure at both $N=30$ and $N=34$. These observations again argue against any significant $\nu p_{1/2}$-$\nu f_{5/2}$ energy spacing.

As already mentioned above, the present reaction of a ^{48}Ca beam on a thick ^{238}U target was selected to investigate Ti nuclei with a large neutron excess because, among stable isotopes, the N/Z ratio of ^{238}U is the highest; i.e., this nucleus represents the largest reservoir of neutrons susceptible to be transferred to a projectile-like reaction product. The high-fold, large coincidence data set obtained here was used together with the earlier ^{48}Ca+^{208}Pb data of Ref. [7] to quantify this conjecture by determining the population yield of the yrast states in an isotopic chain of interest. For example, using $\gamma\gamma\gamma$ coincidence relationships, a feeding pattern of the first 6^+ states in the even-even Ti isotopes was derived. Possible feedings of these 6^+ excitations from β decay were carefully considered and subtracted out. Figure 4 compares the measured distributions for the two reactions of interest. In the figure, the two distributions have been normalized to the measured values for ^{50}Ti. From Fig. 4 it is clear that the conjecture of a more favorable transfer yield with the actinide target has materialized as the yield distribution is extended significantly towards more neutron-rich Ti isotopes: the 6^+ state population yield in ^{56}Ti is larger by a factor of 4 when ^{238}U is used as a target rather than ^{208}Pb. This feature is currently being exploited further in ongoing studies of other neutron-rich nuclei in neighboring isotopic chains of great interest such as those for the Cr and Ca nuclei, for example.

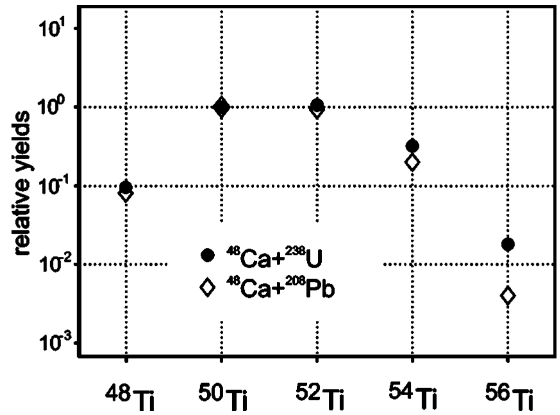

FIG. 4. Distribution of the relative 6^+ state feeding yields in the even-even ^{48,50,52,54,56}Ti products for the two reactions ^{48}Ca+^{238}U and ^{48}Ca+^{208}Pb. Two data sets are normalized for ^{50}Ti.

IV. SUMMARY

Detailed γ-ray coincidence measurements using Gammasphere with the ^{48}Ca+^{238}U reaction at 330 MeV have provided information about the low-spin yrast excitations in ^{56}Ti. The new findings include the 2^+, 4^+, and 6^+ members of $\pi f_{7/2}^2$ multiplet and an additional weak transition deexciting a state of higher excitation energy for which no spin and parity quantum numbers could be established. These data also played a pivotal role in unraveling the ^{56}Sc β-decay measurements discussed in the preceding paper [19] and in Ref. [13]. The experimental results do not support the view that a subshell closure occurs at $N=34$ in neutron-rich isotopes above ^{48}Ca, at least for the Ti isotopic chain. This $N=34$ shell gap had been proposed on the basis of shell model calculations with the newly developed GXPF1 interaction. The data suggest that the energy spacings between the $\nu p_{3/2}$, $\nu p_{1/2}$, and $\nu f_{5/2}$ orbitals require further theoretical consideration as does the degree of admixture between these three states in the wave functions of the ^{56}Ti yrast excitations.

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