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Journal

Physical Review C, 73(3)

ISSN

2469-9985

Authors

Gade, A
Janssens, RVF
Bazin, D
et al.

Publication Date

2006-03-01

DOI

10.1103/physrevc.73.037309

Peer reviewed

Spectroscopy of the odd-odd fp-shell nucleus ^{52}Sc from secondary fragmentation

A. Gade,[1] R. V. F. Janssens,[2] D. Bazin,[1] B. A. Brown,[1,3] C. M. Campbell,[1,3] M. P. Carpenter,[2] J. M. Cook,[1,3] A. N. Deacon,[4] D.-C. Dinca,[1,3] S. J. Freeman,[4] T. Glasmacher,[1,3] B. P. Kay,[4] P. F. Mantica,[1,5] W. F. Mueller,[1] J. R. Terry,[1,3] and S. Zhu[2]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[2]*Physics Division, Argonne National Laboratory, Argonne, IL 60439*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824*
[4]*Department of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[5]*Department of Chemistry, Michigan State University, East Lansing, MI 48824*

(Dated: October 27, 2018)

The odd-odd fp-shell nucleus ^{52}Sc was investigated using in-beam γ-ray spectroscopy following secondary fragmentation of a ^{55}V and ^{57}Cr cocktail beam. Aside from the known γ-ray transition at 674(5) keV, a new decay at $E_\gamma = 212(3)$ keV was observed. It is attributed to the depopulation of a low-lying excited level. This new state is discussed in the framework of shell-model calculations with the GXPF1, GXPF1A, and KB3G effective interactions. These calculations are found to be fairly robust for the low-lying level scheme of ^{52}Sc irrespective of the choice of the effective interaction. In addition, the frequency of spin values predicted by the shell model is successfully modeled by a spin distribution formulated in a statistical approach with an empirical, energy-independent spin-cutoff parameter.

PACS numbers: 23.20.Lv, 21.60.Cs, 25.70.Mn, 27.40.+z

In-beam γ-ray spectroscopy with intermediate-energy exotic beams provides a versatile tool to study various aspects of nuclear structure beyond the valley of β stability. While intermediate-energy Coulomb excitation of the projectile is used to assess the degree of collectivity within an exotic nuclear system [1], direct reactions – one- and two-nucleon knockout from the projectile [2, 3] – are exploited to probe single-particle degrees of freedom. The evolution and occupation of specific orbits within the nucleus can be tracked with this method [4]. Secondary fragmentation, in which multiple nucleons are removed from the projectile, but not necessarily in a direct reaction process, lacks the selectivity alluded to above and, as a result, provides access to a wider variety of excited states [5].

Nuclear structure of exotic species has been found to depart often from expectations based on the properties of nuclei closer to stability. New shell gaps appear [6, 7, 8, 9] and "traditional" magic numbers vanish in the regime of pronounced asymmetry between proton and neutron numbers (e.g. [10, 11, 12, 13, 14, 15, 16]). Those changes are driven, for example, by the tensor force [17] and by the proton-neutron monopole interaction (for a recent reference on this topic, see, e.g., [18]). The predictive power of nuclear structure models is at present quite limited for exotic nuclei, and shell-model interactions are adjusted by exploiting new experimental data as they become available. For example, the GXPF1 effective interaction [7], which was optimized for nuclei in the fp shell, was modified recently following comparisons with new experimental observations [19, 20] in neutron-rich nuclei just above ^{48}Ca, which pointed to the need to adjust matrix elements involving the $p_{1/2}$ orbital. The modified interaction has been labeled GXPF1A [21].

We report here on the first observation of a low-energy γ ray in ^{52}Sc following secondary fragmentation of ^{55}V and ^{57}Cr. This transition had not been observed before and presumably depopulates a low-lying excited state in this fp-shell nucleus. Our experimental result is compared to shell-model calculations using three effective interactions (GXPF1, GXPF1A and KB3G) suited for the fp shell. Furthermore, the shell-model calculations with the GXPF1 effective interaction were probed further by analyzing the frequency of spin values below the neutron separation energy (73 states with $E_x \leq S_n = 5.23$ MeV). It is shown that this frequency can be described satisfactorily within a parameter-free, statistical approach using an empirical, energy-independent spin-cutoff parameter.

