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TRANSITIONS BETWEEN HIGH-SPIN NUCLEAR STATES*

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ABSTRACT: We have measured the energy spectra, angular correlations, and number of continuum gamma rays following several heavy-ion reactions. A separation of the spectrum into yrast and statistical cascades is clearly indicated for the heavier product nuclei studied ($Z \gtrsim 50$), but is not so obvious for the lighter ones. The yrast cascades associated with three particular reaction channels have been interpreted to give moment-of-inertia values for the highest spin states in these channels (up to $60\hbar$).

Studies of transitions between high-spin nuclear states can give information about moments-of-inertia, shapes, and other structural features of such nuclei. High spin values (up to 80ħ) can be brought into compound nuclei following heavy-ion reactions; however, gamma-ray studies following such reactions have thus far produced information mainly on states having spins below ∿ 20ħ. The reason is that all the transitions between higher-spin states are too weak individually to be resolved, and thus comprise an apparent continuum. There were some early attempts to study this continuum,[1,2] but these studies have only recently been resumed.[3-6] In the present work, the energies, angular correlations and number of continuum gamma-rays have been measured, and the information obtained from these quantities has been related directly to nuclear moments-of-inertia at angular momenta up to 60ħ.

We have studied mainly the reactions $^{82}\text{Se}(^{40}\text{Ar},xn)^{122-x}\text{Te}$, and $^{126}\text{Te}(^{40}\text{Ar},xn)^{166-x}\text{Yb}$ using 183 MeV Ar beams from the Lawrence Berkeley Laboratory Superhilac. In addition, a limited survey over target (Al, Cu, As, Ag, Sn, and Sm) and projectile (^{16}O, ^{40}Ar) at several bombarding energies was made. The targets were ∿ 1 mg/cm^2 thick, and were evaporated onto 25 μm Pb backings, which stopped the beam and recoiling nuclei with very little background. To measure the continuum gamma-rays, we used three 7.5 × 7.5 cm NaI(Tℓ) detectors at angles of 0°, 45°, and 90° to the beam direction. Each detector had an absorber of 0.32 cm Pb and 0.32 cm Cu, and was placed 60 cm from the target. This long flight path to the NaI detector permitted an almost complete separation between neutrons and gamma-rays in the time spectrum. The three NaI spectra were recorded event by event in coincidence with pulses from a Ge detector which was 5 cm from the target at an angle of 225° to the beam direction. The Ge singles spectrum was stored simultaneously.

To obtain the true gamma-ray energy spectrum, $N(E_\gamma)$, the pulse-height distribution must be corrected for the detector response. To do this we used a computer code[1] with the response function carefully fitted to our detectors. The raw and unfolded 0° NaI spectra in coincidence with the full Ge spectrum are shown for three targets in Fig. 1. A comparison of the three NaI detectors gives the angular correlation of any given region of the continuum, $W(\theta,E_\gamma)$, provided the recoiling nuclei stop before gamma-ray emission. In fact, it is more likely that the product nuclei are moving at the time of emission, leading to solid-angle and doppler-shift corrections. The uncorrected (stopped) values for the 0°/90° ratio from the raw spectra are given on Fig. 1.and the corresponding values for the unfolded spectra are very similar. The corrected (moving) values for the unfolded spectra are also shown. The calculated beam-γ-γ angular correlation is qualitatively similar to the usual beam-γ distribution i.e., the 0°/90° ratio is about 1.4 for stretched quadrupole radiation and about 0.7 for stretched dipoles. A comparison of any line in the singles Ge spectrum with the corresponding coincident one (together with the known detection probability in the NaI detector) gives the average number of gamma rays, $\bar{N}_\gamma$. These three basic types of information, $N(E_\gamma)$, $W(\theta,E_\gamma)$, and $\bar{N}_\gamma$, reveal some very interesting structure in the continuum spectrum.

For the heavier product nuclei ($Z \gtrsim 50$ or $A \gtrsim 110$), two features of the continuum spectra are clear. Above ∿ 3 MeV the intensity falls off approximately exponentially with increasing energy, whereas somewhere below this energy a prominent bump occurs. These features seem very likely to result from the statistical and yrast cascades as has been predicted,[7] and recently observed in Yb nuclei with ^{16}O projectiles.[6] The slope of the exponential part of the spectrum is rather similar for all the targets we have studied and corresponds to "temperatures" ranging from 0.8 to 1.3 MeV ($T = -dE/d\ell nN$) in good agreement with the expectations[7] for a purely statistical cascade. The bump is shown by the angular correlations to be composed almost completely of stretched E2 transitions whose energies are rather low and decrease with increasing product mass in a very systematic way, suggestive of a moment-of-inertia effect. Also, the energy and intensity of the stretched E2 component of the bump generally increases with angular-momentum input. These properties strongly suggest identification of this bump with the yrast cascade, though there is not yet any direct experimental evidence that this cascade occurs close to the yrast line.

