RECENT RESULTS FROM GAMMASPHERE*

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Three examples of recent nuclear structure studies using Gammasphere are discussed in this paper. (1) A rotational band has been identified in ^{108}Cd. Its moment of inertia and quadrupole moment indicate that this band has a shape with an axis ratio larger than 1.8:1. (2) Possible "Jacobi" shape transitions at high spin were investigated from studies of the continuum gamma rays on a number of nuclei. (3) Population of high-spin states in neutron-rich nuclei were studied in target fragmentation reactions. States with spin up to 6–12$\hbar$ were observed in a wide range of nuclei.

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1. Very extended shapes in ^{108}Cd

Nuclei with superdeformed shapes have been observed in a number of mass regions. Recent calculations by Chasman [1] predict that nuclei with mass near 110 can have prolate deformations with a major-to-minor axis ratio larger than 2:1. In particular, very extended shapes, were found for ^{106}Cd and ^{108}Cd, and these shapes become yrast above $I \sim 60$. Moreover, the barrier against fission is calculated to be larger than 9 MeV at $I = 60$ and larger than 6 MeV at $I = 70$, implying that the nucleus is stable against fission and that it should be possible to observe the discrete gamma-ray decay of states in this deformed minimum over a range of angular momentum. Encouraged by these results, we performed an experiment to search for such shapes in ^{108}Cd. High-spin states in ^{108}Cd were populated in the ^{64}Ni(^{48}Ca,4n) reaction with a 207 MeV beam produced by ATLAS at Argonne National

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Laboratory. Two stacked foils of $500\mu/\mathrm{cm}^2$ ^{64}Ni were used as the target. Gamma rays were detected with the Gammasphere array which for this experiment comprised 101 detector modules. A total of 3×10^9 events, with at least six clean gamma rays, were collected. The offline data analysis was facilitated greatly by the program Blue [2]. This program produced an indexed database containing the energies and angles of all events. From this database, gated spectra of any coincidence fold can be produced in minutes.

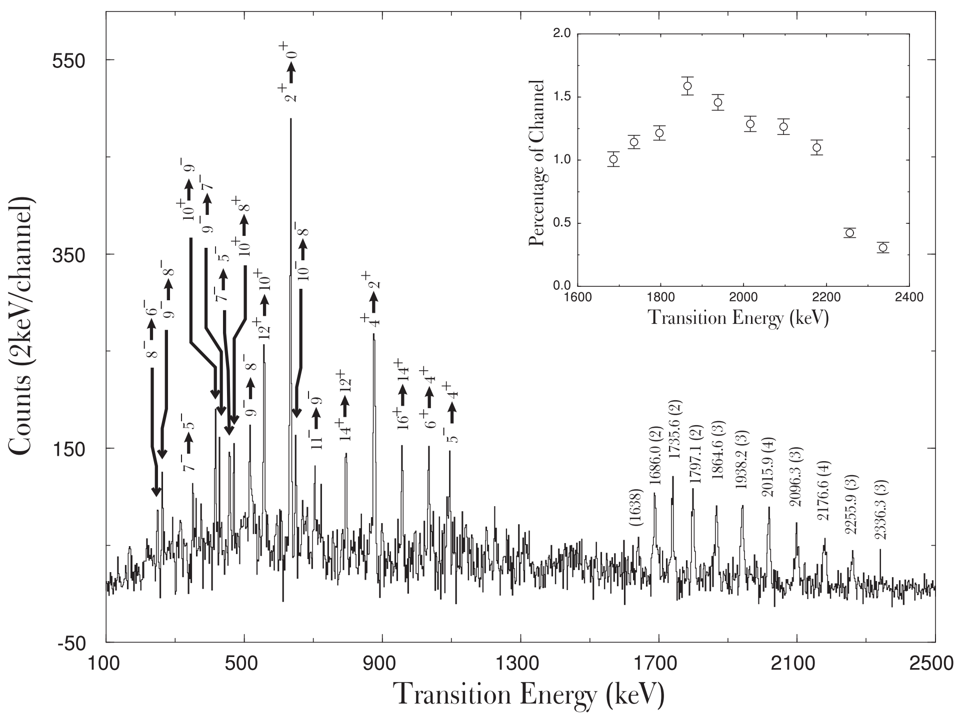

Fig. 1. Spectrum formed from a summation of all triple-gated combinations on in-band transitions for events with fold$\geq$4. Low-lying transitions in ^{108}Cd are marked with the angular momenta and parities of the initial and final states. The in-band transitions are marked with their measured transition energies and uncertainties (in keV). The inset shows the relative intensity (as a percentage of the intensity of the ^{108}Cd channel) of the in-band transitions.

