is consistent with most theoretical calculations.[4-9] The agreement now obtained is doubly reassuring, in that it not only removes a suggestion of serious error in current models of nuclear structure, but also substantially dispels recent suspicions that, when Coulomb excitation probabilities are very small, as in the present case and in the recent controversy[19] regarding Q_{2^+} in ^{18}O, reorientation experiments may be unreliable due to competition from other higher-order processes.

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Energy-Dependent Multiplicities of Continuum γ Rays*

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Multiplicities as a function of γ-ray energy have been measured for continuum γ-ray spectra produced in argon reactions at several bombarding energies on various targets. With the heavier systems there exist regions in the spectra that have particularly high multiplicites which can be associated with the yrast (collective) cascade. The results suggest that the angular momentum in the γ-ray cascade is limited by α emission for $Z \lesssim 60$ and by fission for $Z \gtrsim 60$.

Information about states of very high angular momentum can be obtained from the continuum γ rays following (HI, xn) reactions. Studies of the multiplicities[1] and the energy spectra of these γ rays[2,3] have begun. We report here on the first measurements of the multiplicities as a function of γ-ray energy E_γ and show that, for a wide range of final nuclei, there exist energy regions with high multiplicity.

Targets of ^{12}C, ^{27}Al, KCl, Ti, Fe, ^{68}Zn, ^{82}Se, ^{126}Te, and ^{130}Te, 0.5–1.2 mg cm^{-2} thick, deposited on 0.02-mm Pb backings, were bombarded with ^{40}Ar ions from the Berkeley 88-in. cyclotron; the energy ranged between 119 and 185 MeV. A "multiplicity filter" was used consisting of six 7.5-cm × 7.5-cm NaI(Tl) detectors placed symmetrically around the beam axis, and located upstream from the target in order to minimize the number of neutrons detected. The efficiency of each of these detectors was 2.1% and varied less than 20% between 0.4 and 2.7 MeV. The number of NaI detectors firing in coincidence with events in a 50-cm^3 Ge(Li) detector, placed at an angle of 45° to the beam direction and 7.5 cm from the target, or in a 7.5-cm × 7.5-cm NaI detector at −45° and 60 cm was recorded. Neutron events in this NaI detector were excluded by time of flight. From the probabilities that various numbers of the NaI detectors fired, one can calculate the multiplicity for any selected gating events, where the multiplicity measured here is the total number of γ rays with energy greater than 0.25 MeV. The

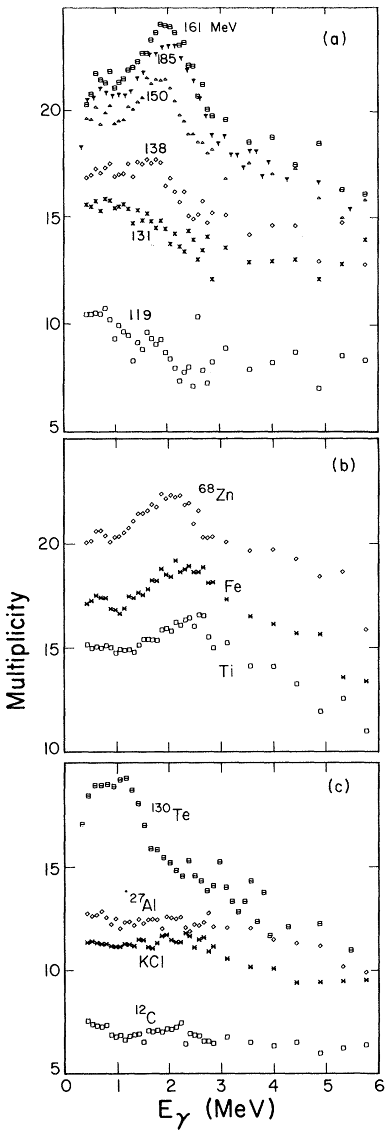

FIG. 1. Multiplicities as a function of γ-ray energy (NaI pulse height) for (a) ^{40}Ar + ^{82}Se at the indicated bombarding energies, and (b) and (c) targets bombarded by ^{40}Ar ions of 161 MeV, except for ^{130}Te (185 MeV) and ^{12}C (131 MeV).

data from the Ge(Li) detector gave multiplicities for individual γ lines, and hence individual reaction channels, while the NaI data gave the multiplicity as a function of E_γ, irrespective of reaction channel.