The yrast bump is generally less prominent for products below Z ∿ 50 as is illustrated by the curve for a Cu target in Fig. 1. Correspondingly, the angular correlations indicate less stretched E2 radiation in this region. If an exponential function is fitted to the portion of each spectrum between 3.2 and 6.2 MeV (solid lines in Fig. 1), and then extended back to 0.6 MeV, one can compare the number of events above this line with those below it. As a comparison of yrast- to statistical-cascade intensities, this probably overestimates the statistical part, but it nevertheless gives an estimate of the prominence of the bump. This procedure gives 3.3, 2.8, and 0.5 for the Te, Se, and Cu cases shown in Fig. 1. These results suggest that the de-excitation mechanism changes somewhat below Z $\sim$ 50, disfavoring strong yrast cascades. The rather sudden onset of the strong yrast bump above Z $\sim$ 50 suggests that there may be shell effects influencing these cascades and a more complete mass survey is needed. There is also some evidence for more complicated structure in the energy spectrum, especially in the lighter-mass targets. We are at present studying this "fine" structure in order to be certain it is real and, if so, to understand what it implies.

More detailed information about yrast energies comes from studies of the individual reaction channels. This is illustrated in Fig. 2, which shows raw and unfolded spectra from the reaction, ^{82}Se(^{40}Ar,xnγ)$^{122-x}$Te, where coincidence requirements in the Ge detector allowed selection of the 4n(^{118}Te; 606, 601, 615, and 753 keV) and 6n(^{116}Te; 679, 681, 643, and 771 keV) reaction channels.[8] These spectra each have a rather sharp drop, but at quite different energies; 2.4 MeV for the 4n reaction and 1.7 MeV for the 6n reaction. An estimate of the angular momentum in each channel can be made from the $\overline{N}_\gamma$ values, which are 29, 20, and 13, for the 4n, 5n, and 6n reactions. Assuming that the few missed transitions below 0.6 MeV compensate for the dipoles present, we can estimate the average angular momentum in these channels to be $\sim 2\ \overline{N}_\gamma$, or 58, 40, and 26$\hbar$. This procedure has been shown in other cases[5] to be consistent with estimates of the channel angular momentum based on cross-section measurements. Since the highest gamma-ray energy in each channel is more likely to be associated with the highest value of the angular momentum having appreciable intensity, rather than with the average value, we must estimate this "highest" value. For the 6n reaction, a point midway between the 6n and 5n average values (33ħ) seems unlikely to be in error by more than ∿ 15%. The 4n value should be rather near the measured average, and 64ħ (the Bass model[9] dynamic limit for this reaction) seems likely to be correct within ∿ 15%. These estimates give $2\mathcal{I}/\hbar^2$ values of 75 MeV^{-1} for $I \sim 33$ and 110 MeV^{-1} for $I \sim 64$. For comparison, the value of $2\mathcal{I}/\hbar^2$ is 39 MeV^{-1} for the $8 \rightarrow 6$ transition[8] in ^{118}Te, and 85 MeV^{-1} for a rigid sphere of mass 118. The liquid-drop estimates[10] for $I = 33$ and 64 in ^{118}Te are 91 and 104 MeV^{-1}. The spectrum for ^{162}Yb from the ^{40}Ar + ^{126}Te reaction is also shown in Fig. 2, and an estimate similar to those above gives $2\mathcal{I}/\hbar^2 \sim 140$ MeV^{-1} at $I \sim 48$. The rigid sphere value for this case is 125 MeV^{-1} and the liquid-drop estimate is 154 MeV^{-1}. There is, no doubt, much yet to be learned about extracting moments-of-inertia from these spectra; however, it is difficult to see how these values could be in serious error.

Even more detailed information on the moments-of-inertia may be contained in these spectra. The upper edge of the bump for ^{118}Te in Fig. 2 is very sharp, and the unfolded spectrum suggests a slight peak prior to this edge. Such a peak (or even the very sudden drop) can only result from a piling up of transition energies somewhere near 60ħ, indicating a rather rapidly increasing moment-of-inertia (a backbending is not excluded). This kind of behavior is expected from liquid-drop model studies[10] of Te nuclei due to shape changes caused by centrifugal forces which eventually are limited by fission. The predicted shape changes can at times be drastic and result in "super-deformed" nuclei.[11] Independent evidence[12] from fusion and fission cross sections suggests that the ^{118}Te produced in this reaction will, indeed, have angular momenta up to the fission limit. Thus the sharp cut-off and the tentative peak in Fig. 2 may be direct evidence for shape (or perhaps other) changes characteristic of nuclei with high angular momentum.

