In-beam $\gamma$-ray spectroscopy at the proton dripline: $^{23}$Al

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We report on the first in-beam $\gamma$-ray spectroscopy of $^{23}$Al using two different reactions at intermediate beam energies: inelastic scattering off $^9$Be at large momentum transfer and heavy-ion induced one-proton pickup, $^9$Be($^{23}$Mg,$^{23}$Al+$\gamma$)X, at 75.1 MeV/nucleon. A $\gamma$-ray transition at 1616(8) keV– exceeding the proton separation energy by 1494 keV – was observed in both reactions. From shell model and proton decay calculations we argue that this $\gamma$-ray decay proceeds from the core-excited $7/2^+$ state to the $5/2^+$ ground state of $^{23}$Al. The proposed nature of this state, $[^{22}\text{Mg}(2f)^+ \otimes \pi d_{5/2}/2l_{7/2}^+ \otimes \beta NMR$ measurement clearly showed that the spin and the parity of the $^{23}$Al ground state are $J^\pi = 5/2^+$ [5], in agreement with the mirror nucleus $^{23}$Ne. Excited states of $^{23}$Al have been studied in $^{24}$Mg($^7$Li,$^8$He)$^{23}$Al reactions [6, 7], in $\beta$-delayed proton decay [8], in Coulomb breakup [9] and most recently in $^{24}$Mg+t+p resonant proton scattering [10]. None of these prior experiments was sensitive to $\gamma$-ray transitions in $^{23}$Al. In the present paper we report on the first in-beam $\gamma$-ray spectroscopy study of $^{23}$Al. Two complementary reactions were used to excite $^{23}$Al: inelastic scattering off a $^9$Be target at large momentum transfer and the heavy-ion induced one-proton pickup reaction, $^9$Be($^{22}$Mg,$^{23}$Al+$\gamma$)X.

Both measurements were performed with an exotic cocktail beam composed of 32% $^{22}$Mg and 3% $^{23}$Al. This secondary beam was produced in-flight by fragmentation of a 150 MeV/nucleon $^{36}$Ar primary beam delivered by the Coupled Cyclotron Facility at NSCL on the campus of Michigan State University. The primary $^9$Be production target (893 mg/cm$^2$ thick) was located at the mid-acceptance target position of the A1900 fragment separator [11]; an achromatic aluminum wedge degrader of 300 mg/cm$^2$ thickness and momentum slits at the dispersive image of the separator were used to select the secondary beam. The slits were restricted to $\Delta p/p = 0.5\%$ total momentum acceptance for the secondary beam.

The $^9$Be($^{23}$Al,$^{23}$Al+$\gamma$)$^{9}$Be inelastic scattering and the $^{9}$Be($^{22}$Mg,$^{23}$Al+$\gamma$)X one-proton pickup reaction were induced by a 188(4) mg/cm$^2$ $^9$Be target placed at the target position of the S800 spectrograph [12]. The reaction target was surrounded by SeGA [13] in its “classic” configuration with nine and seven detectors, respectively, at central angles of 90$^\circ$ and 37$^\circ$ with respect to the beam axis. The SeGA high-purity germanium detectors are 32-fold segmented and allow for an event-by-event Doppler reconstruction of the $\gamma$-rays emitted in-flight by the reacted nuclei. The emission angle that enters the Doppler reconstruction is determined from the location of the segment with the largest energy deposition relative to the target.

Event-by-event particle identification was performed in all entrance and exit channels with timing detectors before the reaction target and with the focal-plane detection system [14] of the S800 spectrograph. The time-of-flight difference measured between the two plastic scintillators located before the reaction target allowed for an unambiguous identification of all constituents of the incoming cocktail beam (see Fig. 2 of [15] and Fig. 1 of [16]). The reaction residues emerging from the $^9$Be target were identified via their time-of-flight measured by plastic scintillators and their energy loss determined with the S800 ion chamber. A software gate on the incoming beam then allowed the selection of only those reaction residues induced by the projectile of interest (see also refs. [15, 16]).

