In-beam $\gamma$-ray spectroscopy at the proton dripline: $^{40}$Sc

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Abstract

We report on the first in-beam $\gamma$-ray spectroscopy of the proton-dripline nucleus $^{40}$Sc using two-nucleon pickup onto an intermediate-energy rare-isotope beam of $^{39}$Ca. The $^{39}$Ca($^{39}$Ca,$^{40}$Sc+$\gamma$) reaction at 60.9 MeV/nucleon mid-target energy selectively populates states in $^{40}$Sc for which the transferred proton and neutron couple to high orbital angular momentum. In turn, due to angular-momentum selection rules in proton emission and the nuclear structure and energetics of $^{39}$Ca, such states in $^{40}$Sc then exhibit $\gamma$-decay branches although they are well above the proton separation energy. This work uniquely complements results from particle spectroscopy following charge-exchange reactions on $^{40}$Ca as well as $^{40}$Ti EC/$\beta^+$ decay which both display very different selectivities. The population and $\gamma$-ray decay of the previously known first (5$^+$) state at 892 keV and the observation of a new level at 2744 keV are discussed in comparison to the mirror nucleus and shell-model calculations. On the experimental side, this work shows that high-resolution in-beam $\gamma$-ray spectroscopy is possible with new generation Ge arrays for reactions induced by rare-isotope beams on the level of a few $\mu$B of cross section.

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Since its discovery in 1955 [1], the neutron-deficient nucleus $^{40}$Sc has attracted attention for a variety of interests ranging from rp-process nucleosynthesis [2,3] to the solar neutrino absorption rate on $^{40}$Ar [4,5]. In fact, $^{40}$Sc – five neutrons removed from stable $^{45}$Sc – is the last proton-bound scandium isotope, with $^{39}$Sc shown to be unstable against proton emission [6]. $^{40}$Sc is peculiarly located on the nuclear chart (Fig. 1): While it is the proton dripline nucleus of the scandium isotopic chain, it is easily produced from charge-exchange reactions on stable $^{40}$Ca (e.g., see [2,7,8]).

Due to the low $^{40}$Sc proton separation energy of $S_p = 529.6(29)$ keV [10], only the 4$^{-}$ ground state and the 34-keV first-excited (3$^{-}$) state are nominally below the proton emission threshold. The nuclear structure interest in this neighboring isobar of $^{40}$Ca has been focused on the particle-hole nature of the states in $^{40}$Sc relative to the doubly-magic $N = Z = 20$ core [7,11], while the quest to constrain the $^{39}$Ca($p,\gamma$)$^{40}$Sc proton capture rate drove the highest-resolution study of $^{40}$Sc yet [2]. To obtain the $^{40}$Ti$\rightarrow^{40}$Sc weak decay rate, which allows determination of the $^{40}$Ar neutrino absorption rate via isospin symmetry [4], the $\beta$ decay of $^{40}$Ti,
populating high-lying, unbound low-spin states of $^{40}$Sc, was studied with proton spectroscopy (e.g., see [5,9]). The work reported here presents the first in-beam $\gamma$-ray spectroscopy of this dripline nucleus, $^{8}$Be+$^{38}$Ca,$^{40}$Sc+$\gamma$X, including observation of decays from states above $S_p$.

The $^{38}$Ca secondary beam was produced by fragmentation of a 140-MeV/nucleon stable $^{40}$Ca beam, accelerated by the Coupled Cyclotron Facility at NSCL [12], impinging on a 799 mg/cm$^2$ $^{9}$Be production target and separated using a 300 mg/cm$^2$ Al degrader in the A1900 fragment separator [13]. The momentum acceptance of the separator was restricted to $\Delta p/p = 0.25\%$, yielding typical rates of 160,000 $^{18}$Ca/s. About 86% of the secondary beam composition was $^{38}$Ca, with the lighter isotones comprising the less intense beam components. The secondary $^{9}$Be reaction target, of 188 mg/cm$^2$ thickness, was located at the target position of the S800 spectograph. The projectile-like reaction products were identified on an event-by-event basis in the S800 focal plane with the standard detector systems [14] (see Fig. 2). The $^{38}$Ca projectiles in the entrance channel were selected through a software gate applied on the time-of-flight difference taken between two plastic scintillators before the target.