We have shown that there are rather prominent features in the continuum gamma-ray spectra following heavy-ion reactions, and that for the heavier product nuclei studied here, these features can almost undoubtedly be identified with the yrast and statistical cascades. For the lighter nuclei, the yrast cascade seems much weaker, or of a different character. We have further shown that the yrast energies, together with the gamma-ray multiplicities, can lead to estimates of moment-of-inertia values for states having spins up to $\sim 60\hbar$. Even details about moment-of-inertia variations with angular momentum can probably be inferred from these spectra. It appears that the gamma-ray continuum will provide access to much of the desired information about high-spin states.

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FOOTNOTES AND REFERENCES

[*] This work done under the auspices of the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

Fig. 1. The raw (dots) and unfolded (triangles) continuum spectra in coincidence with the full Ge spectrum is shown for natural Cu, ^{82}Se, and ^{126}Te targets, The straight lines are fit to the unfolded spectrum between 3.2 and 6.2 MeV (solid portion) and extrapolated to lower energies (dashed portion). The upper plots show the 0°/90° ratios for the raw data (dots) and for the unfolded data, corrected for recoil motion (triangles). The error bars indicate statistical errors only.

Fig. 2. The histograms show the raw continuum spectra in coincidence with the (background corrected) gamma-ray lines from specific reaction products (labeled). Negative or zero counts are plotted at the bottom of the figure. The dots show the unfolded spectra in regions where the statistical variations are not too large.

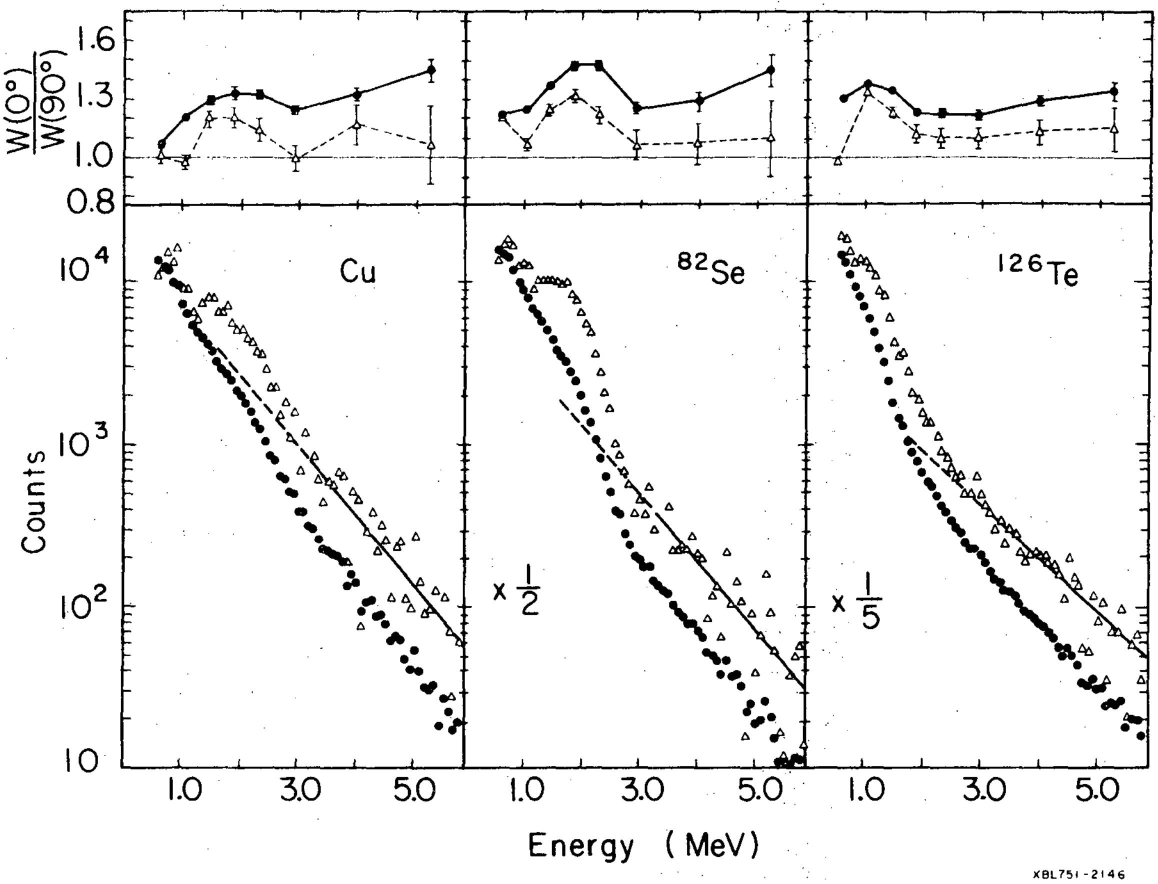
W(0°)/W(90°)
1.6
1.3
1.0
0.8
Counts
10^4
10^3
10^2
10
Cu
^{82}Se
^{126}Te
x 1/2
x 1/5
1.0
3.0
5.0
Energy (MeV)
XBL751-2146

