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Gamma-Ray Spectroscopy in $A \cong 40$ Nuclei via Heavy-Ion–Induced Reactions: High-Spin States in ^{41}K and ^{41}Ca†

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Compound-nuclear reactions induced by bombardment of ^{24}Mg, ^{26}Mg, and ^{27}Al targets with 20–60-MeV ^{16}O, ^{18}O, and ^{19}F beams have been used to study γ transitions between high-spin states in nuclei in the mass region $32 \leq A \leq 44$. Results for ^{41}K and ^{41}Ca are presented to exemplify the method and results. The γ-ray decay of states with probable spins up to $\frac{19}{2}$ are observed in both nuclei.

The (heavy ion, xn, $\gamma\gamma$...) reaction has proven to be a powerful tool for studying nuclear spectroscopy in the mass region $A \gtrsim 100$[1,2] because of (a) large cross section, typically several hundred millibarns, (b) the transfer of large linear and angular momenta, (c) high alignment of the γ-emitting states, (d) strong energy dependence of the reaction cross section on bombarding energy and the concomitant ability to isolate quite well a particular final nucleus (value of x) by the choice of beam energy.

Investigations[3,4] of such reactions for lighter nuclei ($A < 80$) show the power of this method for this mass region, where all of the advantages mentioned above pertain, except (d). The lower Coulomb barrier allows proton and α-particle emission to compete with neutron emission. We then have reactions of the type (heavy ion, xn, yp, $z\alpha$, $\gamma\gamma$...) with x, y, z small integers. Typically ten nuclei are formed with comparable cross sections at any bombarding energy, and the major experimental problem is one of assigning the various γ-ray lines to particular nucleus. However, once the prejudice against studying several nuclei at once is overcome, it can be recognized that this method is a very efficient as well as a powerful spectroscopic tool.

A study of the nuclei with $32 \leq A \leq 44$ has been undertaken using reactions initiated by bombarding ^{24}Mg, ^{26}Mg, and ^{27}Al targets with ^{16}O, ^{18}O, and ^{19}F beams of 20–60 MeV from an MP tandem accelerator at Brookhaven National Laboratory. This provides nine reactions with compound nuclei between ^{42}Ca and ^{46}Ti for which the following experiments have been performed or are in progress: (1) γ-ray thin-target excitation functions, (2) γ-ray angular distributions, (3) γ-γ coincidence measurements, (4) recoil-distance lifetime measurements.

Targets were 200–300-μg/cm^2 metallic films on thick W backings, except for recoil-distance lifetime measurements[5] where a thin Ni backing was used. Excitation functions were taken in 5-MeV steps from 20 to 60 MeV. Angular distributions were recorded at seven angles between 0° and 90°.

The γ-γ coincidence data were recorded in 4096×4096 matrices by two Ge(Li) detectors placed at 0° and 90° to the beam with conventional electronics and a time gate of 60 nsec. After subtraction of random events, a background determined by channels near to a given photopeak was subtracted.

The results reported here for ^{41}K and ^{41}Ca considerably extend the information on high-spin states in mass-41 nuclei. The cross sections for ^{41}K and ^{41}Ca were largest for the ^{18}O + ^{26}Mg reaction, and next strongest in the ^{16}O + ^{27}Al and ^{19}F + ^{24}Mg reactions. The reaction mechanism is envisaged as one in which the formation of a compound nucleus with very high angular momentum (at 40-MeV bombarding energy the grazing angular momentum is $\sim 25\hbar$) is followed by emission of light particles (n, p, α)—often with γ emission competing—until the bound levels of the final nucleus are reached. At bombarding energies of

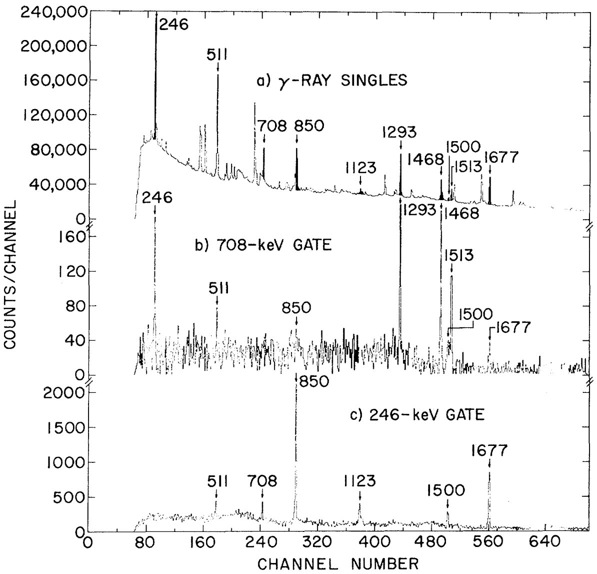

FIG. 1. Portions of 2048-channel Ge(Li) spectra observed for the $^{18}O + ^{26}Mg$ reaction with $E(^{18}O) = 36$ MeV. Transition energies are in keV. Shaded peaks in (a) are assigned to ^{41}K.