As shown in figure 1, a rotational sequence of gamma rays was found. This sequence is in coincidence with known transitions of ^{108}Cd and its intensity is estimated to be 0.014 of the total yield of ^{108}Cd. The angular distributions of the gamma rays are consistent with stretched quadrupole transitions and the in-band transitions are assumed to be electric in nature. A plot the dynamic moment of inertia, $J^{(2)}$, is presented in figure 2. To compare with nuclei with different mass, the moment of inertia was scaled by $A^{5/3}/72$ the value for a rigid sphere. The values of moment of inertia indicate that this band has a superdeformed shape with an axis ratio of ~2:1, similar to that of ^{152}Dy. The rise at low rotational frequency probably indicates a change in the intrinsic configuration. Assuming the kinematic moment of inertia equals the dynamic moment of inertia in the flat region of $J^{(2)}$, we estimate that the lowest state in the band has angular momentum, $I \simeq 40$ and the highest has $I \simeq 60$. Note, the highest angular momentum low-lying discrete state observed in coincidence with this band is 16^+. Thus, no discrete decay pathway was observed between the angular momentum region from 40 to 16.

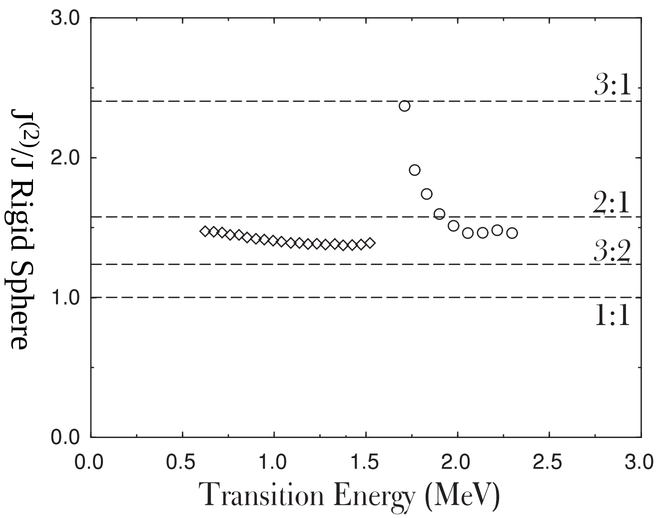

Fig. 2. Dynamic moment of inertia $J^{(2)}$, for the new band in ^{108}Cd (circle) and the yrast SD band in ^{152}Dy (diamond), scaled by the values for a rigid sphere. Also shown with the dashed lines are the expected values for rigid prolate ellipsoids with major-to-minor axis ratios of 1, 3/2, 2, and 3.

In an effort to further define the deformation of this band, limits on the transition quadrupole moment were deduced by measuring the residual Doppler shifts of gamma rays emitted while the recoil nucleus is slowing down in the thin target. A lower limit of 9.5 eb was established for the transition quadrupole moment which corresponds to a shape with axis ratio larger that 1.8:1.

2. Search for the Jacobi shape transition

Sir Isaac Newton pointed out that a rotating self gravitating liquid has an oblate shape with the symmetry axis along the direction of the angular momentum. In 1834, theoretical studies by C.G. Jacobi showed that above a certain critical rotational frequency, the rotating liquid changes to a triaxial shape rotating about its shortest axis. Nuclear liquid drop model calculations, including Coulomb and surface tension forces, have shown this "Jacobi" transition can also happen in nuclei. Figure 3 shows results from several such calculations [3, 4]. For nuclei with mass less than ~160, there is a critical angular momentum $L_{\rm I}$ at which the Jacobi shape transition occurs, and a higher fission limit, $L_{\rm II}$. Nuclei with mass greater than ~ 160 fission directly from oblate shapes without going through the Jacobi transition. The Jacobi shape exists in the high angular momentum region where discrete gamma ray transitions are usually not observed. Therefore, it is necessary to study the continuum gamma rays.

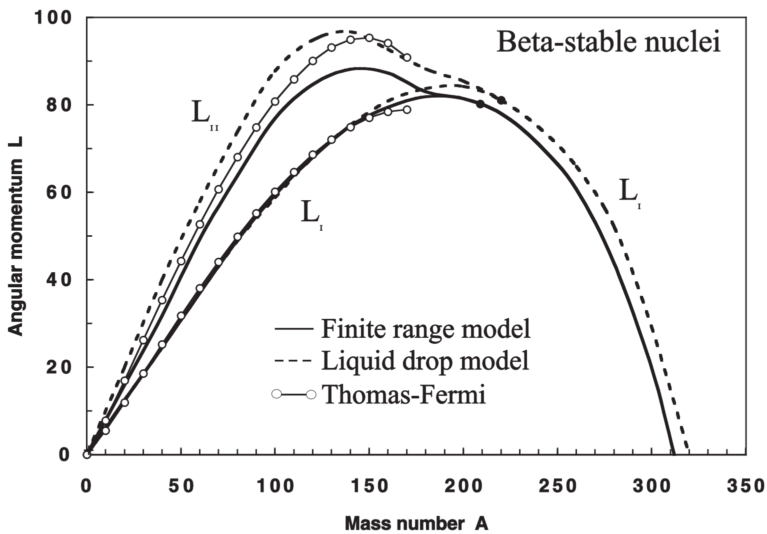

Fig. 3. Angular momenta at which Jacobi shape transition and fission occurs, respectively, calculated using finite range model, liquid drop model and Thomas–Fermi model.