Fig. 1

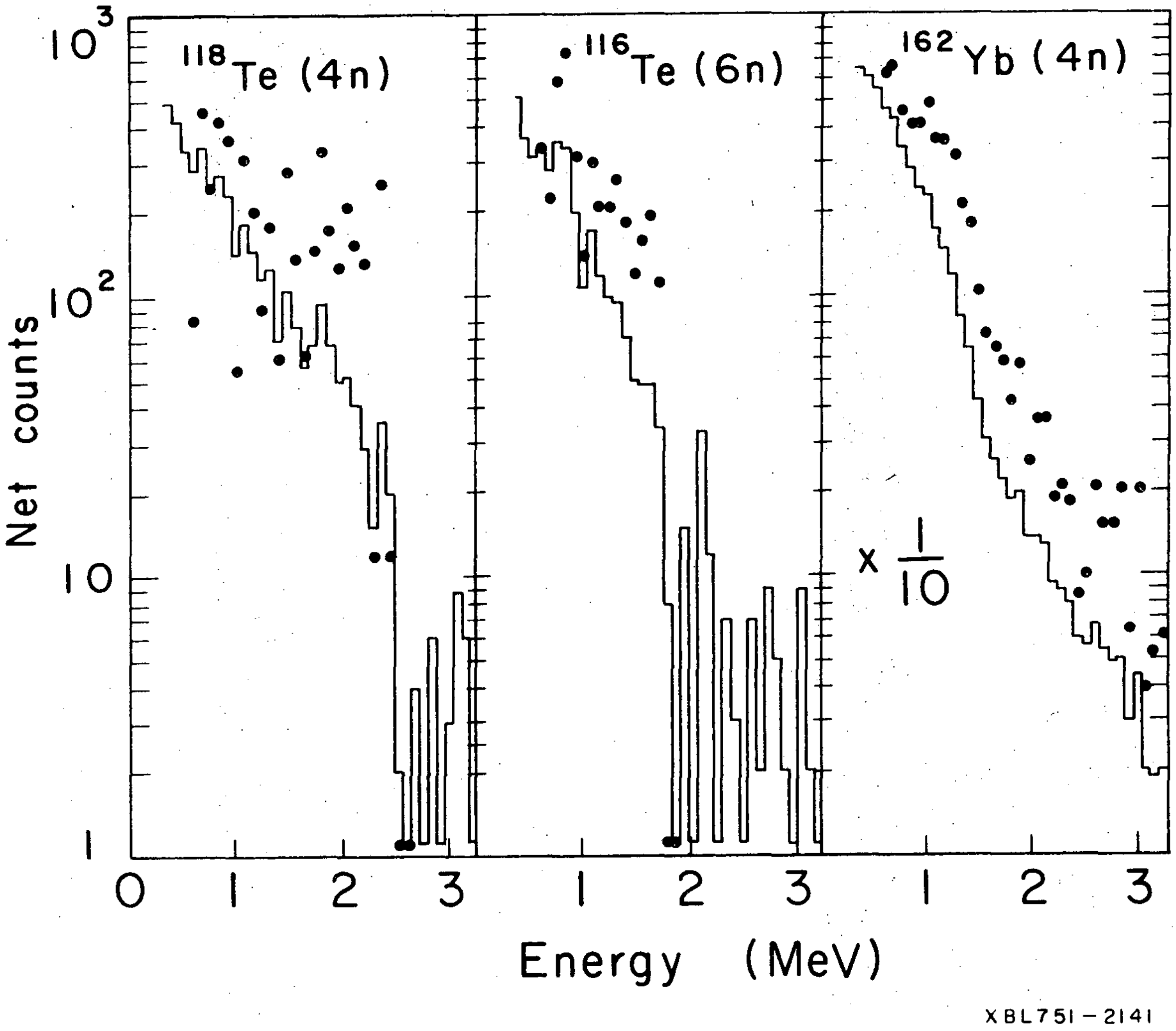
^{118}Te (4n)
^{116}Te (6n)
^{162}Yb (4n)
x $\frac{1}{10}$
Net counts
10^3
10^2
10
1
0
1
2
3
1
2
3
1
2
3
Energy (MeV)
XBL751-2141

Fig. 2

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