Dissipative reactions with intermediate-energy beams – a novel approach to populate complex-structure states in rare isotopes

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A novel pathway for the formation of multi-particle-multi-hole (np – mh) excited states in rare isotopes is reported from highly energy- and momentum-dissipative inelastic-scattering events measured in reactions of an intermediate-energy beam of 38Ca on a Be target. The negative-parity, complex-structure final states in 38Ca were observed following the in-beam γ-ray spectroscopy of events in the 9Be(36Ca, 38Ca + γ)X reaction in which the scattered projectile lost longitudinal momentum of order ∆pL = 700 MeV/c. The characteristics of the observed final states are discussed and found to be consistent with the formation of excited states involving the rearrangement of multiple nucleons in a single, highly-energetic projectile-target collision. Unlike the far-less dissipative, surface-grazing reactions usually exploited for the in-beam γ-ray spectroscopy of rare isotopes, these more energetic collisions appear to offer a practical pathway to nuclear-structure studies of more complex multi-particle configurations in rare isotopes – final states conventionally thought to be out of reach with high-luminosity fast-beam-induced reactions.

Beyond the proof of existence of a rare isotope and the determination of its ground-state half-life, the energies of excited states are typically the first observables that become accessible in laboratory experiments. For excited bound states, depending on their lifetime, prompt or delayed γ-ray spectroscopy is frequently used to obtain precise excitation energies from the measured transition energies [1]. In short-lived rare isotopes, excited states can be populated efficiently in (direct) nuclear reactions [2] or β decay [3], for example, most often exploiting the unique selectivity inherent to each of these different population pathways. The selectivity of one- and two-nucleon transfer and knockout reactions, or inelastic scattering [2, 4–8], often enhances the population of excited states at moderate spin associated with the single-particle or collective degree of freedom. Here, we report the novel, complementary in-beam γ-ray spectroscopy of higher-spin, negative-parity states in 38Ca, observed to be populated in the 9Be(36Ca, 38Ca + γ)X inelastic scattering at high momentum loss. From the peculiar final states observed, we argue that these complex-structure, projectile excited states are formed by the rearrangement of multiple nucleons in a single, highly-energetic projectile-target collision, giving access to multi-particle configurations not expected to be in reach of high-luminosity fast-beam reactions.

The reaction channel analyzed here is populated in the same experiment as reported on in Ref. [9] where the focus was on 40Sc produced in the pn pickup reaction onto the 38Ca projectile. Here, we briefly summarize the experimental scheme below and refer the reader to Ref. [9, 16] for more details. The 38Ca rare-isotope beam was produced by fragmentation of a stable 40Ca beam, accelerated to 140 MeV/nucleon by the Coupled Cyclotron Facility at NSCL [10]. The momentum width transported to the experiment was restricted to ∆p/p = 0.25%, resulting in 160,000 38Ca/s impinging upon a 188-mg/cm²-thick 9Be foil located at the target position of the S800 spectrograph [11]. The setting subject of this publication ran for less than 40 hours. The constituents of the incoming beam and the projectile-like reaction products were identified on an event-by-event basis using the S800 analysis beam line and focal plane with the standard detector systems [12]. As the magnetic rigidity of the S800 spectrograph was tuned for 36Ca, only part of the outermost (exponential) low-momentum tail of the reacted 38Ca distribution was transmitted to the focal plane. Specifically, the S800 momentum acceptance at this setting is p0 ± 330 MeV/c, with p0 = 11.222 GeV/c.

When compared to the parallel momentum distribution of the unreacted 38Ca passing through the target, having suffered only in-target energy losses (p0 = 11.932 GeV/c), the low-momentum, reacted 38Ca events detected in the reaction setting have undergone an additional longitudinal momentum loss of about 700 MeV/c (see Fig. 1). That is, approximately 18 MeV/c per nucleon in momentum or 5.4 MeV/nucleon in energy. The cross section for finding 38Ca with such large momentum loss was extracted to be σ(p0 ± 330 MeV/c) = 3.8(4) mb, making these inelastic large-momentum-loss events rather rare.

The mid-target energy of 38Ca in the 9Be reaction tar-
counts/bin

12000 counts / 5 keV

0 100 200 300 500 1000 1500 2000 2500 3000 3500

γ evidence for a weak 1048-keV transition being in coincidence with the 489-keV transition. There is 1489 keV, and the 214-keV transition lies on top of the 489-keV transition feeds the level depopulated by the 2213-keV line, resembling the situation described here, we propose $J^π = (4^−)$ for the 4191-keV state in $^{38}$Ca. The new 214-keV transition feeding the (4−) level establishes a state at 4405 keV which appears to correspond to the 4586-keV 5− level in the $^{38}$Ar mirror whose far-dominant decay is a 106-keV transition to the $2^+$ state. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV. Based on mirror symmetry, a (5−) assignment is proposed here for the 4405-keV level in $^{38}$Ca. This establishes (5−) → (4−) → (3−) → 214 keV.
scattering populated at large momentum loss.