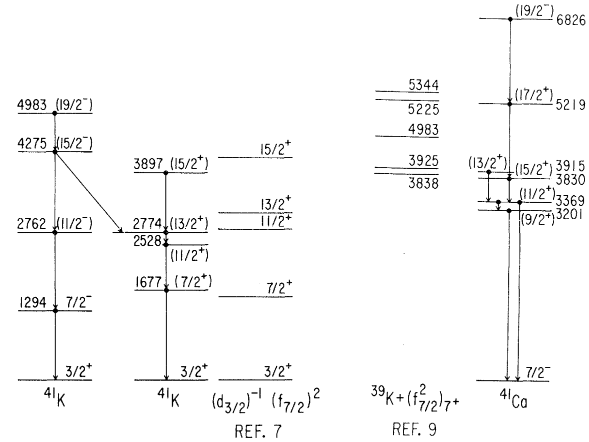

FIG. 2. Decay schemes for ^{41}K and ^{41}Ca as deduced from the present work. The spin and parity assignments, enclosed in parentheses, are based partly on the heavy-ion reaction mechanism and therefore are preliminary. Also shown are theoretical predictions of Beckstrand and Shera (Ref. 7) for ^{41}K and experimental results of Thorn *et al.* (Ref. 9) for ^{41}Ca.

40–45 MeV, three-nucleon emission or αp and αn emissions are favored. A partial 90° singles spectrum and two coincidence spectra obtained from the $^{18}O + ^{26}Mg$ reaction are shown as an example in Fig. 1. The coincidence spectra were crucial to the grouping of γ rays into decay schemes. All the γ rays labeled by their energies (in keV) in Fig. 1(a) are time correlated. In addition, their excitation functions in the $^{18}O + ^{26}Mg$ reaction have nearly identical bell shapes, maximum ~40 MeV, width ~25 MeV. The assignment of these γ rays to ^{41}K was considered definite when comparison to the $^{40}K(n, \gamma)^{41}K$ work of Endt and Van der Leun[6] and Beckstrand and Shera[7] revealed 246-, 850-, 1293-, 1468-, and 1677-keV γ rays in common. The final decay scheme is shown in Fig. 2.

For ^{41}Ca, the excitation functions for $^{18}O + ^{26}Mg$ were also characteristic of three-nucleon emission. Similar γ-γ coincidence information was obtained, and again prior information was used to assign the γ rays to a particular nucleus. The final decay scheme, also shown in Fig. 2, was identified with that of ^{41}Ca because the γ-ray decay modes of the 3201- and 3369-keV states had already been determined.[8] We were also guided by the $^{39}K(\alpha, d)^{41}Ca$ data of Thorn *et al.*[9] which picked out five high-spin states having deuteron angular distributions expected for $(d_{3/2})^{-1} \otimes (f_{7/2})_{7^+}^2$. These states, with excitation energies[9] measured to ±10 keV, are also shown in Fig. 2.

The spin and parity assignments in parenthesis in Table I and Fig. 2 are based mainly on the angular distribution and lifetime measurements. As expected, the γ-ray angular distributions, fitted by the functional form $W(\theta) = A_0[1 + a_2P_2(\theta) + a_4P_4(\theta)]$, were consistent with transitions from highly aligned states with $J_i = J_f + L$. The required degree of alignment was consistent for all transitions, with a slight tendency to increase with the excitation energy of the initial state. The average values of α_K, defined as the ratio of the experimentally observed a_K to that calculated[10] for population of the $m = \pm\frac{1}{2}$ substates only, were 0.65–0.8 and 0.4–0.5 for $K = 2$ and 4, respectively (Table I). The spin and parity assignments are also based on the empirical observation in this and previous work[1,2] that these reactions preferentially populate the yrast levels[1] (the lowest-lying levels of a given J), and thus $J_i \to J_f$ transitions are most likely to have $J_i > J_f$. Aside from the conjectured parities of those levels which decay by dipole radiation, we consider these assignments to have the same degree of confidence as, say, those based on j dependence in a nucleon-transfer reaction; however, it should be emphasized that they are not made

TABLE I. Transitions in ^{41}Ca and ^{41}K observed from ^{26}Mg + ^{18}O (angular distributions) and ^{27}Al + ^{16}O (lifetime measurements).

