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DISCLAIMER

ANGULAR MOMENTUM SELECTION USING TOTAL GAMMA-RAY ENERGIES[*]

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The use of a total γ-energy spectrometer in coincidence with a variety of detectors has led to the observation of the highest multiplicities yet achieved for compound nuclear products, allowing the selection and study of high angular momentum states. It is shown how a differential comparison of coincident γ-spectra corresponding to slices of the total-energy spectrum yields a direct evaluation of the moment of inertia for a rotational nuclear structure.

The study of very high-spin states in nuclei is progressing along two rather different lines, according to whether the observed γ-ray spectrum is resolved or not. In the former case, level schemes are constructed, and, for the most favorable cases, spins as high as 37ℏ have been observed.[1-3] These schemes contain much information about the nuclear structure. For the less favorable examples, or for still higher spins (nuclei can hold up to 65-70ℏ in some cases), one must study the unresolved ("continuum") spectrum. Much progress has recently been made in the latter case for the gamma rays from evaporation residues following heavy-ion reactions. Studies have been made of the shapes of these continuum spectra[4,5] as well as of their multiplicities,[6] angular distributions,[7] conversion coefficients,[8] and lifetimes.[9] It is now established that these spectra consist of a tail above ∿ 2 MeV which decreases exponentially with increasing γ-ray energy, and usually a bump at lower energy which contains the transitions that remove the major part of the angular momentum of the system. The nature of these latter transitions appears quite sensitive to the nuclear structure, whereas the tail seems to be composed of statistical transitions that are nearly independent of the detailed nuclear structure.

Continuum spectra are inherently difficult to study, and one of the essential steps is to isolate those events that correspond to very high initial angular momentum. Two methods have so far been used for that purpose. The first is to select a particular reaction channel. It is well known that in a (HI,xnγ) reaction at a given bombarding energy, the highest angular momentum is in the channels where the fewest neutrons are evaporated (lowest x).[10] Thus a selection of these channels corresponds to a study of nuclei at high angular momentum. A second method has been to utilize multi-counter arrays to detect the γ-rays and select those events where the most γ-rays are emitted.[11] These events are of the highest multiplicity, and thus represent the highest angular momenta in that spectrum. With the arrays used so far, it is not clear which method produces a better (higher and sharper) angular momentum selection. The purpose of this letter is to demonstrate a third method,[12] the use of a total γ-ray energy spectrometer, which may be able to select higher multiplicities than the reaction-channel method described above, and furthermore, to show the kind of information that can directly be extracted from the data. The experiments were performed using ^{40}Ar beams of 185 MeV obtained from the LBL 88-inch Cyclotron.

To obtain the total γ-ray energy spectra, we used a NaI crystal, 33 cm in diameter by 20 cm thick, divided optically into four sectors. There was a 2.6 cm diameter hole along the axis of this crystal so that the beam could hit a target placed at the center. The heavy-ion beam was stopped behind the target ($\sim$1mg/cm^2 ^{124}Sn on a 25μm Pb backing) in a thin lead foil, so that the 0° direction was then open for observation by either a Ge(Li) detector ($\sim$11 cm from the target), a 7.6 x 7.6 cm NaI detector (located $\sim$60 cm from the target), or a multiplicity filter consisting of an array of six 7.6 cm x 7.6 cm NaI crystals (halo counters) at 120 cm from the target. The pulse-height signals of the four sectors were stored separately on magnetic tape and were added together later after gain equalization. Each sector was stabilized with a light-diode pulser system and could be safely operated to rates $<$ 50 KHz. It was normally required (off-line) that all four sectors fired, which did not significantly affect the rate of compound-nucleus events, but strongly reduced low-multiplicity events due to room background, Coulomb excitation, and transfer reactions.

The arrangement with the Ge(Li) detector (0°) and sum crystal was used to find the total γ-energy distribution for each reaction channel. This was done by looking at the summed γ-spectrum in coincidence with known Ge(Li) lines from the 4n, 5n, 6n and 7n channels (^{160,159,158,157}Er). The resulting distributions together with the full summed spectrum are shown in Fig. 1 (top). Clearly the sum spectrometer allows a selection of the reaction channel, particularly for the lowest xn channels.

Three types of information came from the use of the 0^{o} NaI detector and the halo counters. First, the spectrum of γ-rays in the 0^{o} counter was determined for consecutive slices of the total γ-ray energy, including the 0^{o} counter. These spectra will be discussed later. Second, the number of γ-rays (multiplicity) as a function of total energy was determined from the ratios of coincidences to singles for each slice of summed γ-energy. Actually, the multiplicity was derived from the four sectors and the 0^{o} counter by considering the data from the four sectors and the 0^{o} counters as outlined in ref. 12. The values of the multiplicities so determined were in excellent agreement with those obtained from the halo counters using the ratios of their zero-, one-, and two-fold coincidences with the summed-energy slices. This latter method, however, also yielded the width of the multiplicity distribution for each slice, or more precisely, σ_M, the square root of the variance of the distribution.

