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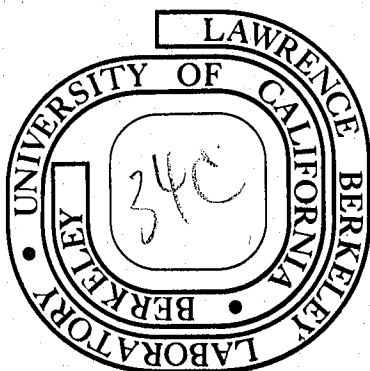
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## NUCLEAR SHAPES AT HIGH ANGULAR MOMENTUM

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### Abstract:

Multiplicities as a function of  $\gamma$ -ray energy have been measured for continuum  $\gamma$ -ray spectra produced in argon- and calcium-induced reactions. A peak sometimes occurs in the multiplicity spectrum, indicating a correlation between  $\gamma$ -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 non-collective motion, and hence spherical or oblate shapes.

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The study of nuclear structure at angular momenta above  $30 \hbar$  presently requires measurements of the continuum  $\gamma$ -ray spectrum. Previous studies<sup>1</sup> have shown this continuum to be composed usually of a lower-energy stretched-E2 bump and a higher-energy tail interpreted as a statistical cascade. Also some measurements<sup>2</sup> of the total delay time to reach the ground-state band imply the occurrence of collective  $\gamma$ -transitions during the deexcitation 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  $\gamma$ -rays (multiplicity) associated with each transition energy in the continuum  $\gamma$ -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  $\gamma$ -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  $^{12}\text{C}$  to  $^{174}\text{Yb}$ , have been bombarded at the LBL 88"-cyclotron and SuperHILAC with either  $^{40}\text{Ar}$  or  $^{48}\text{Ca}$  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  $\gamma$ -ray spectrum is expected to be Doppler shifted due to its

very short lifetime. A set of six 3" x 3" 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  $^{124}\text{Sn} + ^{40}\text{Ar}$  leads to the compound nucleus  $^{164}\text{Er}$  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. 1a for 158, 170, and 185 MeV bombarding energies. The  $\gamma$ -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  $\gamma$ -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  $\gamma$ -rays are thought to occur at all angular momenta. If some kind of rotational behavior is involved in the bump region, the spin, and hence the multiplicity, will increase with the  $\gamma$ -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. 1a, 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.

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 begin to interact<sup>3</sup> is taken to be,  $R = 1.16 (A_1^{1/3} + A_2^{1/3} + 2)$  fm. This leads to a maximum angular momentum,  $\ell_{\max} = 0.219R \sqrt{\mu(E_{\text{cm}} - E_{\text{CB}})}$ , where  $E_{\text{cm}}$  is the center of mass bombarding energy,  $E_{\text{CB}}$  is the Coulomb barrier, and  $\mu$  is the reduced mass. However, the maximum angular momentum in the evaporation residue prior to  $\gamma$ -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  $I_{\max} = 0.78 \ell_{\max}$ , and have used this value in all cases. Also, when  $I_{\max}$  exceeds a certain value,  $I_{\text{er}}$ , 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  $I_{\text{er}}$  somewhat, using  $T_I(\ell) = [1 + \exp((\ell - I)/\Delta I)]^{-1}$  with  $\Delta I = 0.05I$ , to give:  $\sigma_{\text{er}} = \pi \lambda^2 \sum_{\ell} (2\ell+1) T_{I_{\text{er}}}(\ell) T_{I_{\max}}(\ell)$ ; and  $\sigma_{\text{fd}} = \pi \lambda^2 \sum_{\ell} (2\ell+1) T_{I_{\max}}(\ell) - \sigma_{\text{er}}$ , where  $\sigma_{\text{fd}}$  includes both fission and deep-inelastic events. The value of  $I_{\text{er}}$  is obtained by fitting the data.

Two types of gamma rays are assumed to deexcite the evaporation residues: rotational and statistical. A cascade of  $I/2$  rotational transitions is assumed from spin  $I$  to spin 0, whose energies are

$E_\gamma = (\hbar^2/2\mathcal{I})(4I-2)$ , where the moment of inertia  $\mathcal{I}$  is to be determined from the data. Four statistical gamma rays are assumed independent of spin with an energy spectrum given by  $N(E_\gamma) = \sqrt{E_\gamma} \exp(-E_\gamma/T)$ , 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  $^{40}\text{Ar} + ^{174}\text{Yb}$  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  $^{124}\text{Sn} + ^{40}\text{Ar}$  case (Fig. 1b) reproduces the experimental features remarkably well, considering that no adjustment is allowed except that of  $I_{er}$  and  $\mathcal{I}$ . The  $I_{er}$  value obtained by fitting the relative height of the two upper multiplicity curves (60h) 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<sup>4</sup> on the fission barrier (67h), and also that deduced<sup>4</sup> from other experiments (65h). The moment of inertia value corresponds to 95% of  $\mathcal{I}$  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  $\mathcal{I}$ . Nevertheless, these transfer reactions will be included as this seems more realistic to us.