Some of these multiplicity distributions for the NaI pulse-height spectra are shown in Figs. 1(a)–1(c). (Correction for the detector response function does not appreciably change the results.) The characteristic feature is a peak at an energy somewhere between 1 and 3 MeV. The energy region above this peak arises from the statistical emission of γ rays which occurs irrespective of the angular momentum of the system. It would therefore be expected to have about the average multiplicity of all reaction channels. The peak itself arises from the cascade of γ rays parallel to the yrast line. If some type of rotational motion is involved, the highest γ-ray energy in the yrast cascade, E_γ(max), will correspond generally to the highest initial angular momentum and hence the highest multiplicity. With any reasonable values for the moment of inertia, this E_γ(max) will be in the range 1 to 3 MeV for the nuclei and bombarding energies considered here. Thus the multiplicity peak identifies rather directly the γ-ray energies occurring near the top of the yrast cascade.

As the bombarding energy is increased the angular momentum input to the system is increased. This effect is shown in the multiplicity distributions of Fig. 1(a), where the average multiplicity of the "statistical" region increases steadily with energy up to 161 MeV and corresponds quite closely to that expected from reasonable assumptions regarding the angular momentum input for complete fusion. The reduction at 185 MeV must be due to the onset of some other reaction mechanism, such as fission or deep inelastic scattering, where all the angular momentum is not transferred to the internal degrees of freedom of the nucleus. The development of the ~2-MeV peak with bombarding energy shown in Fig. 1(a) is very impressive. The maximum multiplicity in the peak should be somewhat less than that for the optimum channel (fewest evaporated particles) because of dilution by statistical γ rays. The energy of the peak moves up slowly with bombarding energy, but is effectively limited when the highest angular momenta no longer contribute to the yrast cascade.

The angular momentum reaching the yrast region could be limited by (1) the maximum angular momentum involved in complete fusion, (2) fission of the compound system, and (3) particle emission competing with γ emission in the yrast region. For the highest bombarding energies used here, (1) is expected to be well above that observed. We have made estimates for the limiting angular momenta and for the corresponding end-point γ-ray energies for (2) and (3). Those from fission were obtained from the liquid-drop model following the method of Cohen, Plasil, and Swiatecki.[4] (We assumed a fission barrier of 10 MeV, taken to be an effective particle binding energy.) The energy available for particle emission with orbital angular momentum l from an yrast state of angular momentum I can be written: $E_P = \Delta E(I,l) - B_P$, where $\Delta E(I,l)$ is the difference between the yrast energies (taken to be those of spherical rigid rotors) for parent and daughter with spins I and $I-l$, respectively. Also, B_P is the liquid-drop binding energy for the particle P, which is more appropriate than the ground-state binding energy at these high angular momenta. The $E2$-transition energy from the state I is $E_\gamma(I) = (\hbar^2/2\mathcal{I})(4I-2)$, where $\mathcal{I}$ is taken to be the rigid-body moment of inertia for the parent nucleus.

We can evaluate l, $I(\text{max})$, and $E_\gamma(\text{max})$ for the point where the probabilities for γ decay and particle decay are equal, provided some assumptions are made regarding $B(E2)$ and the particle decay width, Γ_P. We have used $B(E2)\downarrow = 1.6(Z/66)^{3/2} \times (A/162)^{4/3}\, e^2 \cdot \text{b}^2$ which is appropriate for rotational transitions and accounts roughly for the variation of equilibrium deformation with mass and charge numbers, A and Z. We also took $\Gamma_P = (T_l)_P D/2\pi$, where $(T_l)_P$ is the transmission coefficient and D the level spacing.[5] We evaluated the $(T_l)_P$ from an optical-model code and for D we took two values, 30 and 3 keV, at $I = 40$ for $A = 104$. Since we do not know the effective excitation energy above the yrast line, we have essentially normalized D to the experimental data, but these values seem plausible. To allow for the variation of D with A and I, we used the triaxial-rotor model of Bohr and Mottelson[6] for the yrast region. This leads to the conclusion that the level spacing near the yrast line is proportional to $IA^{-5/3}$, provided we assume that the shape of the nucleus is independent of A and I. There is considerable uncertainty in our values for $B(E2)$ and especially for Γ_P, but the results show that the limiting angular momenta for proton and neutron emission in these moderately neutron-deficient nuclei are approximately twice those for α emission and hence the limit is given by α emission.

The results for $I(\text{max})$ and $E_\gamma(\text{max})$ are shown in Fig. 2, and there is reasonably good agreement with the experimental data. The limiting angular momenta are low for the lower Z values, which results in smaller peaks since the number of γ rays decreases and $E_\gamma(\text{max})$ increases. Figure 1(b) shows that peaks cannot be observed clearly below the Ti + Ar system ($Z = 40$).