Previous knowledge about excited states of this nucleus stems from the β decay of the ground state of ^{52}Ca [22]. Consistent with the selection rules of this decay mode, only excited states with J^π assignments 1^+,(2^+) have been reported [22]. The ground state is proposed to have tentative spin and parity quantum numbers of 3^+ based on the population pattern of ^{52}Ti excited levels in the β decay of the ground state of ^{52}Sc [22].

The secondary beam cocktail was produced by fast fragmentation of a 130 MeV/nucleon ^{76}Ge primary beam delivered by the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory on a ^{9}Be primary target of 423 mg/cm^2 thickness. The fragmentation products were selected in the A1900 fragment separator [23], which was operated at full momentum acceptance. The cocktail beam containing ^{55}V and ^{57}Cr with an average mid-target energy of 77 MeV/nucleon interacted with a 375 mg/cm^2 ^{9}Be foil placed in the target position of the large-acceptance S800 spectrograph [24]. The reaction residues were identified on an event-by-event basis from the energy-loss measured in the S800 ionization chamber, the time-of-flight measured between plastic scintillators, and the position and angle information obtained with the two position-sensitive cathode-readout drift chambers of the S800 focal plane [24]. ^{52}Sc residues produced from either the fragmentation of ^{55}V or ^{57}Cr could not be disentangled since the reaction products for those two constituents of the cocktail beam overlapped in time of flight. The magnetic field of the spectrograph was set to center two-proton knockout residues in the focal plane, as these were the main focus of the measurements [25]. The large acceptance of the device allowed a fraction of the ^{9}Be(^{55}V,^{52}Sc)X and ^{9}Be(^{57}Cr,^{52}Sc)X residues to enter the S800 focal plane at the edge of the acceptance.

The ^{9}Be reaction target was surrounded by SeGA, an array of 32-fold segmented HPGe detectors [26], arranged in two rings with 90° and 37° central angles with respect to the beam axis. The 37° ring was equipped with seven detectors while ten detectors occupied the 90° positions. The γ rays emitted by fast-moving nuclei are detected with Doppler shifts in the laboratory system. The high degree of segmentation of the SeGA detectors allows for an event-by-event Doppler reconstruction where the angle of the γ-ray emission is deduced from the position of the detector segment that registered the highest energy deposition. The event-by-event Doppler-reconstructed γ-ray spectrum in coincidence with ^{52}Sc residues is shown in Fig. 1. A previously known γ-ray transition is detected at 674(5) keV. This transition was proposed in Ref. [22] to connect an excited (2$^+$) state with the ^{52}Sc ground state. The dominant peak in the spectrum, however, corresponds to a γ-ray transition of 212(3) keV, observed here for the first time.

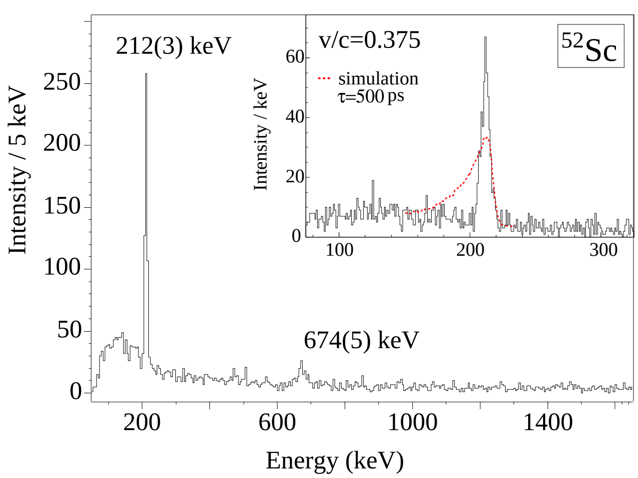

FIG. 1: (Color online) Doppler-reconstructed spectrum detected in coincidence with ^{52}Sc; the 674(5)-keV transition was observed earlier [22] while the prominent 212(3)-keV γ ray is new. It originates from a $(4^+, 5^+)$ state with a mean lifetime much shorter than 500 ps, as demonstrated in the inset by a comparison with a simulation (dashed line). See text for details.

