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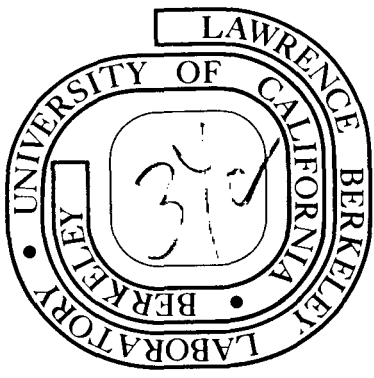
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MULTIPOLARITY OF CONTINUUM γ -RAYS FROM ENHANCED
ANGULAR CORRELATION MEASUREMENTS

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ABSTRACT

We have studied the angular correlation of continuum γ -rays in coincidence with an array of NaI counters following heavy-ion compound-nucleus reactions. This technique can both enhance the angular correlations and enrich the spectrum in high-angular-momentum events. The results extend previous ideas about the quadrupole bumps and exponential tails observed in such spectra, and reveal for the first time intense low-energy stretched dipole transitions in nuclei near closed shells.

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At the present time it appears that most of the information on nuclear structure at high angular momentum is contained in the low-energy bump observed in γ -ray spectra from evaporation residues following heavy-ion compound-nucleus reactions. The high-energy exponential tail in these spectra seems to be statistical in nature and thus contains less-detailed information. The bump very likely consists mainly of stretched E2 transitions, as indicated by previous studies¹ of its systematic behavior and by measurements of the γ -ray anisotropy. However, the latter measurements have been only qualitative, since there has been no proper calculation of the angular correlations expected in the cases where one or more additional γ -rays are detected following the compound-nucleus formation. This work reports on experiments designed to determine the multipolarity of the continuum γ -ray spectrum, making use of a multiple-counter array to enhance the alignment of the nuclei so that the sensitivity to different types of radiation is increased. At the same time the selection of high-multiplicity events enriches the spectrum in γ -rays from states with high angular momentum.

The experimental setup is shown in the inset of Fig. 1. The angular-momentum vectors of the compound nuclei are initially oriented in the plane (XY) perpendicular to the beam direction. Further alignment is produced by requiring coincidences in a set of six 7.6×7.6 cm NaI counters (multiplicity counters) located around the target in a plane (XZ) containing the beam direction. Thus, for example, stretched quadrupole γ -rays detected in these six counters will select preferentially nuclei which are aligned along the Y axis. The angular correlation has been

measured in four 7.6×7.6 NaI detectors placed along the X axis ($\theta = 90^\circ$, $\phi = 180^\circ$; "up" counter) and in the YZ plane ($\theta = 0, 45, 90^\circ$, $\phi = 90^\circ$; "0, 45, 90" counters). These "angle detectors" were located 60 cm away from the target in order to discriminate against neutrons by time-of-flight. Six spectra ("folds"), determined by the number of multiplicity counters in coincidence, were obtained for each angle detector, and then unfolded² to give the primary photon spectra. These were used to obtain the multiplicity and multipole spectra described below.

The multiplicity spectra have been calculated³ from the six fold spectra summed over the four angle detectors. A remaining $\sim 3\%$ correction to the multiplicity for angular correlation effects has been made. Some of the multiplicity spectra are shown in Fig. 2a.

We have considered five types of transitions in the angle counters, namely, quadrupole with $\Delta I (I_i \rightarrow I_f) = 2, 1, 0$, and dipole with $\Delta I = 1, 0$. We have not considered mixed transitions, though these might occur systematically at lower energies (rotational M1-E2 mixtures). We shall present the results only in terms of $\Delta I = 2$ quadrupoles and $\Delta I = 1$ dipoles, because: a) though $\Delta I = 0$ dipoles cannot be distinguished very well here from $\Delta I = 2$ quadrupoles, the initial spins and observed multiplicities do not allow many $\Delta I = 0$ dipoles; and b) whereas the $\Delta I = 0$ and 1 quadrupoles are similar to $\Delta I = 1$ dipoles in the 0/90 ratios, the results from the 45° detector indicate very little of these ($\lesssim 5\%$). Only $\Delta I = 2$ quadrupoles and $\Delta I = 1$ dipoles were considered in the multiplicity counters since the intensities observed in the angle detectors are not very sensitive to this choice.