We have studied reactions induced by a ^{48}Ca beam on thin targets of ^{50}Ti, ^{64}Ni, ^{96}Zr and ^{124}Sn, which produce compound nuclei ^{98}Mo, ^{112}Cd, ^{144}Nd and ^{172}Yb, respectively. Gamma rays were detected in the Gammasphere array, at Argonne National Laboratory, with the "hevimet" shields for BGOs removed to improve the efficiency of gamma-ray multiplicity detection. Gamma-ray spectra associated with each K-value, the number of Ge-BGO modules hit by gamma rays in each event, were obtained from the data. The spectra were then "unfolded" by removing the Compton contribution and corrected for the peak efficiency. These spectra contain information of the evolution of the gamma-ray energy as function of spin. Subtracting the spectra with $K-1$ from the spectra with K, gives the energy distribution

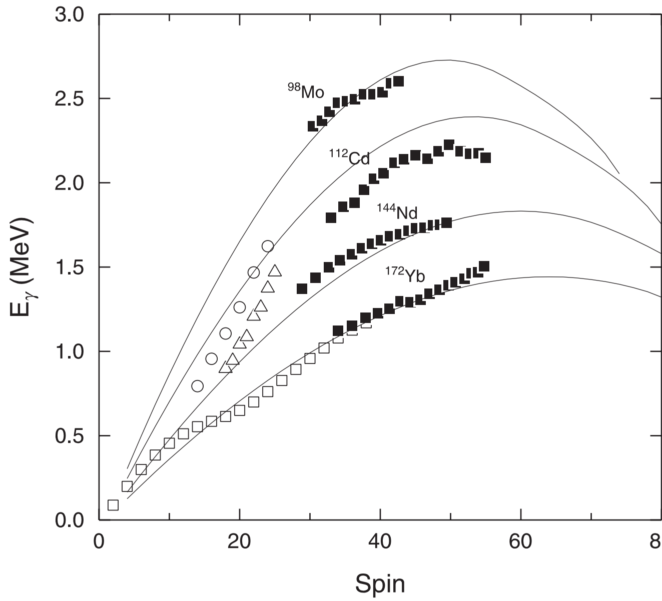

Fig. 4. Gamma-ray energies from continuum (solid squares), discrete lines (open symbols) and calculations (lines) [5] as a function of spin for compound nuclei ^{98}Mo, ^{112}Cd, ^{144}Nd and ^{172}Yb.

of the highest spin gamma ray associated with K. To determine the average spin value for each of the K-value, we first convert the K-value to gamma-ray multiplicity using the multiplicity response of Gammasphere. We then used the gamma-ray multipolarity distribution, from the measured angular distribution, to determine the spin from the multiplicity. Figure 4 shows the measured gamma ray energy as a function of spin compared with results of calculations. A linear relation between the energy and spin would indicate a constant moment of inertia. The decrease of the gamma-ray energy at high-spin observed in Cd indicates an increase in moment of inertia which may be due to the predicted Jacobi shape transition. However, while these data appear consistent with a Jacobi shape transition, other effects such as shell structure and angular momentum alignment can not be ruled out at this time.

3. Population of high-spin states in neutron-rich nuclei

Fragmentation of fast beams is a very effective method for the production of neutron-rich nuclei. A number of nuclear structure studies have been carried out either by using these nuclei as secondary beams or by observing their decay. A large amount of information has been obtained such as evidence for new shell closures and the spatial distributions of neutron orbitals. We are interested in the high-spin properties of the neutron-rich nuclei. To determine the yield of the high-spin states in nuclei produced in the fragmentation reaction, we have measured the prompt gamma rays emitted from these reactions. We used a 30 MeV/A beam of ^{13}C on a thick target of ^{51}V. This reaction is the kinematic inverse of the typical beam fragmentation reaction where a heavy beam bombards targets of lighter nuclei. In our reaction, the slow moving target fragments stop quickly in the thick target and most of the gamma rays will be emitted after stopping and be observed without Doppler broadening. The experiment was carried out using the Gammasphere at LBNL without the hevimet shields on the BGO.