In Fig. 2 the experimental level scheme known so far is compared to the results of full shell-model calculations in the fp model space employing the GXPF1 effective interaction. The OXBASH [27] calculations allowed for the 12 valence particles with respect to the ^{40}Ca core to occupy the $(f_{7/2}, p_{3/2}, f_{5/2}, p_{1/2})$ configuration space. The previously established (2$^+$) and 1$^+$ levels are in good agreement with the calculations: there is a one-to-one correspondence for the first excited (2$^+$) and for the first two 1$^+$ states, while the high level density within the shell model prevents a detailed comparison for levels above 3 MeV. The main components of the shell-model wave functions obtained with the GXPF1 interaction are given in Table I for the first 3$^+$, 4$^+$ and 5$^+$ states. Configurations with the valence protons and neutrons occupying the $f_{7/2}$ and $p_{3/2}$ orbitals clearly dominate the structure of the low-lying states.

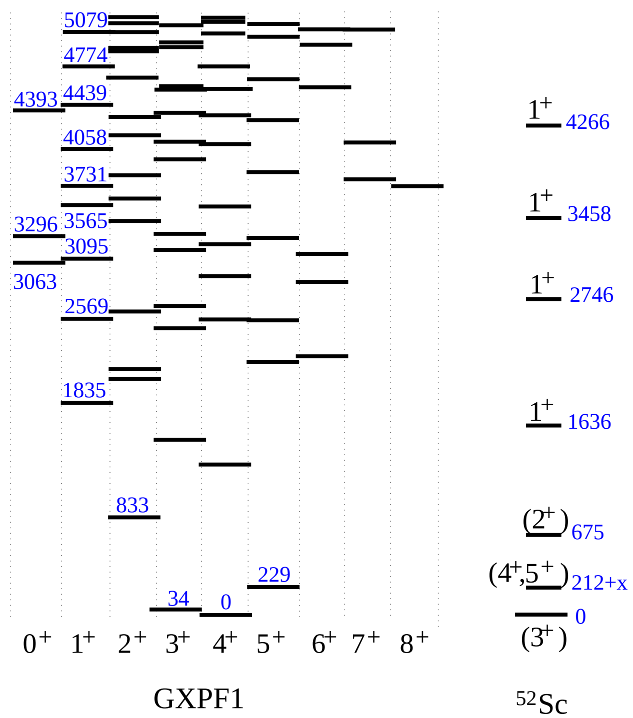

FIG. 2: (Color online) The results of the fp shell-model calculations performed with the code OXBASH using the GXPF1 [7] effective interaction are compared with the experimental level scheme of ^{52}Sc. The calculations are shown up to the neutron separation energy. The experimental level scheme is taken from [22]; a new level depopulated by the 212(3)-keV γ-ray transition reported here for the first time is discussed in the text in more detail.

In the shell model, the first 4$^+$ and 3$^+$ states are almost degenerate with the 4$^+$ state becoming the ground state. Two possible scenarios presented in Fig. 3 arise for the placement of the newly observed low-energy γ-ray transition within the level scheme of ^{52}Sc. Considering the (3$^+$) ground state suggested from β-decay studies [22] and guided by the shell-model calculations, the 212-keV

