

were distributed uniformly among the several unresolved excited states comprising the n_{II} group, this would put the strength for each state close to or below the limit of observation of most noncoincidence measurements.

The effects described here could account for at least part of the discrepancies found in the lead region, where the weak-coupling model works well. Some of the reported width and cross-section discrepancies for ^{207}Pb and ^{209}Bi , however, require an even larger excited-state contribution than is seen in ^{119}Sn . Furthermore, the width anomaly for ^{208}Pb remains³ even at energies too low to populate excited-state analogs. Nevertheless, a careful comparison of measurements taken in an $n\text{-}\bar{p}$ coincidence experiment, such as the present one, with those taken in (p, n) and un gated \bar{p} experiments should give valuable insight about the processes involved in the formation and decay of isobaric analog states.

†Work supported in part by the U. S. Atomic Energy Commission, Contract No. AT(11-1)-1265.

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Transitions between High-Spin Nuclear States*

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(Received 3 February 1975)

We have measured the energy spectra, angular correlations, and number of continuum γ 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 $80\hbar$) can be brought into compound nuclei following heavy-ion reactions; however, γ -ray studies following such reactions have thus far produced information mainly on states having spins below $\sim 20\hbar$. 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 γ 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 $60\hbar$.

We have studied mainly the reactions $^{82}\text{Se}(^{40}\text{Ar}, xn)^{122-x}\text{Te}$ and $^{126}\text{Te}(^{40}\text{Ar}, xn)^{166-x}\text{Yb}$ by using 183-MeV Ar beams from the Lawrence Berkeley Lab-

oratory SuperHILAC. In addition, a limited survey over target (Al, Cu, As, Ag, Sn, and Sm) and projectile (^{16}O and ^{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 γ rays, we used three 7.5-cm \times 7.5-cm NaI(Tl) detectors at angles of 0, 45, and 90 $^\circ$ 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 γ 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 $^\circ$ to the beam direction. The Ge singles spectrum was stored simultaneously.

To obtain the true γ -ray 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 $^\circ$ NaI-detector spectra in coincidence with the full Ge-detector 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 that the recoiling nuclei stop before γ -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 $^\circ$ -90 $^\circ$ ratio from the raw spectra are given in 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 $^\circ$ -90 $^\circ$ 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-detector spectrum with the corresponding coincident one (together with the known detection probability in the NaI detector) gives the average number of γ rays, \bar{N}_γ . These three basic types of information, $N(E_\gamma)$, $W(\theta, E_\gamma)$, and \bar{N}_γ , 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 ap-

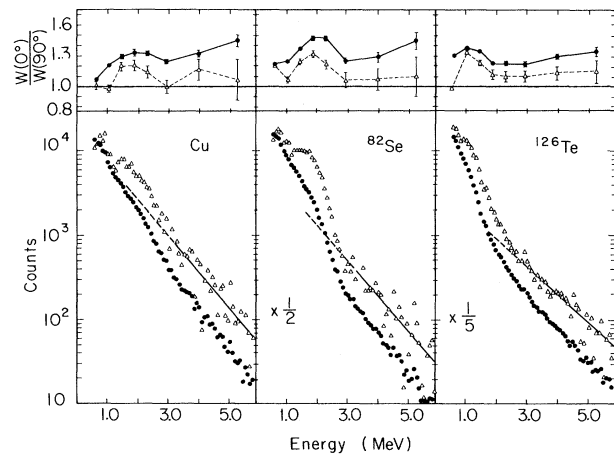


FIG. 1. The raw (dots) and unfolded (triangles) continuum spectra in coincidence with the full Ge-detector spectrum for 183-MeV ^{40}Ar projectiles on natural Cu, ^{82}Se , and ^{126}Te targets. The straight lines are fitted to the unfolded spectrum between 3.2 and 6.2 MeV (solid portion) and extrapolated to lower energies (dashed portion). The upper plots show the 0 $^\circ$ -90 $^\circ$ ratios for the raw data (dots) and for the unfolded data corrected for recoil motion (triangles). The error bars indicate statistical errors only.

proximately 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 1 to 1.5 MeV ($T = -dE/d \ln N$) 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 the intensity of the stretched- $E2$ component of the bump generally increase 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 $Z \sim 50$ as is illustrated by the curve for a Cu target in Fig. 1. Correspond-

ingly, 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 show that for the heavier nuclei nearly all the transitions are contained in the bump, whereas this is not generally true for the lighter ones. This variation 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 $^{82}\text{Se}(^{40}\text{Ar}, xn\gamma)^{122-x}\text{Te}$, 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