The  $^{82}\text{Se} + ^{40}\text{Ar}$  case, which leads to Te nuclei near the  $Z = 50$  closed shell, is quite different (Fig. 1c). There is no significant structure in the multiplicity spectrum for the two lowest 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 multiplicities at 185 MeV are due to the onset of fission and deep-inelastic events. The non-structured multiplicity spectra observed at low  $^{40}\text{Ar}$  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  $\gamma$ -ray spectrum is given by  $N(E_\gamma) = E_\gamma \exp(-E_\gamma^2/\sigma^2)$ , with  $\sigma = 1.13$  MeV independently of the spin value of the emitting state. This non-correlated cascade may contain other than pure stretched-E2 transitions, so that the multiplicity is  $(I/2)(1+P)$  where  $P$  is fit 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 1d shows that the characteristic features are reproduced, with the parameter values:  $I_1 = 27\hbar$ ,  $I_2 = 38\hbar$ ,  $I_{er} = 53\hbar$ ,  $\mathcal{I} = 0.85 \mathcal{I}_{rig}$  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  $\ell_{max}$  values (especially at very low bombarding energies). In the  $^{100}\text{Mo} + ^{48}\text{Ca}$  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 non-correlated cascade very likely indicates non-collective motion. Non-collective 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 (non-collective) 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  $^{82}\text{Se} + ^{40}\text{Ar} \rightarrow \text{Te}$  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  $^{100}\text{Mo} + ^{48}\text{Ca} \rightarrow \text{Sm}$  system. Thus these multiplicity spectra appear to contain rather detailed information about the nuclear shape at high spins.

Andersson et al<sup>5</sup> have calculated potential energy surfaces over the full  $(\beta, \gamma)$  plane for various angular momenta in the nuclei  $^{160}\text{Er}$ ,  $^{118}\text{Te}$ , and  $^{144}\text{Sm}$ . 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  $^{160}\text{Er}$  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,  $^{118}\text{Te}$  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  $^{144}\text{Sm}$  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  $\gamma$ -ray transition energy, one can learn about the nuclear shape 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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## Figure Caption

Fig. 1 Observed and calculated multiplicity spectra for the systems and bombarding energies indicated. One  $\gamma$ -ray spectrum, is also compared for each system.

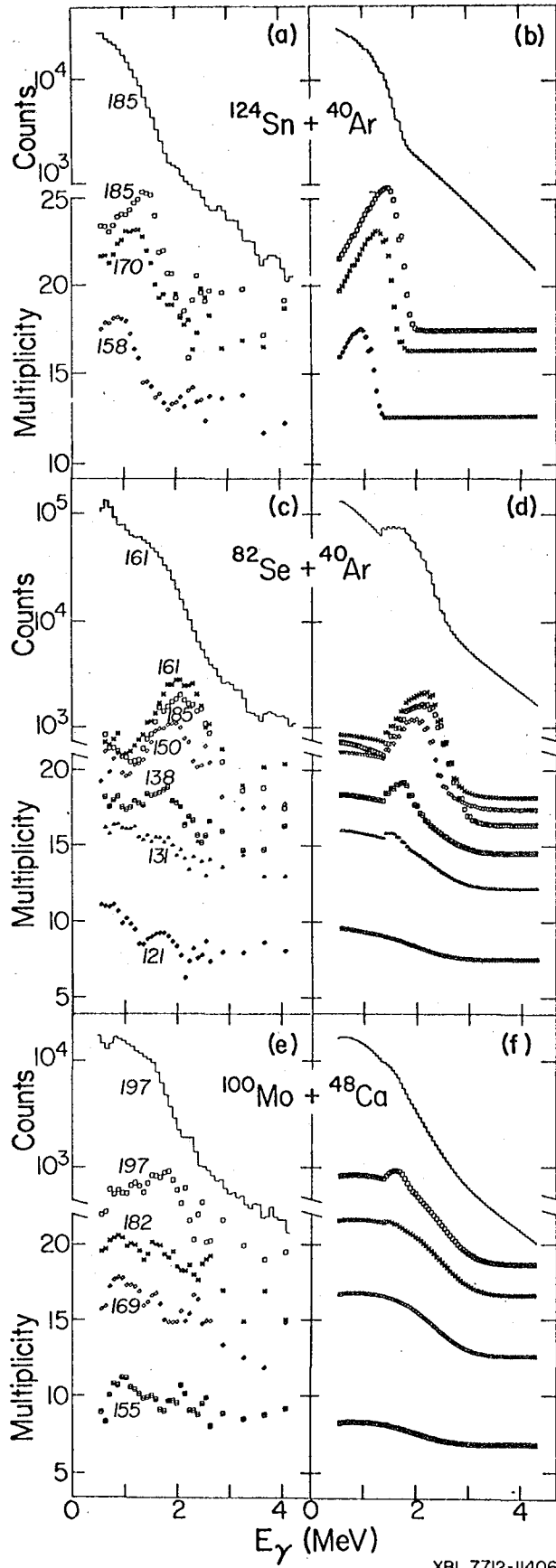


Fig. 1

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