γ ray either depopulates the first 5^+ (Fig. 3(a)) or 4^+ state (Fig. 3(b)). A $5^+ \rightarrow 3^+$ $E2$ transition can be excluded on the basis of lifetime considerations. Indeed, only a lifetime of τ >550 ps would allow for the corresponding $B(E2; 5^+ \rightarrow 3^+)$ transition strength to be below the recommended upper limit (RUL) of 300 W.u. for this mass region [28]. Since the Doppler reconstruction is very sensitive to the position of the nucleus during γ-ray emission (due to its angle dependence), an excited state with $\tau = 550$ ps would decay roughly 5 cm behind the reaction target. This would result in a pronounced low-energy tail for the reconstructed photopeak. As shown in the inset of Fig. 1, the 212-keV line does not exhibit such an asymmetry and, thus, an $E2$ transition can be excluded based on the RUL. However, if the 5^+ state decays to the 4^+ level, presumably almost degenerate with the ground state, the transition could proceed with $M1$ character. Lifetimes of $\tau > 1.1$ ps would conform with the RUL for $M1$ transitions in this mass region. In the event of a near degeneracy of the 4^+ level with the ground state, the $4^+ \rightarrow 3^+$ decay would escape observation due to the detection threshold (Fig. 3(a)). The 212-keV transition could possibly also connect the first excited 4^+ to the (3^+) ground state, leading to the conclusion that the degree of degeneracy of the first 4^+ and 3^+ states is overestimated in the shell-model calculations (Fig. 3(b)).

TABLE I: Dominant wave-function components $(f_{7/2})^{n_7}$ $(p_{3/2})^{n_3}$ $(f_{5/2})^{n_5}$ $(p_{1/2})^{n_1}$ for the first 3^+, 4^+, and 5^+ states of ^{52}Sc from shell-model calculations with the GXPF1 effective interaction. Components with a strength below 1% are not shown.

(n_7, n_3, n_5, n_1)	3_1^+ (%)	4_1^+ (%)	5_1^+ (%)
(9,3,0,0)	67.0	76.2	72.2
(9,2,0,1)	17.4	6.7	5.0
(9,1,0,2)	2.4	2.7	7.4
(9,2,1,0)	1.0	1.8	-
(9,1,2,0)	1.2	1.3	2.1

Full fp shell-model calculations have also been performed with the GXPF1A and KB3G [29] effective interactions in addition to GXPF1. The predicted low-lying level schemes can be found in Fig. 3(c,d,e). The results are very robust and support experimental scenario (a). On the other hand, earlier calculations in the full fp shell with the FPD6 and KB3 effective interactions were shown to differ significantly even for the low-lying states [30]. However, the latter two interactions are known to have shortcomings for neutron-rich nuclei in the region [20]. A truncated shell-model approach employing the TBLC8 interaction [31] is closer to the calculations presented here. The predictive power of the more recent and improved effective interactions is demonstrated by the robustness of the calculations for ^{52}Sc. Odd-odd nuclei are generally assessed to be very sensitive to slight changes in the interaction [30].

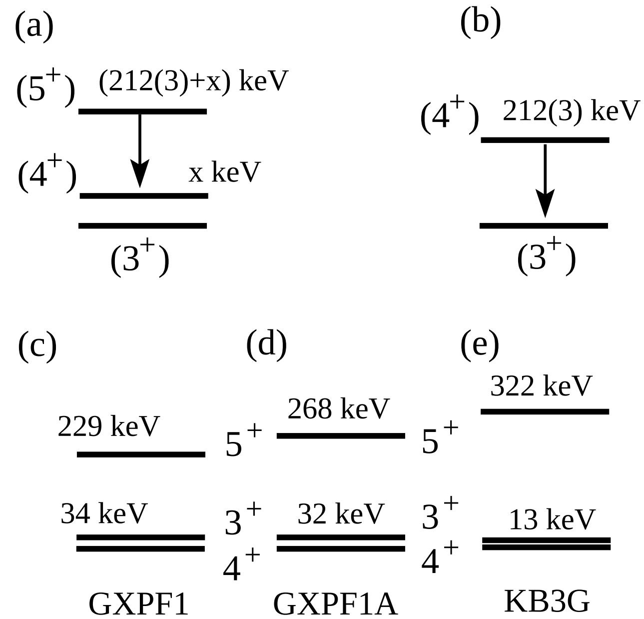

FIG. 3: Two possible scenarios (a) and (b) for the placement of the 212(3)-keV transition in the decay scheme of ^{52}Sc compared with shell model calculations (c)–(e). An $E2$ transition from the 5^+ to the 3^+ level can be excluded as discussed in the text.

