in our 0_g^+ cross section.

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Observation of the Yrast and Statistical Cascades in (Heavy-Ion, $xn\gamma$) Reactions

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The energy spectra and angular distributions of the yrast and statistical cascades in ^{160,162}Yb have been obtained from measurements of the reactions ^{147,149}Sm(^{16}O, 3*n*) and ^{148,150}Sm(^{16}O, 4*n*). An average of about six yrast and six statistical γ rays occur in the 4*n* reaction. The data suggest that the yrast γ rays are mostly stretched *E*2.

In recent years the study of discrete lines from low-lying states of final-product nuclei formed in (heavy-ion, $xn\gamma$) reactions has led to new and valuable information on nuclear states of high angular momentum.[1] However little effort has been devoted to the study of the γ-ray cascade resulting from the decay of the highly excited states. Because of the high level density in this region these γ rays cannot be resolved and they form a continuum.

The present view of the continuum decay[1] is briefly outlined below. States of high angular momentum ($\gtrsim 20\hbar$) lying below about 1 neutron binding energy above the yrast line are expected to decay to states within a region of a few hundred keV above the line, mainly by a few dipole transitions, carrying away on the average little angular momentum but considerable energy. These transitions may have an energy distribution related to a statistical evaporation spectrum. States in the yrast region are forced to decay along this region mainly by stretched transitions to states of lower spin and energy until the ground-state band (gsb) is reached. Decay then proceeds through the gsb. The time of ~10 psec between the initial formation of the compound nucleus and entry to the gsb[1] implies that the states in the intersection region must be heavily admixed and that the transitions in the yrast region must be mainly *E*1, *M*1, or *E*2 and must have little dispersion in energy. The theoretical work of Stephens and Simon[2] suggests that the transitions should be mainly *E*2. Little direct experimental evidence has been presented to support this model although recently Tjøm *et al.*[3] and der Mateosian, Kistner, and Sunyar[4] reported measurements which determine the average numbers of continuum γ rays for several cases without separating the statistical and yrast contributions.

The present experiments were undertaken to investigate the continuum γ rays and in particular to distinguish the yrast and statistical cascades. For this purpose the response function of the detector is much more important than its energy resolution and therefore a 7.5 cm×7.5 cm NaI(Tl) detector was used. Since neutrons as well as γ rays produce events in the detector, these were distinguished by time of flight, the NaI detector being located 59 cm from the target. The zero-time reference was provided by pulses from neutrons with energies greater than ~1 MeV detected in a 7.5 cm×7.5 cm NE 213 scintillator placed 3 cm from the target at 0° to the beam direction. Gamma-ray pulses in the neutron detector were rejected by a n-γ pulse-shape discrimination system. A time resolution of 8 nsec (full width at half-maximum) was obtained. The fraction of counts under the γ-ray time peak due to neutron-induced events in the NaI detector was deduced from a time spectrum taken at a distance of 122 cm, where the neutron and γ-ray distributions were better separated. Approximately 5% of the events in the γ-ray window arose from neutrons and random coincidences. The shapes of the NaI spectra due to these and to γ-ray–induced events were deduced by gating with windows set off and on the γ-ray time peak. This method has the advantages of higher counting rate and of more precise subtraction of the effect of neutrons over the γ-γ coincidence method,[3,4] in which the interposing of lead absorbers can both scatter neutrons and produce γ rays. The n-γ method has the disadvantage that the observed continuum γ rays are not precisely restricted to a single reaction. However the bombarding energy was chosen so that the reaction of interest was dominant.

Two sets of reactions leading to the same final nuclei were studied: (1) ^{147}Sm + 75-MeV ^{16}O, ^{148}Sm + 94-MeV ^{16}O, producing ^{160}Yb and (2) ^{149}Sm + 73-MeV ^{16}O, ^{150}Sm + 88-MeV ^{16}O, producing ^{162}Yb. The ^{16}O beams were provided by the Australian National University 14UD pelletron accelerator. The rolled targets of separated metallic $^{147-150}$Sm were about 4 mg cm^{-2} thick, mounted on uranium backings. Coincidence and singles

