Nuclear Shapes at High Angular Momentum

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Multiplicities as a function of γ-ray energy have been measured for continuum γ-ray spectra produced in argon- and calcium-induced reactions. A peak sometimes occurs in the multiplicity spectrum, indicating a correlation between γ-ray energy and multiplicity (spin). This correlation can be explained by rotational motion of the nucleus, suggesting basically prolate nuclear shapes. Absence of structure in the multiplicity spectrum is interpreted to indicate noncollective motion, and hence spherical or oblate shapes.

The study of nuclear structure at angular momenta above $30\hbar$ presently requires measurements of the continuum γ-ray spectrum. Previous studies[1] have shown this continnum to be composed usually of a lower-energy stretched-$E2$ bump and a higher-energy tail interpreted as a statistical cascade. Also some measurements[2] of the total delay time to reach the ground-state band imply the occurrence of collective γ transitions during the de-excitation process. The aim of the present work is to learn more about nuclear structure at these high angular momenta. The method developed consists of studying the number of γ rays (multiplicity) associated with each transition energy in the continuum γ-ray spectrum. There is no restriction on the reaction channel, so that the whole range of angular momenta produced in the reaction is considered. Furthermore, the evolution of the multiplicity spectrum can be studied as the compound-nucleus angular momentum is increased with increasing projectile energy. If there is some relationship between the γ-ray energy and the angular momentum, like that implied by rotational motion, it will be reflected as structure in the multiplicity spectrum. Conversely, such structure (or the absence of structure) may tell us about the dynamics involved in the nuclear motion, which in turn can be related to nuclear shapes.

In order to recognize possible systematic features, a number of targets, ranging from ^{12}C to ^{174}Yb, have been bombarded at the Lawrence Berkeley Laboratory 88-in. cyclotron and SuperHILAC with either ^{40}Ar or ^{48}Ca projectiles which induce high angular momentum in the compound nucleus. The targets were either self-supporting or evaporated on lead, but in either case the continuum γ-ray spectrum is expected to be Doppler shifted due to its very short lifetime. A set of six 3 in.×in. NaI counters (halo) was placed symmetrically around the beam axis, upstream from the target in order to minimize the number of neutrons detected. A seventh NaI detector was located at 40° to the beam direction, and 60 cm away from the target in order to discriminate against neutrons by time of flight. The unfolded spectra from the seventh detector in coincidence with one to six of the halo counters were used to obtain the multiplicity spectrum. In the following, three examples will be discussed as representative of the characteristic features observed.

The system $^{124}Sn + ^{40}Ar$ leads to the compound nucleus ^{164}Er and the possible residual nuclei are known to be rotational at angular momenta up to around $20\hbar$. The multiplicity spectra are shown in Fig. 1(a) for 158-, 170-, and 185-MeV bombarding energies. The γ-ray spectrum (sum of the six unfolded spectra) is also shown for the 185-MeV energy. For all the bombarding energies, the multiplicity has a peak at lower γ-ray energies, and then drops to a roughly constant value for the statistical part of the spectrum. This latter value is expected to be near the average multiplicity for all the reaction channels as the statistical γ rays are thought to occur at all angular momenta. If some kind of rotational behabior is involved in the bump region, the spin, and hence the multiplicity, will increase with the γ-ray transition energy ($I \propto E_\gamma$) until the highest angular momentum is reached. This could give rise to the multiplicity peaks observed, and indeed, not only does the height of the whole multiplicity spectrum increase as more angular momentum is brought in, but also the upper edge of the peak moves toward higher energies in agreement with the rotational hypothesis. Another important feature is indicated by the two upper multiplicity curves in Fig. 1(a), which are significantly closer to each other than the two lower, though they correspond to almost the same increase in angular momentum. This suggests the onset of fission or deep-inelastic events (for which the multiplicity is lower) at the highest angular momenta.