The high-resolution $\gamma$-ray spectrometer GRETINA [15,16], an array of 36-fold segmented high-purity germanium detectors assembled into modules of four crystals each, was used to measure the prompt $\gamma$ rays emitted by the reaction residues in flight. The 12 detector modules available were arranged in two rings with four located at 58° and eight at 90° with respect to the beam axis. Online pulse-shape analysis provided the $\gamma$-ray interaction points for event-by-event Doppler reconstruction of the $\gamma$ rays emitted in-flight at about 30% of the speed of light [16]. The momentum vector of projectile-like reaction residues as ray-traced through the S800 spectograph was incorporated into the emission-angle determination entering Doppler reconstruction. Fig. 3 displays the Doppler-reconstructed $\gamma$-ray spectrum obtained for $^{40}$Sc with nearest-neighbor addback included [16].

The inclusive cross section for the two-nucleon pickup from $^{38}$Ca to $^{40}$Sc was determined from the number of $^{40}$Sc detected in the S800 focal plane relative to the number of $^{38}$Ca projectiles and the number density of the target. The rigidity of the spectrograph was chosen to center the two-neutron knockout residue $^{36}$Ca in the S800 focal plane and, therefore, $^{40}$Sc was off-center. Fig. 4 shows the parallel momentum distribution of $^{40}$Sc within the acceptance of the spectograph. Assuming that the maximum of the distribution is at about 11.983 GeV/c (see Fig. 4) and has a shape similar to what was observed in [18] for one-proton pickup from a $^{9}$Be target, a potential acceptance loss of 20% is estimated. Including this uncertainty, the inclusive cross section amounts to $\sigma_{inc} = 8.0(6)_{-1.6}^{+1.8}\,\mu$b (with 3.75% statistical and 7% systematic uncertainty included in the symmetric error bars and additional +20% of uncertainty accounting for a possible acceptance cut.). The systematic uncertainty is attributed to the determination of a very low cross section in the presence of background from pile-up.

While, due to its unbound target final states, the present reaction mechanism is too complex to allow quantitative dynamical calculations, in common with other linear- and angular-

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1 We note that the exact shape and centroid of the momentum distribution from this novel $^{9}$Be-induced reaction is not precisely known and future measurements of the shape and energetics may clarify the reaction mechanism and allow for a more precise estimate of the acceptance loss. This is not critical for the results of the present work.
momentum mismatched two-nucleon transfer reactions, such as $(\alpha, d)$ and its inverse, see e.g. [21,22], its strong selectivity of (stretched) transitions involving maximal orbital angular momentum transfer is a firm qualitative feature. Such large $\ell$-selectivity in one-neutron pickup at intermediate energy is shown in Fig. 2 of Ref. [23] and where, for a $^6\text{Be}$ target, the reaction proceeds by the pickup of well-bound nucleons leaving the target residue in the continuum [19]. Importantly, unlike the $(\alpha, d)$ reaction, where the transfer vertex selects an np-pair with spin $S = 1$, here there is no such restriction, allowing, for example, for the direct population of $(\pi f_{3/2}, v f_{3/2})^{(J=5^-)}$ final state. This difference is illustrated by the $^{38}\text{Ar}(\alpha, d)^{40}\text{K}$ reaction to the mirror of $^{40}\text{Sc}$ that was found to populate the $(\pi f_{3/2}, v f_{3/2})^{(J=7^+)}$ configuration but not the corresponding $6^+$ state [24] or by the $^{40}\text{Ca}(\alpha, d)^{42}\text{Sc}$ reaction to the neighboring $\text{Sc}$ isotope that populated the $7^+$ and $5^+$ states but not the $6^+$ [25].