The percentage of different multiplicities for each transition energy (channel) in the γ -ray spectrum was deduced by comparing the experimental and calculated fold spectra. Due to the large solid angle of the multiplicity counters (1.8%), the theoretical angular correlation coefficients have to be corrected for summing effects, which depend^{3,4} on the multiplicity and are around 10% in the present case. Because of the small variation of the calculated spectra with multiplicity, the average multiplicity in the reaction has been used to calculate the fold spectra rather than the appropriate multiplicity for each γ -ray energy. Figure 1 shows an example of the sensitivity of the angular correlation functions for the 3- and higher-fold coincidences calculated by a semi-classical method.⁴ Quantum-mechanical effects are estimated to be less than 7%, and are partly compensated by attenuation effects from the finite solid angle of the detectors and from side feeding. The 0/90 ratio has been used to determine the multipole ratios, but in several cases we have also calculated them from the 0/up, 45/90, and 45/up ratios; all gave similar results. From these multipole ratios and any angle detector spectrum, we can reconstruct the stretched quadrupole and dipole spectra, and when the integral of these two spectra is normalized to the (average) multiplicity, the resulting spectra give the number of transitions of each type per channel (160 keV interval). Some of these spectra are shown in Fig. 2b.

Previous studies¹ of multiplicity spectra have shown different behavior in strongly and weakly deformed nuclei. Based on this experience we have studied the following systems: $^{116}\text{Cd} + ^{48}\text{Ca}$ and $^{124}\text{Sn} + ^{40}\text{Ar}$ leading to rotational Er residual nuclei; $^{130}\text{Te} + ^{48}\text{Ca}$ and $^{122}\text{Te} + ^{48}\text{Ca}$

leading to rotational Hf nuclei; $^{106}\text{Cd} + ^{48}\text{Ca}$, $^{82}\text{Se} + ^{40}\text{Ar}$, and $^{110}\text{Pd} + ^{40}\text{Ar}$ leading to residual nuclei near closed shells. Three or four different bombarding energies were used for each system.

The data contain many detailed features, but the discussion here will be confined to three general properties which are clearly established. These are: 1) the quadrupole bump, 2) the dipole bump, and 3) the tail region. The multipole spectra in Fig. 2b confirm that in the rotational nuclei, the low-energy bump is composed of $\Delta I = 2$ quadrupole transitions. The multiplicity spectra of Fig. 2a show that in these cases there is a correlation between γ -ray energy and spin (multiplicity), and both types of spectra show that the γ -ray energies increase with increasing spin (higher bombarding energies). The $^{116}\text{Cd} + ^{48}\text{Ca} \rightarrow ^{164}\text{Er}^*$ and $^{124}\text{Sn} + ^{40}\text{Ar} \rightarrow ^{164}\text{Er}^*$ systems have these rotational properties. From the height of the bump⁵ for $^{116}\text{Cd} + ^{48}\text{Ca}$, shown in Fig. 2b, we can estimate: $2\mathcal{I}/\hbar^2 = 175 \pm 18 \text{ MeV}^{-1} = (1.2 \pm 0.1) 2\mathcal{I}_0/\hbar^2$, where \mathcal{I}_0 is the moment of inertia of a rigid sphere of mass 160.

The data for $^{122}\text{Te} + ^{48}\text{Ca} \rightarrow ^{170}\text{Hf}^*$ are not so simple in that 1) the edge does not move up in energy much with increasing bombarding energy, and 2) the height of the quadrupole bump increases with bombarding energy. This indicates that the correlation of γ -ray energy with spin is not so sharp, although the multiplicity peak shows that generally the transitions in the quadrupole bump come from the highest spin states. This behavior could be caused either by a mixture of bands with different moments of inertia, where at higher spins the bands with larger moments of inertia are favored, or by increasing moments of inertia with increasing spins in the bands populated. In the latter case the change could be either irregular

(backbending) or regular ($\mathcal{J} \propto I$). Since the heavier Hf nuclei are still deformation-aligned⁶ at spins up to $22\hbar$, a shift to rotation-aligned systems may come at still higher spins, i.e., in the continuum region, and this change could produce the required spread in moments of inertia. In the Er nuclei, this change comes as a backbend at $I \sim 18$ and causes the small peak at 0.64 MeV, but therefore has a smaller effect on the higher continuum region.