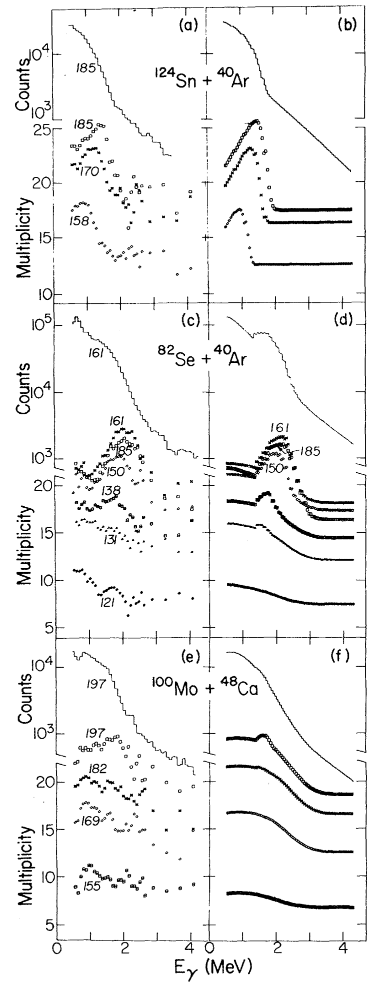

FIG. 1. Observed and calculated multiplicity spectra for the systems and bombarding energies indicated. One γ-ray spectrum is also compared for each system. Note that the order of the curves on the right side of the figure (calculated) is in all cases the same as that for the experimental curves on the left side.

An attempt to explain the data more quantitatively has been made by calculating the energy and multiplicity spectra. The separation distance, R, between nuclei when they being to interact[3] is taken to be $R = 1.16(A_1^{1/3} + A_2^{1/3} + 2)$ fm. This leads to a maximum angular momentum, $l_{\max} = 0.219R \times [\mu(E_{\text{c.m.}} - E_{\text{CB}})]^{1/2}$, where $E_{\text{c.m.}}$ is the center-of-mass bombarding energy, E_{CB} is the Coulomb barrier, and μ is the reduced mass. However, the maximum angular momentum in the evaporation residue prior to γ-ray emission, $I_{\max}$, is lower because (1) not all the collisions at this separation lead to fusion, and (2) the evaporated particles have removed some angular momentum. In this work, we have found empirically that $I_{\max} = 0.78\, l_{\max}$, and have used this value in all cases. Also, when $I_{\max}$ exceeds a certain value, I_{er}, then an evaporation residue is not formed, and the system either fissions or undergoes a deep-inelastic scattering. We have rounded these values of $I_{\max}$ and I_{er} somewhat, using $T_I(l) = [1 + \exp((l - I)/\Delta I)]^{-1}$, with $\Delta I = 0.05I$, to give

$$\sigma_{er} = \pi\lambda\!\!\!^{-2} \sum_l (2l+1) T_{I_{er}}(l) T_{I_{\max}}(l),$$

$$\sigma_{fd} = \pi\lambda\!\!\!^{-2} \sum_l (2l+1) T_{I_{\max}}(l) - \sigma_{er},$$

where σ_{fd} includes both fission and deep-inelastic events. The value of I_{er} is obtained by fitting the data.

Two types of γ rays are assumed to de-excite the evaporation residues: rotational and statistical. A cascade of $I/2$ rotational transitions is assumed from spin I to spin 0, whose energies are $E_\gamma = (\hbar^2/2\mathscr{I})(4I - 2)$, where the moment of inertia $\mathscr{I}$ is to be determined from the data. Four statistical γ rays are assumed independent of spin with an energy spectrum given by $N(E_\gamma) = E_\gamma^{1/2} \exp(-E_\gamma/T)$, where values of T from 0.8 to 1 MeV are required to fit the high-energy tails of all the spectra. For the fission and deep-inelastic events we use a multiplicity of 10 (derived from the ^{40}Ar + ^{174}Yb data which lead mostly to such events) and, for simplicity, take the shape of the statistical spectrum. We have also included a transfer cross section of 100 mb, having a multiplicity of 6 and also the statistical spectrum shape.

The calculation for the ^{124}Sn + ^{40}Ar case [Fig. 1b)] reproduces the experimental features remarkably well, considering that no adjustment is allowed except that of I_{er} and $\mathscr{I}$. The I_{er} value obtained by fitting the relative height of the upper two multiplicity curves ($60\hbar$) is reasonably consistent with the angular-momentum value corresponding to an upper limit for the fusion of the two incoming nuclei (calculated before particle emission) based[4] on the fission barrier ($67\hbar$), and also that deduced[4] from other experiments ($65\hbar$). The moment-of-inertia value corresponds to 95% of $\mathscr{I}$ for a rigid sphere, also in excellent agreement with previous experience. In general, calculations without including the 100 mb of transfer reactions give equally good fits to the data but require small systematic changes in $I_{\max}$ and $\mathscr{I}$. Nevertheless, these transfer reactions will be included as this seems more realistic to us.