For the system ^{40}Ar + ^{124}Sn at 185 MeV, the multiplicities from slices of summed γ-energy about 4 MeV wide are plotted in Fig. 1 (bottom). Two curves are shown; the dashed one is derived directly from the ~ 0^{o} NaI counter data, and the full line is calculated from the same data corrected for the angular correlation of 80% stretched E2 transitions and 20% stretched dipole transitions. Also, we have corrected the total γ-energy scale in Fig. 1 for the counter transparency, that is, for the γ-rays that leak out entirely and those that Compton scatter out. For our sum crystal configuration, the average energy efficiency is about 0.75. It is clear that there is a strong correlation of γ-ray multiplicity with summed γ-energy, and since multiplicity is closely related to angular momentum (the exact relationship is not always clear, but for this case of a good rotor the relation $I \approx 2\ (M_\gamma-4)$, is probably about right),[4] there is implied a very strong dependence of the angular momentum on total γ-energy. The multiplicity widths are also plotted in Fig. 1; it must be noted that the values at low sum energies are probably too high because we are averaging over a 4 MeV wide slice in a region of steeply rising multiplicities (bottom part of figure) and of steeply rising intensities (top part).

In order to compare these values of the multiplicity, $\langle M \rangle$, and their rms variance, σ_M, with those from the individual reaction channels, we replaced the sum crystal with a Ge(Li) detector, leaving the array of NaI counters unchanged. This allowed a conventional measurement[11] of the γ-ray multiplicity distribution and of the average γ-ray energy for each channel. The corresponding multiplicities and widths for the 4n, 5n, and 6n and 7n channels are also shown in Fig. 1, where they are plotted at summed γ-energy values derived from the product of the average γ-ray energy and the average multiplicity. (It should be noted that these energies coincide with the peaks of the corresponding channel distributions in the top part of the figure.) All these values are for 0° angle, corrected for the angular correlation as before. The two different types of measurements are seen to be in good agreement.

It is clear that the multiplicities reach higher values at high total γ-energies than the average value for the observed reaction channels. In fact they reach the highest values so far observed for compound-nuclear reactions; the observed multiplicity for the highest summed energies implies average angular momenta for these slices as high as $60\hbar$. More importantly, spectra corresponding to a range of multiplicities (angular momenta) can be compared in detail, as will be illustrated below. However, one should realize that the slices in angular momentum are still not so narrow. The observed values of σ_M yield, for the highest slices, $\sigma_M/\langle M \rangle \approx 1/3$. This is comparable to the ratio obtained for an individual reaction channel (Fig. 1), and so is still not very sharp.

But the power of the total γ-energy method appears in comparing the effects of relatively small increases in the average angular momentum, such as those in adjacent slices of the total γ-energy spectrum. This leads to the possibility of directly observing changes in the structure of the nucleus. Figure 2 (top) shows the unfolded[4] 0^{o} NaI spectra from the ^{124}Sn + ^{40}Ar system in coincidence with ~4 MeV wide slices of summed energy. These spectra are normalized to give the average multiplicity in each slice; the ordinate scale is absolute if energy bins of 200 KeV are taken on the abscissa. Two features are apparent. First, up to about slice 4 or 5 (~17 MeV), the height (number of counts per event) in the most intense region (500-600 keV) increases, reflecting an increasing percentage of compound-nucleus events. And second, beyond slice 5, the height no longer increases but the upper edge of the bump moves to higher energy. This is the expected rotational behavior for these Er product nuclei. The higher angular momentum events do not add more transitions per event at lower energies (transitions between lower-spin states), but only add transitions at the highest energies and spins ($E_\gamma^{(rot)} \propto 4I-2$). By subtracting successive slices, we get the curves in the bottom of Fig. 2, which show the very regular increase in average energy of these transitions up to slice 8 (~32 MeV). If we integrate the difference spectrum for slice 7 - slice 6, and take its centroid, we find 3.4 transitions were added having an average energy of 1.40 MeV. Similarly, slice 6 - slice 5 gives 4.0 transitions with an average energy of 1.20 MeV. From the difference in transition energy (0.20 MeV) and the average number of transitions, 3.7, we find the effective moment of inertia to be

$$2\mathcal{J}/\hbar^2 \approx 4\Delta I/\Delta E_\gamma = 4\mathrm{x}2\mathrm{x}3.7/0.20 \approx (150 \pm 25)\ \mathrm{MeV}^{-1}$$

for an average transition energy of 1.30 MeV. Using these values of $\mathcal{J}$ and E_γ, we calculate a spin around 50ħ; this is for states at the top of slice 6, and is in reasonable accord with the spin estimated from the multiplicity in Fig. 1. This is surely the simplest and clearest view we have had yet of the transitions at such spins in any nucleus. The previous methods[4] for obtaining moments of inertia either require the spin to be determined by some other method, or depend on the height of the yrast bump in the intensity spectrum and thus require full population in the spin region (restricting one to considerably lower angular momentum). The present method is simple and straightforward for any rotational case where the edge of the bump moves as the angular momentum increases.