Fig. 1(a) shows the particle identification spectrum – energy loss vs. time-of-flight – for the spectrograph setting that was optimized on the one-proton pickup channel. The particle identification spectrum only contains reaction products from $^{22}$Mg. The one-proton pickup residue $^{23}$Al can be clearly separated from the fragmentation products that enter the S800 focal plane as well. Fig. 2(a) shows the event-by-event Doppler reconstructed...
\[ \gamma/p \leq 0.02 \]

\[ 0.0 \leq \Delta p/p \leq 0.02 \]

100 200 300 400 500

\[ \text{Time of flight (a.u.)} \]

\[ \text{Energy loss (a.u.)} \]

\[ 23 \text{Al} \]

\[ \Delta \]

\[ p \]

\[ 7.990 \text{ GeV/c} \]

\[ 23 \text{Al} \]

\[ 22 \text{Mg} \]

\[ \text{FIG. 1: Left: Identification spectrum – energy loss vs. time of flight – of } \]

\[ \text{23Al produced in one-proton pickup onto 22Mg projectiles. Right: Parallel} \]

\[ \text{momentum distribution of 23Al (relative to } p = 7.990 \text{ GeV/c); shown is} \]

\[ \text{the full momentum acceptance of the spectrograph.} \]

\[ \gamma \text{-ray spectrum in coincidence with 23Al produced in the} \]

\[ \text{one-proton pickup reaction. A photopeak at 1614(9) keV is clearly visible and} \]

\[ \text{marks a } \gamma \text{-ray transition in 23Al.} \]

\[ \text{FIG. 2: Doppler-reconstructed } \gamma \text{-ray spectrum detected in co-} \]

\[ \text{incidence with 23Al reaction residues produced in one-proton pickup (upper} \]

\[ \text{panel) and inelastic scattering (lower panel). The energy uncertainty is} \]

\[ \text{dominated by the uncertainty in the target position which is systematic and} \]

\[ \text{common for both measurements.} \]

\[ \text{FIG. 3: Left: Identification spectrum – energy loss vs. time of flight – } \]

\[ \text{of the (in)elastically scattered 23Al nuclei. The spectrograph magnetic} \]

\[ \text{rigidity was centered on the one-neutron removal products from 24Si. Right: Parallel} \]

\[ \text{momentum distribution of the scattered 23Al (relative to } p = 8.339 \text{ GeV/c).} \]

\[ \text{Due to the magnetic rigidity setting optimized on reaction residues with one} \]

\[ \text{neutron less than the projectile, only the low-momentum tail of scattered} \]

\[ \text{23Al enters the focal plane.} \]

\[ \text{The observed } \gamma \text{-ray energy is consistent for the two measurements and implies an} \]

\[ \text{excited state at 1616(8) keV in 23Al, 1494 keV above the proton separation} \]

\[ \text{energy. This state has a significant } \gamma \text{-ray branch to the proton-bound} \]

\[ \text{ground state. If this } \gamma \text{-ray transition were to originate from an even higher} \]

\[ \text{excited state it would either populate a proton-unbound excited state and} \]

\[ \text{could not have been observed here as a coincidence with 23Al is required or} \]

\[ \text{would feed an excited state that also has a significant } \gamma \text{-ray decay branch which} \]

\[ \text{then should have been detected as well.} \]

\[ \text{All excited states of 23Al are reported to decay to 100} \%

\[ \text{by proton emission, including the first excited state, } E(1/2^+) = 550(20) \text{ keV, with} \]

\[ \Gamma_p/\Gamma_\gamma \sim 10^8 \text{ [17]. Figure 4 compares the level schemes of the mirror} \]

\[ \text{nuclei 23Al and 23Ne below 2.3 MeV excitation energy. We tentatively assign} \]

\[ \text{spin and parity } J^\pi = (7/2^+) \text{ to the excited state at 1616(8) keV observed in the} \]

\[ \text{present work. There is a one-to-one correspondence for the states below} \]

\[ 2.3 \text{ MeV. The energy difference of the } 1/2^+ \text{ first excited state can be explained by the} \]

\[ \text{Thomas-Ehrenberg shift [18] which influences } \ell = 0 \text{ orbits the most. In the following} \]

\[ \text{FIG. 3: Right: Parallel momentum distribution of the scattered 23Al (relative to } p = 8.339 \text{ GeV/c).} \]
proton scattering cross section was calculated for $\ell = 23$ at 1616(8) keV in $^{23}$Al was observed for the first time in the present experiment.

we discuss the structure of the proposed 7/2$^+$ state, in particular the occurrence of a significant $\gamma$-ray branch, within the USD shell model and argue the consistency of this assignment with the reaction mechanisms that led to its observation.