The ^{82}Se + ^{40}Ar case, which leads to Te nuclei near the $Z = 50$ closed shell, is quite different

[Fig. 1(c)]. There is no significant structure in the multiplicity spectrum for the lowest two bombarding energies. A multiplicity peak only begins to appear at 138 MeV and then develops for higher bombarding energies, suggesting the onset of rotational motion only at the higher angular momenta. The lower multiplicites at 185 MeV are due to the onset of fission and deep-inelastic events. The nonstructured multiplicity spectra observed at low ^{40}Ar energies correspond to a cascade where there is no strong correlation between the transition energy and the spin. We have tried to reproduce this feature in the calculation by assuming that up to a certain spin, I_1, the γ-ray spectrum is given by $N(E_\gamma)=E_\gamma \exp(-E_\gamma^2/\sigma^2)$, with $\sigma=1.13$ MeV independent of the spin value of the emitting state. This noncorrelated cascade may contain other than pure stretched-$E2$ transitions, so that the multiplicity is $(I/2)(1+P)$, where P is fitted to the data. Between I_1 and another spin I_2, there is a competition between this cascade and a rotational cascade, and above I_2 the cascade is rotational. Figure 1(d) shows that the characteristic features are reproduced, with the parameter values $I_1=27\hbar$, $I_2=38\hbar$, $I_{cr}=53\hbar$, $\mathcal{I}=0.85\,\mathcal{I}_{\rm rig}$, and $P=0.17$. The difference between the calculated and experimental curves may be due partly to errors in the bombarding energies, which affect the $l_{\rm max}$ values (especially at very low bombarding energies). In the ^{100}Mo $+{}^{48}$Ca case, which leads to nuclei in the $N=82$ closed-shell region, it is immediately apparent that the absence of structure remains up to high spins; indeed, the rotational competition starts only around spin 50.

Since almost any type of collective motion would lead to a strong correlation between transition energy and spin, the noncorrelated cascade very likely indicates noncollective motion. Noncollective high-spin states are expected to lie lowest in oblate or spherical nuclei, since the largest moment of inertia in these cases corresponds to rotation (noncollective) around the symmetry axis. On the other hand, collective high-spin states are expected to be lowest in basically prolate (including somewhat triaxial) nuclei, since in this case the largest moment of inertia corresponds to rotation (collective) around an axis perpendicular to the symmetry axis. Thus the interpretation of the ^{82}Se$+{}^{40}$Ar$\rightarrow$Te data would be that the residual Te nuclei are nearly spherical or oblate at low spins, and then between spins 27 and 38 deform to a basically prolate shape. This change seems to occur only around $50\hbar$ for the ^{100}Mo$+{}^{48}$Ca$\rightarrow$Sm system. Thus these multiplicity spectra appear to contain rather detailed information about the nuclear shape at high spins.

Andersson *et al.*[5] have calculated potential-energy surfaces over the full (β,γ) plane for various angular momenta in the nuclei ^{160}Er, ^{118}Te, and ^{144}Sm. They used a cranked modified-oscillator potential with a Strutinsky-type normalization to the liquid drop. It is interesting to notice that the shapes they found are in agreement with our results. The nucleus ^{160}Er is found to be prolate up to spin $60\hbar$ which represents the upper limit reached in our experiment. Starting from a prolate shape at very low angular momentum, ^{118}Te is already oblate at $I=10\hbar$ and stays oblate up to spin $30\hbar$, where it becomes triaxial and is well deformed at $I=40\hbar$. The spherical nucleus ^{144}Sm starts deforming only around spin $40\hbar$ to $50\hbar$. This agreement with our conclusions is remarkable, but may be accidental.