In conclusion, the total γ-ray energy technique appears to be the best method presently known for isolating high-angular-momentum events. It also allows the selection of different angular-momentum populations, which makes the corresponding changes in the γ-ray spectrum easy to study. For good rotational nuclei these techniques lead to an evaluation of moments of inertia for the highest spin states populated. We should note, it is also quite easy to identify the irregularities associated with deviations from rotational behavior. It is presently a challenge to learn something about the nuclear structure from such irregularities.

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Fig. 1. (top) Experimental total sum spectrum and the xn reaction product components obtained by gating on known lines in the coincident Ge spectrum.

(bottom) Plot of multiplicity and square root of the variance σ_M, against total γ energy (~4 MeV wide slices). The points on the dashed line correspond to the experimentally measured multiplicity, while the points on the solid line correspond to an angular correlation correction to the data which assumes 80% stretched quadrupoles and 20% stretched dipoles. The multiplicity results from Ge(li) discrete lines are indicated by the triangle at the energy $\langle M \rangle * \langle E_\gamma \rangle$ (see text).

Fig. 2. (top) Number of transitions per 200 keV per event (unfolded spectra) as a function of γ-ray transition energy in a 0° NaI detector 60 cm from the target, for each of the ~4 MeV wide slices taken in the total-energy spectrum. The numbers shown are the ordinal number of the slices. Representative statistical error bars are shown for slice 6 and for each slice near 1.2 MeV when larger than the line.

(bottom) Differences in the pairs of spectra from consecutive slices in the total-energy spectra shown at top, that is, differences in the number of transitions per 200 keV per event for consecutive spectra as a function of γ-ray transition energy.