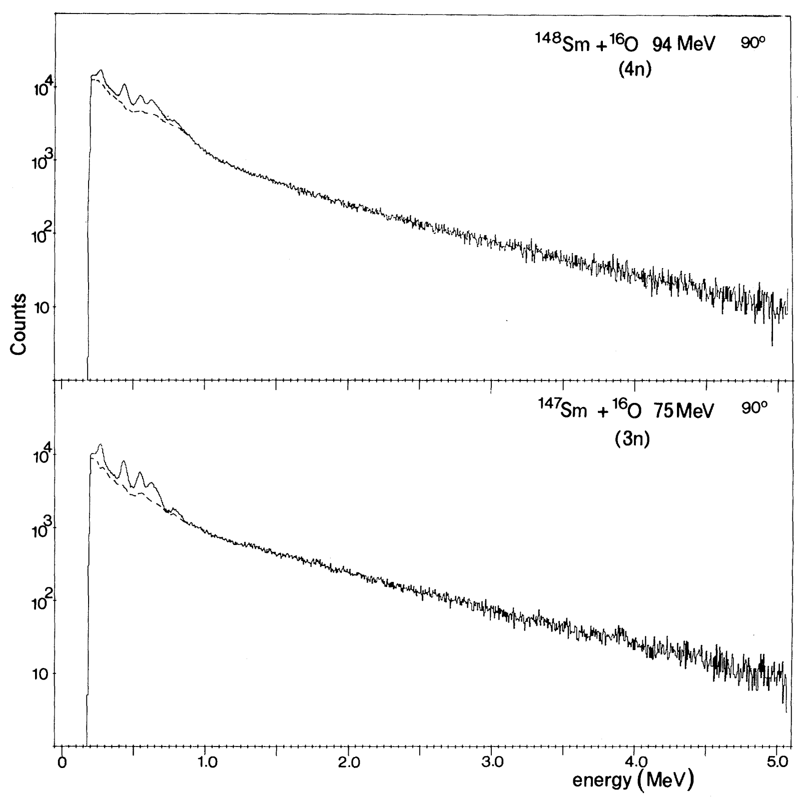

FIG. 1. Pulse-height spectra of γ rays gated by neutrons; dashed lines indicate results after subtraction of discrete lines. Subtractions have no effect above 0.8 MeV.

measurements were taken at angles of 30°, 60°, and 90° with the NaI detector, and also with a Ge(Li) detector placed at 17 cm from the target.

Typical NaI γ-ray spectra in coincidence with neutrons are shown in Fig. 1. Rather few yrast γ rays are expected in the $3n$ reaction ($l_{max} \approx 21$) but many in the $4n$ reaction ($l_{max} \approx 39$). In all cases the shapes of the spectra above 1.5 MeV (statistical) are very similar, but below 1 MeV the $4n$ spectra rise more sharply than do the $3n$ spectra. The shapes of the continuum spectra (Fig. 1) were determined by removing the discrete lines whose intensities ($\gtrsim 5\%$ of that of the $4 \to 2$ transition) were derived from the gated Ge(Li) spectra. The discrete NaI spectra were constructed with the aid of a computer program which interpolated between measured monoenergetic line shapes. Each $3n$ spectrum was then subtracted from the appropriate $4n$ spectrum after normalization of the regions from $E_\gamma = 2.5$ to 4.5 MeV. Results for the case of ^{160}Yb are shown in Figs. 2(a) and 2(b).

If, as seems plausible, all of the statistical spectra have the same shape over the whole range of γ-ray energies and if the average numbers of statistical γ-rays per $4 \to 2$ transition are the same, this subtracted spectrum will correspond to the difference between the *yrast* spectra for the $4n$ and $3n$ reactions. The second assumption is supported by the near equality of the numbers $\overline{N}_{>1.0}$ of γ rays with energies greater than 1 MeV (Table I). Gamma-ray intensity distributions for ^{160,162}Yb, obtained by correcting the subtracted pulse-height spectra for the detector response, are shown in Fig. 2(c). Although the errors involved in these distributions are large (up to $\pm 20\%$ on some low-energy points), the shapes appear to be significantly different, a strong peak at about 700 keV being evident for ^{160}Yb.

The average numbers $\overline{N}_{>E}$ (per $4 \to 2$ γ ray) of continuum γ rays with energies greater than E (MeV) in the original and subtracted spectra, determined with an estimated uncertainty of $\pm 20\%$, are shown in Table I. Estimated values for l_{rms} and values $\overline{N}_{yt}$ for the number of yrast γ rays deduced from the following simple model are also shown in Table I. It was assumed that after an initial compound-system state of angular momentum $l\hbar$ was formed, $3\hbar$ on the average was lost in neutron and statistical γ-ray emissions, and that the yrast γ rays were stretched $E2$. Hence $\overline{N}_{yt}(l) = (l - 3 - I_{max})/2$, where I_{max} is the spin of the highest rotational state populated with at least half of the intensity of the $4 \to 2$ transition. The relative populations of initial states of different l were obtained from an optical-model calculation. There is fair agreement between the values of the $\overline{N}_{>0.3}$ for the subtracted spectra and those for $\overline{N}_{yt}$. Our value of 7.9 for $\overline{N}_{>0.62}$ in the reaction ^{150}Sm(^{16}O, $4n$)^{162}Yb is in good agreement with the value of 9 obtained by Tjøm *et al.*[3] for $\overline{N}_{>0.6}$ in the same reaction.