The next strongest populated level is the $2^+_2$ state at 3684 keV for which only the transition to the ground state is observed here. A $0^+$ state at 4748(5) keV is claimed in $^{38}$Ca from the $(^3$He,$n$) transfer reaction, however, with the suspicion of a doublet [15]. Due to the transition to the $(3^-)$ state, a $0^+$ assignment is excluded and the level established here is tentatively assigned (3+), consistent with the 4877-keV 3+ level in the $^{38}$Ar mirror, which also decays predominantly to the $2^+_1$ and 3$^+_1$ states [15].

It is interesting to explore which low-lying levels have not been observed in the present experiment. This is, most prominently, the $0^+_2$ state reported at 3084 keV which would decay to the first $2^+$ state with a 871-keV transition [15]. There is no evidence for an appreciable presence of that transition in Figs. 2 and 3 (the 871-keV transition would be 13 keV above the background feature originating from neutron-induced background as indicated in Fig. 2).

In the following, we discuss the configurations of the states observed. Many properties of $^{40}$Ca and the surrounding nuclei can be interpreted relative to a doubly-closed shell structure for the ground state of $^{40}$Ca with the $sd$ shell filled and the $pf$ shell empty. The first excited state of $^{40}$Ca has $J^\pi = 0^+$ and is qualitatively associated with a four-particle four-hole (4p-4h) state relative to the $^{40}$Ca closed-shell ground state [18]. We will use $\Delta$, the number nucleons moved from $sd$ to $fp$ orbitals, to characterize the structure of the states. In this notation, the 4p-4h states in $^{40}$Ca have $\Delta = 4$. To remove spurious states, the $\Delta$ basis includes all components associated with the $\Delta\hbar\omega$ basis constructed in the $0s-0p-0d1s-0f1p$ model space).

In Ref. [20], a Hamiltonian was developed for these pure $\Delta$ configurations. This Hamiltonian served as the starting point for the new Florida State University (FSU) Hamiltonian for pure $\Delta$ states [21, 22]. The $A = 38$, FSU results are compared to experiment in Fig. 4, the overall agreement with experiment being good. The calculated configurations can be divided into those with $\Delta = 0$ with positive parity (green), those with $\Delta = 1$ with negative parity (blue) and those with $\Delta = 2$ with positive parity (red).

In the present $^{38}$Ca level scheme, the strongest $\gamma$ rays come from the $2^+_1$ state, which is predicted to be of $sd$-shell origin, and from states with $\Delta = 1$, including the highest $J^\pi = 5^-$ level possible for this $\Delta$. The $\gamma$-ray decay of the $2^+_2$ state is also observed. In the $^{36}$Ar($^3$He,$n$) reaction in [23] this state is found to have a strong $(f_{7/2})^2$ form factor which would come from $\Delta = 2$ configurations in the FSU spectrum. However, the $0^+_2$ state, which also has $\Delta = 2$, was not populated.

In the following, we propose a view that puts the pop-
lated states within the context of the observed high-momentum-loss reaction events. From the approximately 200 MeV of energy loss in the reaction, and given that the detected $^{38}$Ca are largely within laboratory scattering angles of 3-4°, about 150 MeV must be dissipated in the $^9$Be nuclei, with a total binding of 58 MeV. Thus, there must be disintegration of the target nucleus into a number of energetic fragments. The emerging picture is then one of multiple nucleons interacting in a single collision with the formation of complex multi-particle multi-hole configurations, in contrast to the situation in far-less-dissipative, surface-grazing collisions. We exclude scenarios where a $^{38}$Ca projectile undergoes multiple collisions within the target as an explanation for the observed cross sections. High-momentum loss events creating $mp$-$nh$ excitations in such a scenario would require a sequence of knock-out and/or pickup processes and such pickup mechanism cross sections are small – with a typical upper limit of 2 mb at these beam energies [24].

Connecting to the shell-model picture, excitations within the FSU model space are described by many-body transition densities. In the simplest scenario, excitation of the $\Delta = 1$ negative-parity states involve the $\Delta = 0$ to $\Delta = 1$ one-body transition densities (OBTD). The OBTD to those states observed are all large. The $\Delta = 2$, $2^+_2$ state involves the $\Delta = 0$ to $\Delta = 2$ two-body transition density (TBTD). The TBTD connecting the $\Delta = 0$ and $\Delta = 2$ $^+$ wave functions are the same ones that enter into the Hamiltonian matrix for mixing these two states. We expect that the microscopic, two-nucleon excitation mechanism should involve an operator similar to that of the two-body mixing Hamiltonian (e.g. dominated by pairing). This would explain why excitation of the $0^+_2$ is not observed – the mixed $0^+_1$ and $0^+_2$ eigenfunctions are orthogonal with respect to the two-nucleon excitation operator. We note that in $^{40}$Ca($p,t$) [25] the $0^+_2$ state is only very weakly populated compared to the $2^+_2$ state (see Fig. 1 in Ref. [25]).