This work has shown that from study of the multiplicity spectra as a function of γ-ray transition energy, one can learn about the nuclear shape and and dynamics at spins up to 60. Simple calculations based on plausible assumptions about the motion of the nucleus are found to reproduce the main features observed. In particular, we are able to recognize rotational motion as a characteristic peak in the multiplicity spectrum, to determine the spin regions where it occurs, and to deduce the moment of inertia of the nucleus in these regions.

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Electron Scattering from the Octupole Band in ^{238}U

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A simple model for nuclear surface vibrations in permanently deformed nuclei does well in reporducing electron scattering cross sections of rotational levels built on a $K^{\pi} = 0^-$ intrinsic octupole vibration in ^{238}U.

Among the normal modes of nuclei with large permanent deformation, one expects to find a series of states corresponding to rotations built upon the $K = 0, 1, 2, 3$ components of the one-phonon octupole vibration. In ^{238}U, the group of levels 1^- (0.680 MeV), 3^- (0.732 MeV), 5^- (0.827 MeV), 7^- (0.970 MeV), ..., 19^- (2.687 MeV) has been identified as belonging to the $K = 0$ octupole vibration.[1] Measurements[2,3] of $B(E3)$ between the 0.732-MeV state and the ground state are in reasonable agreement with the calculation of Neegard and Vogel[4] and support this interpretation. In this Letter, we report data on the electron excitation of the triplet at 0.680, 0.732, and 0.827 MeV and compare the data with calculations based on a simple model for these states. From this comparisons, we not only find qualitative support for this identification and good agreement between our extracted $B(E3)$ and previous measurements, but we also extract a value for the $B(E5)$ to the 0.827-MeV level.

This work was performed as part of the current research program being carried out at the Massachusetts Institute of Technology–Bates 400-MeV linear electron accelerator in single-arm electron scattering on strongly deformed nuclei. The data were taken at scattering angles of 60° and 90° with incident beam energies from 90 to 300 MeV. The targets were isotopically pure ($\gtrsim 99\%$ ^{238}U) metal foils of 10.5 and 27.1 mg/cm^2 thickness. The energy-loss spectrometer system at Bates was used to obtain resolution of $\Delta E/E \simeq 1.5 \times 10^{-4}$. These data were taken on a multiwire proportional chamber using a delay-line timing technique described in detail elsewhere.[5] A typical ^{238}U spectrum showing the ground-state band as well as the observed members of the octupole band is shown in Fig. 1.

Using the rotational model of the nucleus,[6] we represent the intrinsic time-dependent excitation as a small-amplitude axially symmetric octupole vibration in the nuclear radius, i.e.,

$$\vec{R}(t) - \vec{\xi}(t) = \vec{R}_0(\theta) - \alpha_{30}(t) Y_{30}(\theta),$$

where $\vec{R}(t)$ is measured from the center of mass of the nucleus and $\vec{\xi}(t)$ is the effective shift of the origin of the octupole deformation necessary to preserve the center of mass. The model is then one in which there is a $K = 0$ octupole surface oscillation about a deformed equilibrium density represented by $\rho(\vec{r})$. Performing a Taylor expansion of the total density in terms of the small parameter α_{30} and including center-of-mass corrections allows us to write the octupole transition

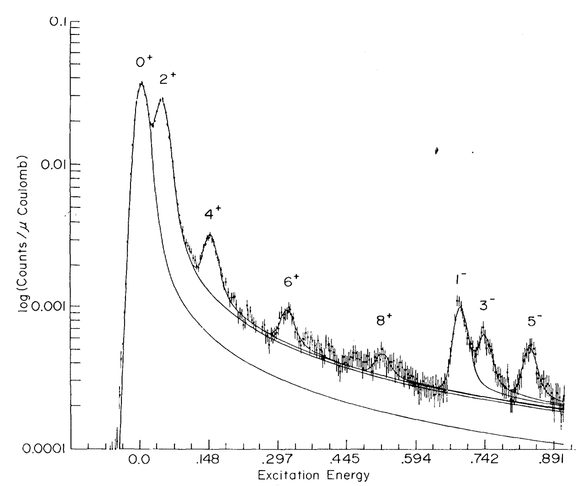

FIG. 1. Spectrum of electrons with incident energy 175.45 MeV scattered from ^{238}U at 90°. The 1^-, 3^-, and 5^- members of a $K = 0$ octupole band can clearly be seen as well as several members of the ground-state band.