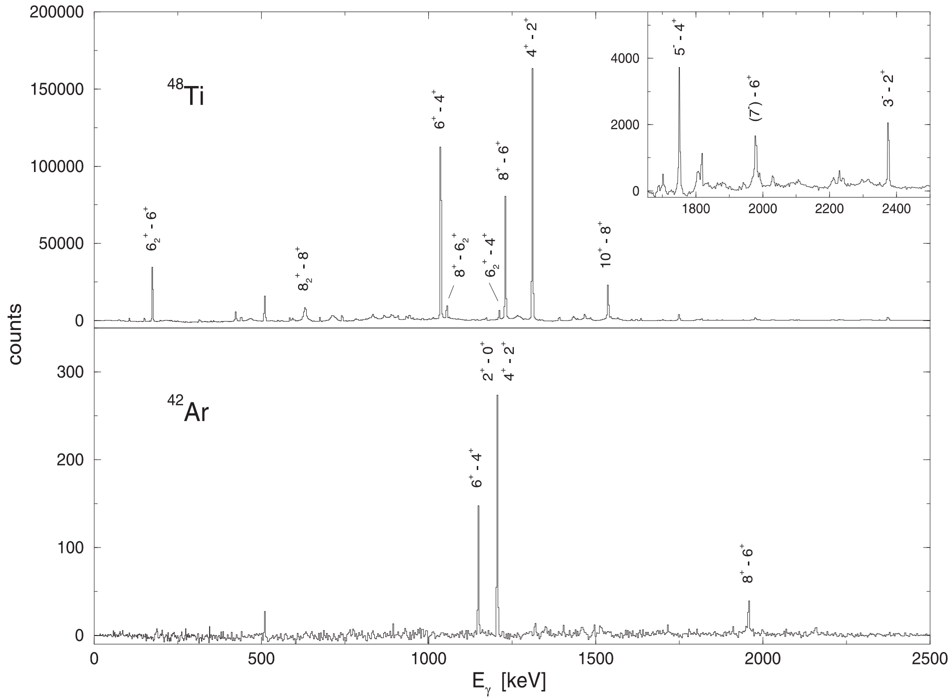

Fig. 5. Single gated spectrum of ^{48}Ti and double gated spectrum of ^{42}Ar obtained using a 30 MeV/A beam of ^{13}C on a thick target of ^{51}V.

Figure 5 shows a typical single- and a double-gated spectrum. From these spectra, we have identified about 70 nuclei from ^{31}Si to ^{56}Fe and the most neutron-rich nuclei observed are along the line connecting ^{40}Cl and ^{52}Ti. We have observed sharp discrete lines from states with spins in the range of 6 to 12. Using the coincidence fold of the gamma rays, we obtained an independent measure of the total angular momentum input of the reaction

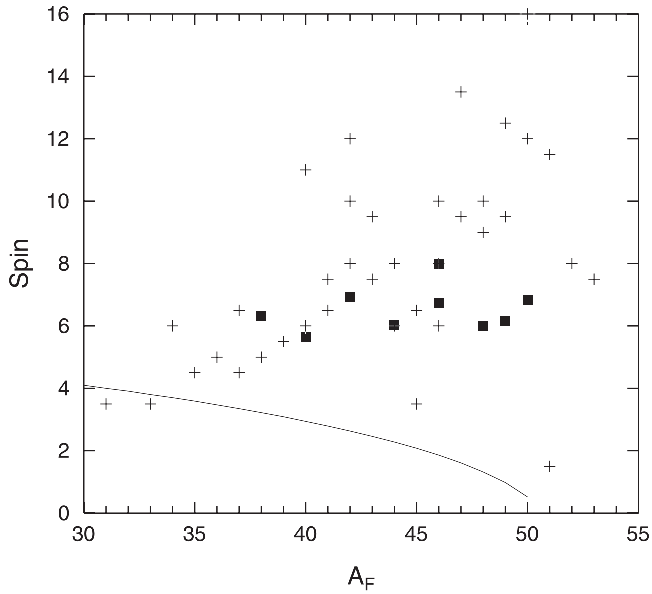

Fig. 6. Highest spin discrete transition (crosses) and the average spin from coincidence fold (squares) observed from the $^{13}C+^{51}V$ reactions as a function of the fragment mass. The line indicates the results of a fragmentation model calculation [6].

channel. Figure 6 shows the highest spin discrete transition observed and the estimation of the average angular momentum from the coincidence fold. The results show a trend of higher spins for heavier mass fragments which is opposite to the results of fragmentation model calculation [6]. This may indicate that other reaction mechanism contribute at this beam energy of 30 MeV/A, which transfer additional angular momentum to the fragments.

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