Shell-model calculations for the energies, spectroscopic factors and electromagnetic matrix elements were carried out with the USDB effective interaction (results with USDA were similar) [19]. The calculated half-life of the 7/2$^+$ state, $T_{1/2} = 23$ fs, corresponds to a $\gamma$ width of $\Gamma_\gamma = 0.020$ eV. The spectroscopic factor for the $d_{5/2}$ orbit connecting the $^{23}$Al, $J^\pi = 7/2^+$ and $^{22}$Mg, $J^\pi = 2^+$ levels is large indicating a dominance of the $^{22}$Mg, $[^{22}\text{Mg}(2^+_1) \otimes d_{5/2}]_{7/2^+}$ configuration in the wavefunction. From the energetics summarized in Fig. 5, it follows that the $Q$-value for this decay is $Q_p = 244(21)$ keV.

![Diagram](image)

**FIG. 5:** Proposed decay scheme of the 7/2$^+$ core-coupled state at 1616(8) keV in $^{23}$Al. The state at 1616(8) keV in $^{23}$Al was observed for the first time in the present experiment.

To quantify the proton decay of the 7/2$^+$ state, the proton scattering cross section was calculated for $\ell = 2$ at $Q_p = 244$ keV with a Woods-Saxon potential and the resulting resonance width was used as the single-particle proton decay width, $\Gamma_p = 0.0024$ eV. With the value $S = 0.46$ for the 7/2$^+$ to $[^{22}\text{Mg}(2^+_1) \otimes d_{5/2}]$ spectroscopic factor, from the USDB shell-model calculations, this yields a proton decay width of $\Gamma_p = S \times \Gamma_p = 0.0011$ eV for the decay of the 7/2$^+$ state of $^{23}$Al to the first excited 2$^+$ state of $^{22}$Mg. In conclusion, the proposed structure of the 7/2$^+$ state, together with the energetics of the proton decay (see Fig. 5), results in $\Gamma_p/\Gamma_p \sim 20$ consistent with the observation of the $\gamma$-decay of this state. We note that proton detection was not possible with our experimental setup. Furthermore, $^{22}$Mg residues populated by the proton decays of excited states of $^{23}$Al could not be distinguished from $^{22}$Mg produced by the fragmentation of the $^{23}$Al projectiles, for example. Proton decay to the $^{22}$Mg ground state could proceed by $\ell = 4$. The single-proton particle decay width from the potential scattering calculations for $\ell = 4$ with $Q_p = 1.49$ MeV is 10 eV. If we assume that the proton width is approximately less than or equal to the gamma width then $S \leq 0.002$ for the $g7/2$ spectroscopic factor. Thus, the $g$-orbital admixture into the $sd$ model space is very small.

In our experiment, the state at 1616 keV was excited in the inelastic scattering of $^{23}$Al from a $^9$Be target. In odd-A nuclei, core-coupled states are most likely excited in inelastic scattering processes or Coulomb excitation. This is consistent with the spin and parity assignment of $J^\pi = 7/2^+$ for this state and the proposed structure discussed above.

However, our analysis was restricted to scattering events with a large momentum loss, as only the low-momentum tail of the scattered $^{23}$Al nuclei was within the acceptance of the S800 spectrograph. To probe which states are excited in the scattering at the largest momentum transfer, the inelastic scattering of $^{22}$Mg under identical conditions was analyzed. In the same reaction setting where the low-momentum tail of the $^{23}$Al projectile distribution passing through the target was used to study the inelastic scattering, the low-momentum tail of the $^{22}$Mg projectiles within the same cocktail beam entered the focal plane as well. The event-by-event Doppler reconstructed $\gamma$-ray spectrum in coincidence with these inelastically scattered $^{22}$Mg projectiles is shown in Fig. 6. The photopeaks of the $2^+_1 \rightarrow 0^+_1$ and $4^+_1 \rightarrow 2^+_1$ $\gamma$-ray transitions are clearly visible. The intensities show that, predominantly, the $2^+_1$ state of $^{22}$Mg is excited in the inelastic scattering of $^{22}$Mg projectiles from the $^9$Be target. This is again consistent with the proposed structure of $[^{22}\text{Mg}(2^+_1) \otimes d_{5/2}]$ for the 1616 keV state excited in the inelastic scattering of $^{23}$Al.

