is not rising because the low-Z_3 fragments are preferentially populated by low-l waves. The analysis of the Z distributions and angular distributions as a function of Z performed independently by some of us has led to the same conclusion.[1,8] The explanation for such an effect is simple. The potential energy versus mass asymmetry depends strongly on angular momentum. In the present case, at the entrance-channel asymmetry, the potential energy slopes gently towards symmetry for small angular momentum and it becomes progressively steeper with increasing angular momentum. Therefore only the lowest-l waves contribute to the population of fragments substantially lighter than the projectile. These preliminary conclusions about the fractionation of the angular-momentum distributions are of interest because of their implication for the l dependence of particle, energy, and angular momentum transfers. Further studies along the present lines will be needed to clarify these essential aspects of heavy-ion reactions.

This work was done with support from the U. S. Department of Energy.

[a]On leave from Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Domaine du Haut-Vigneau, 33170 Gradignan, France.

[b]Present address: Physikalisches Institut der Universität Heidelberg, Philosophenweg 12, D-69 Heidelberg, W. Germany.

[c]On leave from Institut de Physique Nucléaire, 91406 Orsay, France.

[1]L. G. Moretto and R. Schmitt, J. Phys. (Paris), Colloq. 37, C5-109 (1976), and references therein; W. U. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. 27, 465 (1977), and references therein.

[2]P. Glässel, R. S. Simon, R. M. Diamond, R. C. Jared, I. Y. Lee, L. G. Moretto, J. O. Newton, R. Schmitt, and F. S. Stephens, Phys. Rev. Lett. 38, 331 (1977).

[3]M. Ishihara, T. Numao, T. Fukada, K. Tanaka, and T. Inamura, ANL Report No. ANL/PHY 76-2 (unpublished), p. 617.

[4]M. Berlanger, M. A. Deleplanque, C. Gerschel, F. Hanappe, M. Leblanc, J. F. Mayault, C. Ngô, D. Paya, N. Perrin, J. Péter, B. Tamain, and L. Valentin, J. Phys. (Paris) 37, L323 (1976).

[5]H. Sann, A. Olmi, Y. Civelekoglu, D. Pelte, U. Lynen, H. Stelzer, A. Gobbi, Y. Eyal, W. Kohl, R. Renfordt, I. Rode, G. Rudolf, D. Schwalm, and R. Bock, Gesellschaft für Schwerionenforschung MbH, Darmstadt, Report No. GSI-P-5-77 (to be published).

[6]G. B. Hagemann, R. Broda, B. Herskind, M. Ishihara, S. Ogaza, and H. Ryde, Nucl. Phys. A245, 166 (1975).

[7]P. O. Tjøm, F. S. Stephens, R. M. Diamond, J. de Boer, and W. E. Myerhof, Phys. Rev. Lett. 33, 593 (1974).

[8]L. G. Moretto, Lawrence Berkeley Laboratory Report No. LBL-6572 (to be published).

Evidence for a Dipole Component in the Yrast Cascade

J. O. Newton, S. H. Sie, and G. D. Dracoulis
Department of Nuclear Physics, The Australian National University, Canberra, Australian Capital Territory, Australia
(Received 15 November 1977)

The shapes and angular distributions of continuum γ-ray spectra for $^{174,175}W$ and ^{161}Yb, produced through (^{16}O,xn) reactions, have been measured down to $E_\gamma \simeq 300$ keV. Large negative anisotropies are observed at the lower energies, suggesting the existence of a dipole component in the yrast cascade. A simple model gives good agreement with the results.

The properties of nuclei with very high angular momentum are of great topical interest. Information on states of spin $I \gtrsim 22$ is very fragmentary and comes almost entirely from studies of the "continuum" γ rays following (heavy ion,xn) reactions.[1-5] It was suggested[6] that these γ rays arise from a cascade of statistical, mainly dipole, γ rays from the initial highly excited states to the region near to the yrast line, and a cascade of stretched $E2$ transitions down collective bands nearly parallel to the yrast line. When the ground-state band (gsb) becomes the yrast band, usually for $I \lesssim 16$, the population gradually transfers to the gsb via "dumping transitions," the transfer being almost complete by $I \simeq 8$. Strong discrete transitions are seen from the gsb. The statistical and yrast cascades and the dumping transitions form effective continua since the weak individual γ rays in them cannot be resolved. The dumping continuum consists only of direct transitions from the yrast region to the gsb; i.e., cross-band transitions within the yrast region are included in the yrast cascade, and therefore it has a multiplicity $\bar{M} \lesssim 1$ and is weaker than the other two. It might be expected to show little dependence on angular-momentum input except when this is very low. The present study is concerned with the shapes of the continuum spectra. Such measurements yield values for $d\bar{M}/dE_\gamma$ as a function of γ-ray energy E_γ, which can be interpreted in terms of an average moment of inertia $\mathscr{I}_y(I)$ of the collective bands in the yrast region.

In measuring continuum spectra the response function of the detector is much more important than its energy resolution. For this reason, NaI(Tl) rather than Ge(Li) detectors have been used. However, because of the relatively poor resolution of the NaI detector, the discrete transitions, which in rare-earth nuclei have $E_\gamma \lesssim 700$ keV, cannot be clearly resolved from the continuum spectrum. The $E2$ part of the continuum spectrum extends below 700 keV because $\mathscr{I}_y(I) > \mathscr{I}_{\text{gsb}}(I)$, while any dipole part that may exist might be completely obscured since probably $E_\gamma(\text{dipole}, I) \simeq \frac{1}{2}E_\gamma(E2, I)$. Hence to see all of the continuum spectrum, which is necessary if the yrast cascade is to be property understood, it is essential to subtract out the effect of the discrete lines.