In the $^{82}\text{Se} + ^{40}\text{Ar} \rightarrow ^{122}\text{Te}^*$ system, the evolution of the $\Delta I = 2$ part of the spectrum with increasing bombarding energies confirms¹ that the rotation-like behavior sets in only at rather high spin ($\sim 35\hbar$). (Note the absence of structure (correlation) in the multiplicity spectrum at the 131 MeV bombarding energy.) The peak in the quadrupole transitions around 0.7 MeV for the $^{40}\text{Ar} + ^{82}\text{Se}$ system comes from the known low-lying weakly collective states in the Te nuclei.⁵ The lack of any systematic variation of these energies with spin explains the absence of structure in the multiplicity spectrum. In both this system and the $^{110}\text{Pd} + ^{40}\text{Ar} \rightarrow ^{150}\text{Gd}^*$ system there is at low spins a strong competition to the rotation-like behavior from a mechanism producing stretched dipole transitions.

The dipole part of the multipole spectrum is a much newer feature, whose occurrence in rotational nuclei has recently been suggested.⁷ In the rotational nuclei we do find evidence for a weak low-energy ($\lesssim 0.6$ MeV) bump of mainly $\Delta I = 1$ dipole transitions (sizeable amounts of $\Delta I = 1$ quadrupole cannot be excluded). On the whole, this feature seems consistent with a contribution of $\Delta I = 1$ (E2, M1, or mixed) rotational cascade transitions. A completely new feature, however, is the large amount of $\Delta I = 1$ dipole transitions in the $^{110}\text{Pd} + ^{40}\text{Ar} \rightarrow ^{150}\text{Gd}^*$ and $^{82}\text{Se} + ^{40}\text{Ar} \rightarrow ^{122}\text{Te}^*$ cases.

To a lesser extent $^{106}\text{Cd} + ^{48}\text{Ca} \rightarrow ^{154}\text{Er}^*$ also shows this. The overall percentage of $\Delta I = 2$ quadrupoles is around 80% for the rotational nuclei, 70% for the ^{106}Cd target, 60% for the ^{82}Se target, and 50% for the ^{110}Pd target. Thus the systems leading to products near closed shells have strong $\Delta I = 1$ dipole radiation, which the variation with bombarding energies shows to be concentrated at lower spins. This radiation gives little or no structure in the multiplicity spectra and corresponds to the "non-correlated" component previously identified.¹ The main difference between the ^{82}Se and ^{110}Pd systems seems to be the presence of $\Delta I = 1$ transitions at the lowest spins in the Pd system instead of the $\Delta I = 2$ quadrupoles (0.7 MeV) observed in the ^{82}Se system. Thus a pattern seems to emerge where we find with increasing collectivity: first, many $\Delta I = 1$ transitions (^{110}Pd system), later mostly $\Delta I = 2$ transitions but uncorrelated (^{82}Se at 131 MeV), and finally highly correlated $\Delta I = 2$ transitions — no doubt the rotational electric quadrupoles.

In the high-energy tail region we find two features. First, the 0/90 ratios are very similar for all cases and are close to unity. This implies roughly equal amounts of $\Delta I = 2$ quadrupole and $\Delta I = 1$ dipole. But, since the statistics are poor, large amounts of other components cannot be excluded. And second, all systems studied have about the same number of transitions in the tail. These properties suggest a similar decay mode for all nuclei from the high temperature region down towards the yrast line, in contrast to the transitions parallel to (or along) the yrast line, where differences in the nuclear structure can be inferred from the different observed decay modes.