The shell-model calculations show, as expected, a rather high level density for the odd-odd nucleus ^{52}Sc: a total of 73 states are predicted below the neutron separation energy of $S_n = 5.23$ MeV. The number of states together with the dominance of the single-particle degree of freedom make a Fermi-gas model applicable to the description of the "bulk" properties of the excitation spectrum within the shell model. These considerations prompted the study of the theoretical level scheme with respect to statistical properties given below.

Similar to the analyses presented in [32, 33, 34, 35] for experimental level schemes of heavier nuclei closer to stability, a statistical approach with an empirical spin-cutoff parameter was chosen to describe the distribution of spin values in the excitation spectrum of ^{52}Sc predicted within the shell model. A separable expression for the level density $\rho(E, J) = \frac{1}{2}\rho(E)f(J)$ with an energy-dependent term $\rho(E)$ and the spin distribution $f(J)$,

$$f(J) \approx \frac{2J+1}{2\sigma^2} e^{-(J+1/2)^2/2\sigma^2}, \qquad (1)$$

with the spin-cutoff parameter σ was assumed. We focused solely on the description of the spin distribution using an empirical, energy-independent expression for the spin cutoff for a nucleus with mass A [32, 34]:

$$\sigma = (0.98 \pm 0.23)A^{(0.29\pm0.06)}, \qquad (2)$$

yielding $\sigma = 3.08$ for $A = 52$. Fig. 4 presents the spin frequency from the shell-model calculations using the GXPF1 effective interaction in comparison to the statistical approach. A good agreement is reached with this parameter-free description.

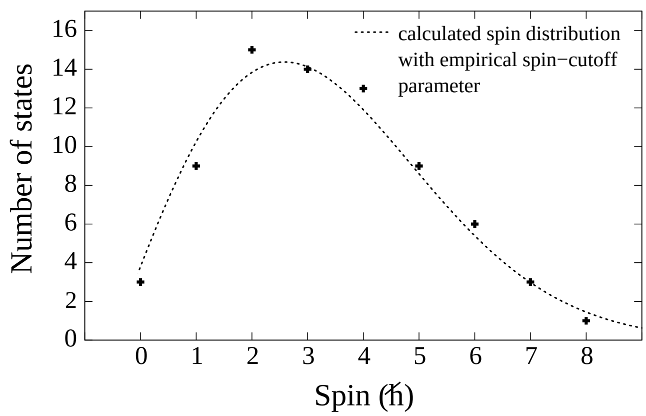

FIG. 4: Number of states per spin value in the shell-model calculations compared to the spin distribution modeled within the framework of a constant-temperature model with an empirical spin-cutoff parameter. The calculated spin distribution is drawn continuously to guide the eye. All 73 shell-model states with $E \leq S_n = 5.23$ MeV are included.

In summary, the odd-odd fp-shell nucleus ^{52}Sc was investigated with in-beam γ-ray spectroscopy following fragmentation of ^{55}V and ^{57}Cr. A new γ-ray transition was observed at 212(3) keV and was assigned to the low-lying level scheme of ^{52}Sc. All known states were compared to full fp-shell calculations with the GXPF1 effective interaction. The placement of the new γ decay was also discussed in comparison to shell-model calculations with the GXPF1A and KB3G effective interactions. All three interactions predict a very similar low-lying level scheme, illustrating the predictive power of these more modern interactions for the fp shell. The frequency of spin values from the GXPF1 shell-model calculation was successfully modeled by the spin distribution formulated in a purely statistical approach using an empirical, energy-independent spin-cutoff parameter that is only a function of the mass number A.

We thank T. Baumann, T. Ginter, M. Portillo, A. Stolz, and the NSCL cyclotron operations group for the high-quality secondary and primary beams. This work was supported by the National Science Foundation under Grants No. PHY-0110253 and PHY-0244453, and by the U.S. Department of Energy, Nuclear Physics Division, under Contract Nos. W31-109-ENG-38.

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