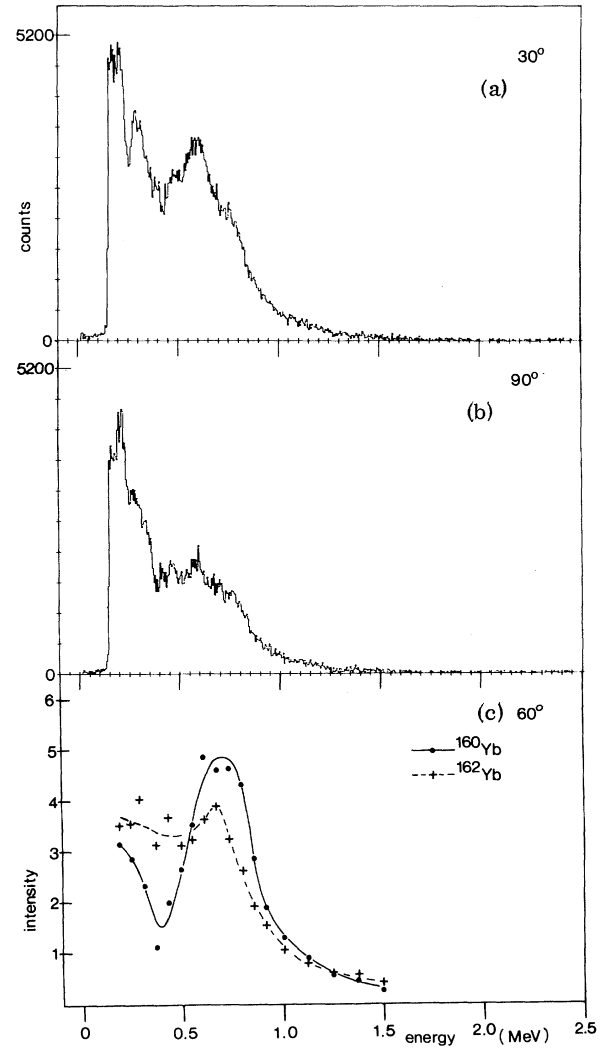

FIG. 2. (a), (b) Subtracted $(4n) - (3n)$ spectra for reactions leading to ^{160}Yb. (c) γ-ray intensity distributions at 60° derived from the subtracted spectra by unfolding with the detector response function. The full and dotted lines are intended to guide the eye.

The angular-distribution measurements led to the following values for the coefficients A_k in the usual expansion $W(\theta) = 1 + \sum_k A_k P_k(\cos\theta)$. In the energy range 2.5 to 4.5 MeV (statistical region), the A_2 for all four reactions are consistent with a value of 0.06 ± 0.07. For the energy range of 0.7 to 1.25 MeV in the subtracted spectra, values of A_2 and A_4 of 0.43 ± 0.1 and -0.4 ± 0.12 were obtained for ^{160}Yb and 0.27 ± 0.10 and -0.16 ± 0.13 for ^{162}Yb. These values are close to those for the gsb γ rays and are consistent with their corresponding to stretched $E2$ transitions. We do not quote values for energies less than 0.7 MeV because of uncertainties arising from the subtraction of the discrete γ rays. However qualitatively it appears that below about 0.5 MeV the angular distributions of the subtracted spectra become more isotropic, possibly even changing the sign of the anisotropy. This effect, seen in Figs. 2(a) and 2(b), may be due to the presence of stretched dipole γ rays in the lower-energy region.

From Table I, it can be seen that the number of γ rays in the $3n$ reactions with $E > 0.3$ MeV ($\bar{N}_{>0.3}$) is about 8, of which a large fraction (~50%) have $E < 1.0$ MeV. This would be an unreasonable energy distribution if all of these γ rays were statistical. However, the measured angular distributions in the $3n$ reactions are anisotropic below 1.5 MeV in contrast to the isotropic distribution above 1.5 MeV. We attribute this anisotropy to the effect of nonstatistical γ rays. To estimate the nonstatistical contribution the 90° spectrum was subtracted from the 30° and 60° spectra for each $3n$ reaction. Assuming that their angular distributions correspond to stretched $E2$ transitions, we find that for $E > 0.3$ MeV the number of nonstatistical γ rays per $4 \rightarrow 2$ transition ($\bar{N}_N$) is $2.3^{+0.8}_{-0.5}$ for both $3n$ reactions. It follows that the number of statistical γ rays ($\bar{N}_S$) is about 6 for the $3n$ reactions.