In summary, we have developed methods to enhance the angular correlations of continuum γ -rays following heavy-ion compound-nucleus reactions and to evaluate these angular correlations in terms of the transition types present. The most striking new feature observed is the presence of intense $\Delta I = 1$ (mostly dipole) transitions at relatively low-spin values in the nuclei near closed shells. These transitions appear to be an alternative to collective transitions at lower spins, and their study should teach us something about the competition of collective and non-collective motion in such nuclei.

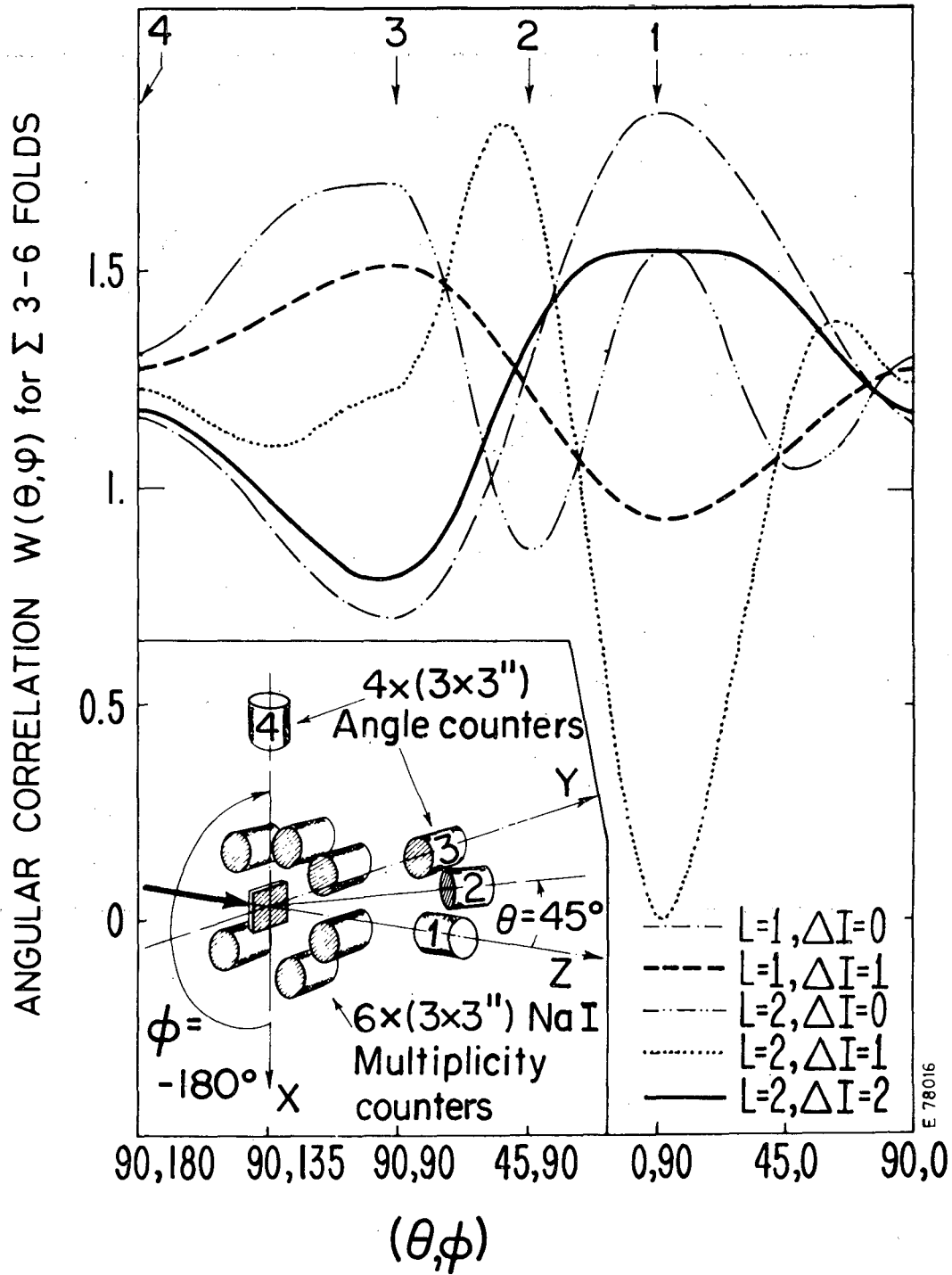
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FIGURE CAPTIONS