Transition $E_i \to E_f$ (keV)	E_γ (keV)	J^π_i	J^π_f	Multi-polarity	τ initial level (psec)	Transition Strength (Weisskopf Units)	Angular Distribution Coefficient[a,b] a_2 (%)	a_4 (%)	χ^2
					^{41}Ca				
6826 → 5219	1607.24 ± 0.50	(19/2$^-$)	(17/2$^+$)	E1	> 0.2	< 10^{-3}	-31.3 ± 10.4	4.4 ± 8.7	0.5
5219 → 3830	1389.21 ± 0.25	(17/2$^+$)	(15/2$^+$)	M1	< 2.0	> 0.006	-21.4 ± 14.0	0	0.9
3830 → 3369	460.27 ± 0.10	(15/2$^+$)	11/2$^+$	E2	4500 ± 500	1.02 ± 0.11	26.1 ± 2.5	-11.1 ± 2.9	1.1
3915 → 3369	545.48 ± 0.15	(13/2$^+$)	11/2$^+$	M1	> 0.2	< 1.0	-44.1 ± 6.8	0	0.9
3369 → 3201	168.39 ± 0.10	(11/2$^+$)	(9/2$^+$)	M1	29.6 ± 2.0[c]	0.14 ± 0.01	-27.0 ± 2.6	0	0.7
3369 → 0	3369.24 ± 0.22[d]	(11/2$^+$)	7/2$^-$	M2	29.6 ± 2.0[c]	0.109 ± 0.008	66.7 ± 3.8	26.1 ± 4.4	1.0
3201 → 0	3200.85 ± 0.20	(9/2$^+$)	7/2$^-$	E1	(27±24)x10^{-3}[e]	> 4.2x10^{-4}	-34.4 ± 2.6	0	2.4
					^{41}K				
4983 → 4275	708.46 ± 0.15	(19/2$^-$)	(15/2$^-$)	E2	140 ± 20	3.8 ± 0.5	29.0 ± 1.0	-12.3 ± 1.1	0.2
4275 → 2762	1512.78 ± 0.15	(15/2$^-$)	(11/2$^-$)	E2	f	--	22.7 ± 2.0	- 5.6 ± 2.3	0.7
2762 → 1294	1468.15 ± 0.15	(11/2$^-$)	7/2$^-$	E2	--	--	19.5 ± 1.2	- 8.9 ± 1.2	3.4
1294 → 0	1293.58 ± 0.12	7/2$^-$	3/2$^+$	M2	(10.4±0.3)x10^{3}[g]	0.098 ± 0.003	26.5 ± 1.0	- 8.8 ± 1.0	4.2
4275 → 2774	1500.09 ± 0.25	(15/2$^-$)	(13/2$^+$)	E1	f	--	-37.2 ± 2.8	0	5.9
3897 → 2774	1122.99 ± 0.50	(15/2$^+$)	(13/2$^+$)	M1	> 0.2	< 0.11	-20.2 ± 4.1	0	1.1
2774 → 2528	246.53 ± 0.07	(13/2$^+$)	(11/2$^+$)	M1	67.8 ± 2.0	0.031 ± 0.001	-26.7 ± 0.6	0	3.9
2528 → 1677	850.43 ± 0.10	(11/2$^+$)	7/2$^+$	E2	199.0 ± 10.0	1.07 ± 0.05	27.9 ± 0.8	- 8.8 ± 0.8	1.1
1677 → 0	1677.22 ± 0.20	(7/2$^+$)	3/2$^+$	E2	13.7 ± 6.2	0.52 $^{+0.43}_{-0.15}$	21.5 ± 1.0	- 6.3 ± 1.1	7.4

[a]A zero entry for a_4 means $W(\theta) = A_0[1 + a_2 P_2(\theta)]$ was assumed. The measured a_4 was consistent with zero in these cases.

[b]The theoretical coefficients for (a) full alignment, (b) the experimentally observed ratio of side feeding to cascade feeding, and (c) the indicated pure multipolarities are in the range $a_2 = +(0.42-0.45)$, $a_4 = -(0.18-0.24)$ for quadrupole transitions, and $a_2 = -(0.29-0.31)$ for dipole transitions.

[c]The branching ratio for the 3369-keV level is (62 ±2)% for the 168-keV γ ray and (38 ±2)% for the 3369-keV γ ray.

[d]This energy is computed as the sum of the energies of the cascade transitions (168 and 3201 keV).

[e]Ref. 8.

[f]τ not measured. The branching ratio for the 4275-keV level is (80 ±3)% for the 1513-keV γ ray and (20 ±3)% for the 1500-keV γ ray.

[g]Ref. 6.

via rigorous methods and thus need verification.