A similar procedure for the $4n$ spectra, together with the near equality of $\bar{N}_{>1.0}$ for the $4n$ and $3n$ spectra, leads to the same value of $\bar{N}_S$ for the $4n$ reactions. Then the number of nonstatistical γ rays $\bar{N}_N = \bar{N}_{>0.3} - \bar{N}_S$ is 6 in the $4n$ reactions as compared with 2 in the $3n$ reactions. This result for the $4n$ reactions is in good agreement with the model predictions for the yrast γ rays. In the case of the $3n$ reactions the experimental value appears to be significantly larger than the prediction. A possible source of nonstatistical γ rays (other than yrast γ rays) is from the decay mode suggested for low-angular-momentum reactions.[5] In these reactions the observation that more angular momentum is lost before entry into the gsb than would be expected from a simple statistical cascade led to a model which invoked decay via a few stretched transitions in rotational bands based on two-quasiparticle states.

TABLE I. Average numbers $\bar{N}_{>E}$ of continuum γ rays with energies greater than E (MeV). The number $\bar{N}_{\text{yt}}$ is an estimate for the yrast γ rays.

Reaction	l_{rms}	$\bar{N}_{>0.3}$	$\bar{N}_{>0.62}$	$\bar{N}_{>1.0}$	$\bar{N}_{\text{yt}}$
^{160}Yb					
$3n$	12	8.5	6.0	4.1	0.9
$4n$	26	12.7	9.0	4.7	6.5
$(4n) - (3n)$		4.2	3.0		5.6
^{162}Yb					
$3n$	10	7.8	5.9	4.5	0.5
$4n$	23	11.6	7.9	4.6	5.2
$(4n) - (3n)$		3.8	2.0		4.7

In this investigation, it has been possible for the first time to distinguish between the yrast and statistical cascades, to show that the average numbers of γ rays involved in them are in accordance with simple estimates, and to show that the shape and intensity of the statistical spectrum are approximately independent of the reaction. Although there is not a great difference in $l_{\max}$ for the two $4n$ reactions, the shapes of the yrast spectra are significantly different, thus making it of considerable interest to extend this type of measurement to many more cases. It is shown that the higher-energy portion of the yrast spectrum is consistent with stretched $E2$ transitions. The detailed spectrum shape at low energies ($\lesssim 0.5$ MeV) is extremely sensitive to the accuracy of subtraction of the discrete lines, and an investigation of the possible dipole component would require greater accuracy than we have been able to achieve so far.

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Production of Prompt Muons by the Interaction of 28-GeV Protons*

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Analyses of measurements of muons produced directly, in the forward direction, by the interaction of 28-GeV protons with uranium show that the muon/pion production ratio for negative particles is 13×10^{-5} for 11.6-GeV particles, 2.6×10^{-5} at 20.3 GeV, 1.3×10^{-5} at 23.5 GeV, and 7.0×10^{-6} at 25 GeV. The largest ratio is similar to ratios measured at higher energies and large transverse momenta and none of the ratios are easily explained in terms of conventional mechanisms.

In work reported previously,[1,2] we presented measurements of a substantial flux of prompt muons produced by the interaction of 28-GeV protons with uranium. Here we define prompt leptons as leptons produced very near the point of the hadron interaction, excluding muons derived from the decay of long-lived mesons. While production cross sections for such prompt muons were determined and discussed[2]—and attributed, tentatively, to electromagnetic production of muon pairs—the ratio of prompt-muon to pion production was not calculated for all of the measurements, and such ratios cannot be derived in any very transparent manner from the published data. In view of the considerable interest in the measurements of the ratios of prompt leptons to pions produced at large transverse momenta[3-6] by proton-nucleon interactions at very high energies, we have calculated these ratios for our data. Our measurements are complementary to the high-energy data inasmuch as our determinations were made in the forward direction, at large values of the Feynman variable x, and at the moderate proton energy of 28 GeV.

The experimental measurements made at the Brookhaven alternating-gradient synchrotron, and described in detail in Ref. 2, were conducted by determining the flux of muons which stopped in an aluminum and scintillator sandwich, where the muons were produced in a series of segmented uranium targets backed by a steel-filled magnet and steel absorbers. The energy of the muons was defined by the thickness of the steel absorber; the sign of the muon charge was determined by the magnetic deflection and the lifetime in aluminum; and the characteristics of the origin of the muons were defined by the variation of muon flux with the effective density of the target. Three targets were used: one of solid uranium with an average density $\rho(1)$, one of alternate sections of uranium and air with an average density $\rho(2)$ equal to $\frac{1}{2}\rho(1)$, and a third with an effective density $\rho(3)$ of $\frac{1}{3}\rho(1)$. The targets each had a thickness of about 5 proton interaction lengths of uranium backed by meters of steel: We can consider that the targets were effectively of infinite thick-