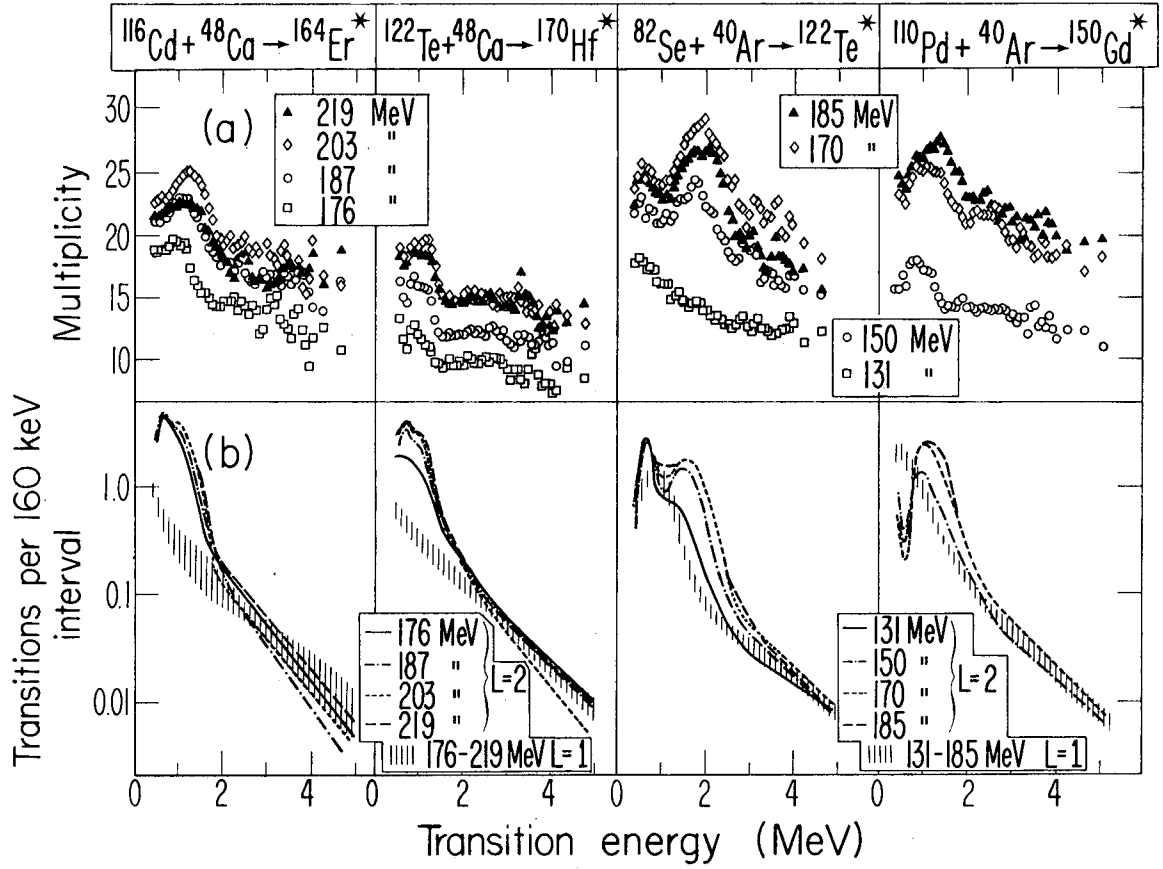
Fig. 1. The angular correlation functions are shown versus angle for the five transition types considered, with the assumption that three or more of the multiplicity counters fired. The numbers, 1-4, indicate the actual counter position. The inset shows the experimental arrangement.

Fig. 2. a) The multiplicity spectra are shown for the four indicated systems at several bombarding energies. b) The corresponding multipole spectra are shown for stretched quadrupole and dipole components. Each hatched area covers the full range of the dipole spectra for all bombarding energies listed.



XBL 784-8204A

Fig. 1



XBL 785-2522

Fig. 2

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