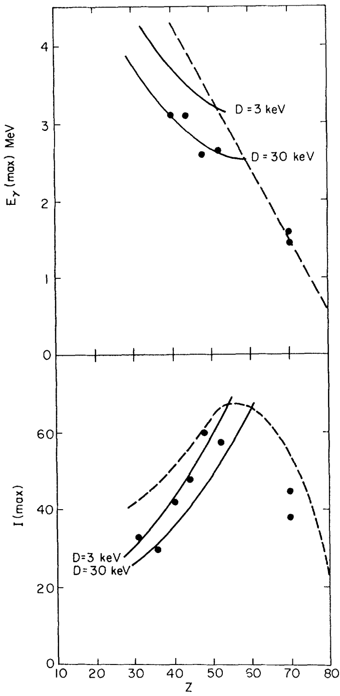

FIG. 2. The solid (dashed) lines show the calculated $E_\gamma(\text{max})$ and $I(\text{max})$ values given by α-particle emission (fission). The experimental points come from Fig. 1, where $I(\text{max})$ is twice the maximum multiplicity which in turn is estimated to be $\frac{3}{2}$ of the average multiplicity (see text).

It should be pointed out that variations from the rather smooth behavior of the lines in Fig. 2 will occur since both $B(P)$ and the fission limits change appreciably for a change in neutron number for fixed z. Also, theoretical calculations[7] indicate that shell effects should not be completely absent at high angular momenta, and may show up as local variations in the moment of inertia. If these shell effects are large, then the estimate for $E_\gamma(\text{max})$ may be better than that for $I(\text{max})$, since the energy available for α emission depends more on the local slopes of the yrast lines than on the value of I.

The experimental technique used provides a general method for identifying the high-multiplicity regions of the γ-ray continuum spectra. The results show that the spectra from nuclei with $Z \gtrsim 40$ involve a multiplicity peak somewhere between 1 and 3 MeV. This clearly supports the interpretation that these spectra consist of yrast and statistical cascades. We have shown that the observed limiting multiplicities and yrast γ-ray energies can be understood in terms of a simple model, where the upper angular-momentum limit for the γ-ray cascade is imposed either by fission or by α-particle emission.

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Evidence for Collective $M1$ Strength in ^{208}Pb between 8 and 10 MeV*

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Very-high-energy-resolution photoneutron time-of-flight measurements in combination with high-resolution measurements of photoneutron polarizations from the reaction $^{208}\mathrm{Pb}(\gamma,n_0\uparrow)^{207}\mathrm{Pb}$ have enabled us to identify seven probable 1^+ resonances at excitations between 8.2 and 9.5 MeV. These resonances have a total strength $B(M1)\uparrow \gtrsim (8.5\pm0.5)\mu_0^2$. This strength plus that previously reported at 7 and at 8 MeV can account for the $M1$ sum rule in ^{208}Pb.

The giant $M1$ resonance in ^{208}Pb is of particular interest because of the large number of nucleons in this nucleus that can undergo spin-flip transitions. Calculations[1-3] have predicted that the collective $M1$ strength in ^{208}Pb should be observed at excitations that fall in a range from 7.5 to 8.3 MeV. Recent experiments,[4,5] however, have shown that there is considerably less $M1$ strength near these energies than expected. Part of the missing strength may be below the neutron threshold, and there are experimental indications of at least one strong 1^+ state near 7 MeV.[6] In the present Letter, we report evidence for a significant amount of $M1$ strength at higher excitations which could account for the remaining portion of the $M1$ sum rule.

In order identify these $M1$ resonances in ^{208}Pb, we have employed two techniques. First, we have measured the polarization of ground-state photoneutrons at an angle of 90° with high energy resolution. A nonzero polarization can arise at 90° in the reaction $^{208}\mathrm{Pb}(\gamma,n_0\uparrow)$ only when there is an interference either between an $E1$ and $M1$ transition or between an $E1$ and $E2$.[7] Second, we have developed a *subnanosecond* time-of-flight spectrometer which enables us to unravel, with much higher energy resolution than has previously been possible, the underlying level structure which produces the observed polarization. The key to this second technique is the unique electron beam available from the Argonne National Laboratory high-current linac, which provides a 200-A peak current in 35-ps-wide pulses. By comparing the strengths of resolved overlapping resonances associated with a measurable polarization with the maximum amount of $E2$ strength that would be consistent with high-resolution inelastic electron scattering data from Darmstadt,[8] it has been possible to make probable $M1$ assignments for seven states.

The details of the photoneutron polarization technique have been discussed.[4,9] An electron beam (800-Hz, 4-ns pulse width, 10-A peak current) is used to produce bremsstrahlung which irradiates a 100-g target of 99% ^{208}Pb. Partially polarized photoneutrons from the reaction $^{208}\mathrm{Pb}(\gamma,n_0\uparrow)^{207}\mathrm{Pb}$ are then analyzed at the end of a 10.5-m flight path oriented at 90° with respect to the photon beam. In this experiment, a liquid O_2 analyzer (7.6 cm in diameter, by 15.2 cm) was used for neutron energies below 1.5 MeV, and a ^{12}C analyzer (cylinder: 7.6-cm i.d., 10.2-cm