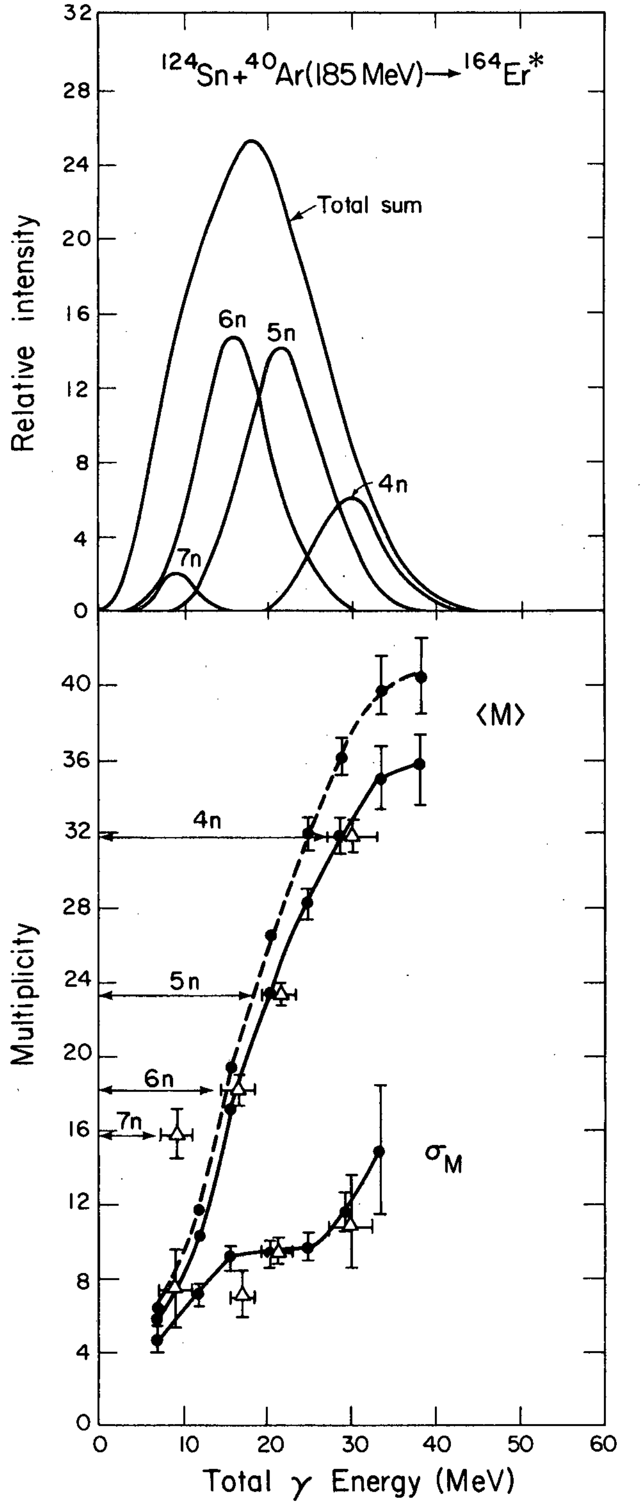

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Fig. 1

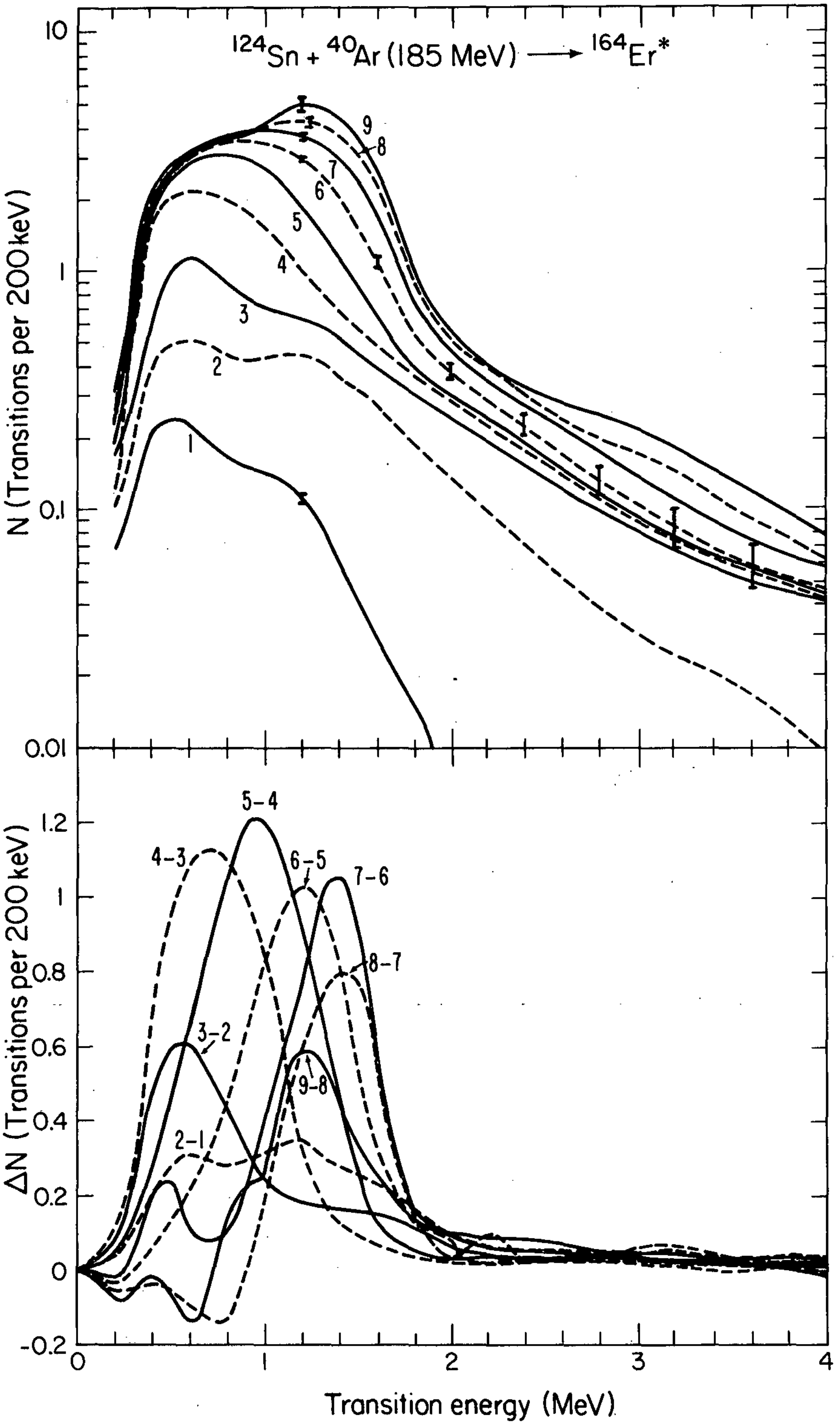

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Fig. 2

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