The proposed (7/2$^+$) excited state in $^{23}$Al was also populated in the one-proton pickup reaction $^9$Be$(^{22}$Mg, $^{23}$Al+$\gamma$)X. The $^{22}$Mg energy was 75.1 MeV/nucleon at mid-target. The potential of using inverse-kinematics one-proton pickup reactions
The required proton-core projectile overlaps, $^{22}\text{Mg}(J')\otimes\pi d_{5/2}$, and their spectroscopic amplitudes were guided by the USDB shell model calculations. As is noted in Fig. 7 there are interfering spectroscopic amplitudes $\alpha$ and $\beta$ for population of the $^{23}\text{Al}(gs)$ via the $^{22}\text{Mg}(0^+)\otimes\pi d_{5/2}$ in $^{22}\text{Mg}(J^\pi)\otimes\pi d_{5/2}$ transfers, respectively. The $^{23}\text{Al}(7/2^+)$ state is populated by $^{22}\text{Mg}(2^+)\otimes\pi d_{5/2}$ transfers. The USDB shell model spectroscopic factors of these overlaps are $S=0.33, 0.84$ and 0.46, respectively. The associated $\pi d_{5/2}$ single particle states were calculated in real Woods-Saxon potential wells with radius and diffuseness parameters $r_0 = 1.25$ fm and $a_0 = 0.7$ fm and a spin-orbit interaction of strength 6 MeV with the same geometry parameters. The bound $\pi d_{5/2}$ configurations used the physical separation energies. The very narrow resonant $\pi d_{5/2}$ state, relevant to the $7/2^+$ transition with $S_p = -244$ keV, was accurately described by a bound proton state with separation energy of $S_p = +5$ keV.

The calculated yields, inclusive with respect to the three $^8\text{Li}(I^\pi)$ final state contributions, were as follows.
The cross section for direct population of the $^{23}\text{Al}(7/2^+)$ state is 0.022 mb, underproducing the measured yield of 0.07(2) mb. The calculations were also sensitive to the relative phase of the spectroscopic amplitudes $\alpha$ and $\beta$ that feed the $^{23}\text{Al}(gs)$, Fig. 7. The shell-model calculations for the spectroscopic amplitudes together with the electromagnetic matrix element, predict that these paths interfere destructively to give $^{23}\text{Al}(gs)$ and inclusive cross sections of 0.26 and 0.28 mb, the latter to be compared with the experimental value of 0.54(5) mb. Inelastic $5/2^+ \rightarrow 7/2^+$ (single particle) coupling in $^{23}\text{Al}$, shown in Fig. 7, was found to have negligible effect on the calculated $^{23}\text{Al}(7/2^+)$ yield. We conclude that the relative yields of the $^{23}\text{Al}(5/2^+)$ and $^{23}\text{Al}(7/2^+)$ are reasonably reproduced by the model calculations. The inclusive cross section is a factor two smaller than that measured. These lower cross sections were not unexpected since we include only the three (lowest) $^8\text{Li}$ final states with summed spectroscopic factors of 0.97 ($p_{3/2}$) and 0.36 ($p_{1/2}$). Further consideration of strength leading to the $^8\text{Li}$ continuum is needed to assess the absolute cross sections. As was noted above, the low-momentum tail seen in the $^{23}\text{Al}$ distribution in Fig. 1 suggests a significant missing dissipative mechanism such as coupling to the $^8\text{Li}$ continuum.

In summary, the $\gamma$-decay of an excited state in $^{23}\text{Al}$ has been observed for the first time in (i) $^{23}\text{Al}$ inelastic scattering from $^9\text{Be}$ at large momentum transfer and (ii) in the heavy-ion induced one-proton pickup reaction $^9\text{Be}(^{22}\text{Mg}, ^{23}\text{Al}+\gamma)X$. The corresponding excited state at 1616(8) keV lies 1494 keV above the proton separation energy of $^{23}\text{Al}$. The presence of the $\gamma$-ray decay branch and the population of this state in the two reaction mechanisms is consistent with the state being the $7/2^+$ core-excited configuration, $^{22}\text{Mg}(2^+)\otimes d_{5/2}/d_{7/2}^2$, predicted by the shell model to be the second excited state. We have shown that the proton decay of this state, which will proceed by emission of a proton from the $d_{5/2}$ orbit to the first $2^+$ state of $^{22}\text{Mg}$, is hindered by the small $Q$-value of $Q_p = 244(21)$ keV. A branching ratio of $\Gamma_\gamma/\Gamma_p \sim 10$ is estimated from shell model and proton decay calculations.

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