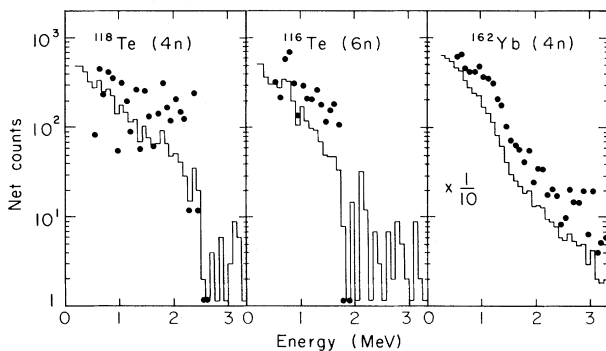


FIG. 2. The histograms show the raw continuum spectra in coincidence with the (background-corrected) γ -ray lines from specific reaction products (labeled). Negative or zero counts are plotted at the bottom of the figure. The dots show the unfolded spectra in regions where the statistical variations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

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 \bar{N}_γ 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 $\sim 2\bar{N}_\gamma$, or 58, 40, and $26\hbar$. This procedure has been shown in other cases⁵ to be consistent with estimates of the channel angular momentum based on cross-section measurements. Since the highest γ -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 ($33\hbar$) seems unlikely to be in error by more than $\sim 15\%$. The $4n$ value should be rather near the measured average, and $64\hbar$ (the Bass-model⁹ dynamic limit for this reaction) seems likely to be correct within $\sim 15\%$. These estimates give $2g/\hbar^2$ values of 75 MeV^{-1} for $I \sim 33$ and 110 MeV^{-1} for $I \sim 64$. For comparison, the value of $2g/\hbar^2$ is 39 MeV^{-1} for the $8 \rightarrow 6$ transition⁸ in ^{118}Te , and 85 MeV^{-1} for a rigid sphere of mass 118. The liquid-drop estimates¹⁰ for $I = 33$ and 64 in ^{118}Te are 91 and 104 MeV^{-1} . The spectrum for ^{162}Yb from the $^{40}\text{Ar} + ^{126}\text{Te}$ reaction is also shown in Fig. 2, and an estimate similar to those above gives $2g/\hbar^2 \sim 140 \text{ MeV}^{-1}$ at $I \sim 48$. The rigid-sphere value for this case is 141 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 seems likely that these transition energies and associated spins are roughly correct.

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 $60\hbar$, indicating a rather rapidly increasing moment of inertia (a backbending is not excluded). This kind of behavior is expected from liquid-drop-model studies¹⁰ of Te nuclei as a result of shape changes caused by centrifugal forces which eventually are limited by fission. The predicted shape changes can at times be drastic and result in "superdeformed" nuclei.¹¹ Independent evidence¹² 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 cutoff 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 γ -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 γ -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 γ -ray continuum will provide access to much of the desired information about high-spin states.

We are indebted to W. J. Swiatecki for many stimulating discussions, and to P. O. Tjøm, J. de Boer, and W. E. Meyerhof for their help in the early phases of this work. We also thank K. S. Krane and P. C. Simms for their help with the angular-correlation calculations. The cooperation and support of the SuperHILAC operating crew is gratefully acknowledged.

*Work done under the auspices of the U. S. Atomic

Energy Commission.

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Interference between Direct and Indirect Modes in Two-Nucleon Transfer Reactions with Heavy Ions*

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(Received 3 February 1975)

Direct and indirect transitions to the lowest 2^+ collective states are shown to interfere constructively in the pickup reaction $^{122}\text{Sn}(^{16}\text{O}, ^{18}\text{O})^{120}\text{Sn}$ at 104 MeV, and destructively in the inverse stripping reaction $^{120}\text{Sn}(^{18}\text{O}, ^{16}\text{O})^{122}\text{Sn}$ at 99 MeV.

The presence of indirect transitions in two-neutron transfer reactions to vibrational states in the Sn isotopes has been predicted to have the

interesting consequence that the interference between direct and indirect modes is destructive in stripping and constructive in pickup.^{1,2} The effect