Turning to the $\gamma$-ray spectrum and the level structure of $^{40}\text{Sc}$, the very favorable peak-to-background ratio manifested in Fig. 3 enables the spectroscopy of rare isotopes produced at the level of $\mu$b. The $\gamma$ ray observed at 892(3) keV (see Fig. 3) most certainly corresponds to the decay of the previously reported ($5^-$) state at 893.5(20) keV to the $4^-$ ground state [17]. Since this is the first $\gamma$-ray spectroscopy of $^{40}\text{Sc}$, we resort to the mirror nucleus $^{40}\text{K}$ and shell-model calculations for guidance on other potential decay branches from this state. The shell model for $^{40}\text{Sc}$ uses the $\text{sdpf-wb}$ effective shell-model interaction [26], a $(sd)^{-1}(fp)^{+1}$ model space for the low-lying negative-parity states, and a $(sd)^{-2}(fp)^{-2}$ model space for the positive-parity states. In $^{40}\text{K}$, the $5^{-} \to 4^{-}$ transition to the ground state dominates over the decay to the excited $3^{-}$ state with a branching ratio of 100 vs. 0.15 (see Fig. 5), consistent with the observation of only the 892 keV $\gamma$ ray here. This is also in agreement with the shell-model calculations that predict the $5^{-}$ to $3^{-}$ branch is even more suppressed.

The population of the $5^{-}$ state in the reaction used here very likely corresponds to the pickup of the proton into the $f_{3/2}$ orbital and the neutron into the partially filled $d_{3/2}$ orbital, consistent with a resulting stretched configuration of $(\pi f_{3/2}^1, v d_{3/2}^{-1})^{(J=5^-)}$.

The selectivity of the reaction mechanism favors population of high-angular-momentum states and, thus, supports this picture. The proton decay of the state is presumably hindered by the angular momentum barrier ($\ell = 3$) and the low $Q_{\gamma}$ value for the $\gamma$ emission to the only energetically allowed state in $^{39}\text{Ca}$, the $3/2^+$ ground state (see Fig. 5). The $4^{-}$ and $3^{-}$ ground and first-excited states are expected to have the same $(\pi f_{3/2}^1, v d_{3/2}^{-1})$ particle-hole configuration based on $(p,n)$ reaction studies [7] but their population would not be observable through prompt $\gamma$-ray spectroscopy (from the mirror nucleus, the $3^{-}$ state is expected to be a nanosecond isomer, also with the $\gamma$-ray energy below threshold in this work). The reaction mechanism also disfavors population of a $3^{-}$ configuration due to the lower orbital angular momentum transfer relative to the $5^{-}$ level.

In the following, we explore the origin of the $\gamma$-ray transition at 1852 keV. The next configuration that allows for high angular momentum can be realized by the pickup of the proton and neutron into the corresponding $f_{3/2}$ orbitals; our selectivity to high-angular-momentum configurations is again commensurate with the observation of a $\gamma$-ray decay. The highest $J^\pi$ states of the resulting $(f_{3/2})^2$ multiplet would be $6^+$ and $7^+$. In $^{40}\text{K}$, the lowest-lying $7^+$ and $6^+$ states are reported at about 2.54 and 2.88 MeV excitation energy, respectively, both with decays to the $5^-$ state and to each other (Fig. 5). For $^{40}\text{Sc}$, if the 1852-keV $\gamma$ ray, observed here for the first time, were to feed the $(5^-)$ state, this would place a new excited state at 2744(5) keV in the region where the high-spin positive-parity states are expected. Also, the shell-model calculations performed using the $\text{sdpf-wb}$ Hamil-

![Fig. 5. Level schemes of the mirror pair $^{40}\text{Sc}$ and $^{40}\text{K}$ together with shell model for $^{40}\text{Sc}$ (using the $\text{sdpf-wb}$ Hamiltonian [28]) and the $^{40}\text{Ca}$+$p$ system relevant to explore proton emission from the relevant excited states in $^{40}\text{Sc}$. For all states of $^{40}\text{Sc}$ discussed here, $p$ emission can only reach the $3/2^+$ ground state of $^{40}\text{Ca}$ due to the energetics of the two systems. Levels known in $^{40}\text{Sc}$ but not observed here are indicated by a dashed line. Literature data taken from [17].]
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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