The events at momentum losses of 600-700 MeV/c, studied here, are also reminiscent of observations in the work of Podolyak et al. [30]. There, in the two-neutron knockout from $^{56}$Fe to $^{54}$Fe at 500 MeV/nucleon, the population of a $10^+$ isomer of complex structure was observed in the low-momentum tail of the parallel momentum distribution at about the same absolute momentum loss. The authors attributed this population to the excitation of the $\Delta(1232)$ resonance at their relativistic beam energies. This mechanism is not available to our intermediate-energy beams of tens of MeV/nucleon. One may speculate that the population of the complex-structure state in the two-neutron knockout from $^{56}$Fe is rather due to a simultaneous multi-nucleon rearrangement as hypothesized here, without evoking quark degrees of freedom and consistent with the reduction of multi-step processes at their relativistic energies. For example, population of the $10^+$ state could be due to the $\Delta J = 6$ excitation of a $(f_{7/2})^2$ $6^+$ configuration in $^{56}$Fe combined with the removal of two neutrons from the $1p_{3/2}$ and $0f_{7/2}$ orbitals having $\Delta J \geq 4$.

In Ref. [16], from the high-spin spectroscopy of states up to $J = 15/2$ in $^{39}$Ca, we argue that such simultaneous multi-nucleon rearrangement is also at play in intermediate-energy nucleon transfer reactions, such as $^9$Be($^{38}$Ca$^*$, $^{39}$Ca+$\gamma$)X. Once again, these excitations are seen in events in the tail of the longitudinal momentum distribution at a momentum loss of 600-700 MeV/c.

In the present work, the specific reaction dynamics at play in the observed large momentum loss collisions are unclear and remain a challenge for future, more complete and exclusive measurements. Specifically, it would be critical to detect the dissociation of the $^{39}$Be target nuclei in the large-momentum-loss events and clarify the kinematics of the residues.

While there is much to be discovered about this type of reaction, it is evident that this presents a new opportunity in the fast-beam regime which uniquely complements classic low-energy reactions, such as multi-step Coulomb excitation and multi-nucleon transfer. Fast beams allow for the use thick targets and capitalize on an increase in $\gamma$-ray yield by a factor of about 4300 for the specific example of a 188-\text{mg/cm}^2 $^9$Be target used here vs. a 1-\text{mg/cm}^2 Pb target often employed for multi-step Coulomb excitation, for example. Also, strong forward focusing enhances the collection efficiency as compared to low-energy reactions that fill a larger phase space.

Multi-step Coulomb excitation studies with low-energy rare-isotope beams have been performed at beam intensities similar to those used here, but have been limited to a complementary level scheme selectively comprising cascades connected by strong $E2$ transitions, with at most the first $3^-$ state [7, 26]. We illustrate this with the example of the state-of-the-art low-energy Coulomb excitation of the neighboring Ca isotope $^{42}$Ca on Pb [27]. The measurement was performed at 1 \text{pA} stable-beam intensity for 5 days (resulting in more than 110,000 times the number of Ca projectiles on target as in the present measurement) – excited states up to the $4^+_1,2$ states were reported with no evidence for any of the negative-parity cross-shell excitations observed here.

Multi-nucleon transfer, largely limited to stable beams at \text{pA} beam intensities, is known to populate complex-structure states, however, without efficiently reaching $^{38}$Ca in spite of $^{40}$Ca being an often-used beam (see [28] and references within). When low-energy neutron-rich beams become available at near stable-beam intensities, multi-nucleon transfer may become an alternative to access such states in selected neutron-rich nuclei [29]. While it is interesting to also extend our approach to collective nuclei, it already promises to be a unique method to probe cross-shell excitations near magic numbers, elucidating shell evolution in rare isotopes and exploring the necessary model spaces for a region’s description on the
quest for a predictive model of nuclei.

In conclusion, the in-beam $\gamma$-ray spectroscopy is reported of higher-spin, complex-structure negative-parity states in $^{40}\text{Ca}$ populated in highly-dissipative processes induced by a fast $^{38}\text{Ca}$ projectile beam reacting with a $^9\text{Be}$ target. This work constitutes the first high-resolution $\gamma$-ray spectroscopy of $^{38}\text{Ca}$ with a modern HPGe $\gamma$-ray tracking array. The final states observed in the inelastic scattering, $^9\text{Be}(^{38}\text{Ca},^{38}\text{Ca}+\gamma)X$, at large momentum loss are characterized through their particle-hole character relative to the $^{40}\text{Ca}$ closed-shell ground state. Excellent agreement is obtained with shell-model calculations using the FSU cross-shell effective interaction. Based on the strongly populated negative-parity states and the non-observation of the first excited $0^+_2$ state, we propose a consistent picture in which these multi-particle multi-hole states are formed by simultaneous rearrangement of multiple nucleons in a single, highly-dissipative collision. These reaction processes, seen here in the extreme low-momentum tail of $^{38}\text{Ca}+^9\text{Be}$ inelastic scattering, identify a new pathway to gain access to excited states not usually observed in fast-beam induced reactions and likely out of reach for low-energy reactions.

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