It seems probable that the even-parity states of Fig. 2 are predominantly 1h-2p (one hole, two particle) [mainly $(d_{3/2})^{-1}(f_{7/2})^2$] and the odd-parity states, other than the ^{41}Ca ground state, are 2h-3p [mainly $(d_{3/2})^{-2}(f_{7/2})^3$]. As is shown, the spectrum of even-parity states in ^{41}K agrees well with the $\pi(d_{3/2})^{-1}\nu(f_{7/2})^2$ calculation of Beckstrand and Shera.[7] Likewise, in ^{41}Ca we identify our new states at 3830, 3915, and 5219 keV with the $(d_{3/2})^{-1} \otimes [(f_{7/2})^2]_{7^+}$ states reported at 3838, 3925, and 5225 keV, respectively, by Thorn *et al.*[9] Incidentally, these authors considered the 5225-keV level as the most probable candidate for the $\frac{17}{2}^+$ member of the $(d_{3/2})^- \otimes [(f_{7/2})^2]_{7^+}$ quartet.

The high-spin odd-parity yrast spectrum of ^{41}K in Fig. 2 bears a strong resemblance to that of ^{43}Sc as would be expected for a $(d_{3/2})^{-2}(f_{7/2})^3$ configuration. The *possible* $\frac{19}{2}^-$ state of ^{41}Ca at 6826 keV would presumably also be of the same configuration.

The angular distributions were all in fair agreement with those expected (footnote b of Table I) for the lowest allowed multipolarity and the above-mentioned α_K's except for the ^{41}Ca 3369 → 0 transition which had too large an a_2 coefficient and an a_4 coefficient of the wrong sign. This indicates an $M2$-$E3$ mixture, which was quantitatively determined using the angular distribution of the 3369 → 3201 dipole transition to establish the alignment. The result for the mixing ratio was $x(E3/M2) = -(0.31 \pm 0.10)$ or $-2.75^{+1.0}_{-0.6}$. These two solutions correspond to $E3$ strengths of 4.1 ± 2.3 and 39 ± 4 W.u. (Weisskopf units), respectively. In an extreme weak-coupling model, with an $f_{7/2}$ neutron coupled to the 3737-keV 3^- state and to the 0^+ ground state of ^{40}Ca to give, respectively, the ^{41}Ca 3369-keV level and the ^{41}Ca ground state, the predicted transition strength is 12/56 times that for the $E3$ core transition. From the measured strength of the ^{40}Ca transition, 31 W.u.,[11] we expect 6.6 W.u. for the $3369 \rightarrow 0$ transition. Since this should be a rough upper limit to the $\frac{11}{2}^+ \rightarrow \frac{7}{2}^-$ $E3$ rate, the solution $x = -(0.31 \pm 0.10)$ and $B(E3) = 4.1 \pm 2.3$ W.u. appears the most probable. The $M2$ strength is then 0.10 ± 0.01 W.u.

Results from heavy-ion–induced compound-nucleus reactions, exemplified here by data for ^{41}K and ^{41}Ca, will obviously be a powerful stimulus for detailed model predictions. For instance, the small $E2$ strengths encountered here are most intriguing (the average of the four values listed in Table I is only about 1 W.u.). It will be interesting to see how well these $E2$ strengths can be understood.

A limitation on the use of these reactions, for the present, is the difficulty of obtaining rigorous spin assignments without time-consuming γ-γ directional correlation measurements. Possibly one could obtain quite reliable assignments by coupling these studies with a theoretical or phenomenological description of the reaction mechanism. Thus, more information on the reaction mechanism is important, both for its own sake and for the aid it would provide to nuclear-spectroscopy studies.

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Excitation of Giant Resonances in ^{58}Ni via Inelastic Scattering of Polarized Protons*

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Measurements of the analyzing power and the differential cross section in the nuclear continuum for the reaction ^{58}Ni(p,p') initiated by 60-MeV polarized protons provide strong evidence for a quadrupole ($E2$) interpretation for the giant resonance at $E_x \approx 63/A^{1/3}$ MeV. A resonance approximately 3 MeV lower in excitation energy has also been observed.

Experiments on the inelastic scattering of electrons,[1-3] protons,[4-7] and ^{3}He particles[8,9] have established the existence of a giant resonance in the nuclear continuum, which is consistently 2–3 MeV lower in excitation energy than the well-known giant dipole ($E1$) resonance.[10] The observed excitation energy, $E_x \approx 63/A^{1/3}$ MeV, agrees well with predictions[11] for an isoscalar giant quadrupole ($E2$) resonance.

Angular distributions for the resonance from electron scattering are consistent with either an $E2$ excitation or an $E0$ giant monopole excitation.[1-3] Angular distributions from proton scattering were initially interpreted as evidence for an $E2$