With one exception,[2] the present work is the only case where the discrete lines have been subtracted. This has enabled us to obtain evidence for the existence of a substantial number of continuum γ rays with low energies. We have also, for the first time, made an attempt at detailed fitting of the shapes of yrast cascade spectra.

The method is an improved version of that of Ref. 2. The reactions ^{148,149}Sm(^{16}O,xn)^{161}Yb at bombarding energies of 75 and 88 MeV, respectively, ^{163,164}Dy(^{16}O,xn)^{175}W at 82 and 98 MeV, and ^{162,163}Dy(^{16}O,xn)^{174}W at 81 and 96 MeV were initiated with beams from the Australian National University's model 14UD Pelletron. Enriched, $\simeq$4-mg$\cdot$cm^{-2}, metal targets on 0.12-mm uranium backings were used. γ rays with $E_\gamma \lesssim 5$ MeV were detected in a 7.5×7.5-cm NaI(Tl) detector, placed at 58 cm from the target, and in a Ge(Li) detector, subtending the same solid angle, at angles of 30°, 45°, 60°, and 90° to the beam direction. Both were taken in coincidence with neutron pulses from a 7.5×7.5-cm NE 213 scintillator, placed at 4 cm from the target and 3° to the beam direction; a lead absorber attenuated most of the γ rays, the remainder being rejected by pulse shape discrimination. A large proportion of the neutron-induced events in the NaI detector were rejected by time of flight and small corrections were made for the fraction of them ($\simeq$4%) under the γ-ray time peak and for radiation from the uranium backing. This method lacks the specificity to a particular reaction of some methods[3,5] but has the advantage of much higher data collection rate. By optimizing the bombarding energy we estimate that $\gtrsim 65\%$ of the cross section goes into the dominant xn reaction, most of the remainder going to $(x \pm 1)n$ reactions, ~10% into charged-particle reactions, and ~1% into fission. γ rays from Coulomb excitation and most of those from transfer reactions are eliminated by the $n\gamma$ coincidence requirement. Most of the evidence so far,[3,5] including the present study, has shown little difference in the continuum spectra for adjacent odd-mass and doubly even nuclei. In this paper, data for a particular xn reaction mean those for the optimized reaction.

For $E_\gamma \lesssim 1.3$ MeV the NaI spectra show discrete lines together with a broad structure mainly from the yrast cascade [Figs. 1(a) and 1(b)]. Above this energy all of the spectra fall approximately as $\exp(-\alpha E_\gamma)$, the constant α being independent, and the multiplicity nearly so of whether the final nucleus is produced by an xn or an $(x+1)n$ reaction. This part, attributed to the statistical cascade, has an approximately isotropic angular distribution. Each spectrum was first corrected for the discrete lines, whose energies and intensities were deduced from a Ge(Li) spectrum taken at the same angle; all lines with intensities $\gtrsim 5\%$ of the $4 \to 2$ transition were included. From these and from the relative efficiencies of the Ge(Li) and NaI detectors, a NaI spectrum was generated with a computer program which, in essence, interpolated between measured spectral shapes for twelve γ rays, with 0.122 MeV $\leqslant E_\gamma \leqslant 6.14$ MeV. Pulse height spectra for ^{174}W, before and after discrete-line subtraction, are shown in Fig. 1.

Since we were primarily interested in the yrast cascade, we tried to minimize the effect of the unknown shapes of the statistical and dumping spectra below $\simeq$1.3 MeV. Assuming reaction independence for these also, we normalized for each angle the regions 2 MeV $< E_\gamma <$ 4.5 MeV of the xn and $(x+1)n$ spectra and subtracted them

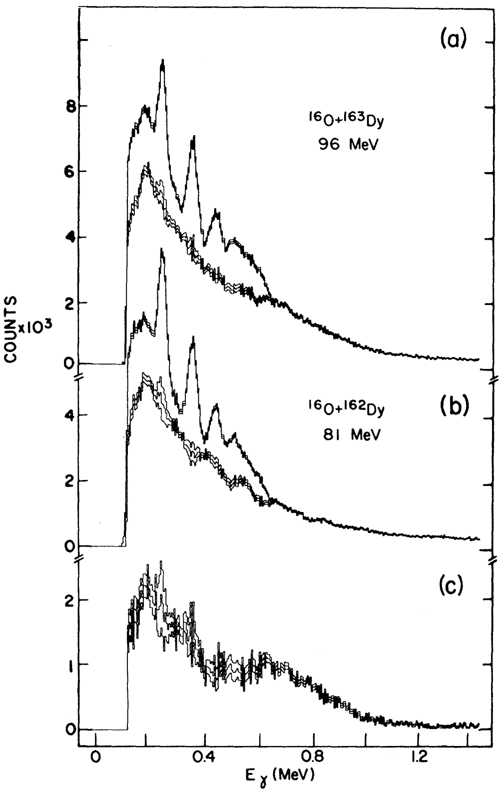

FIG. 1. Pulse-height spectra for reactions leading to ^{174}W ($\theta = 60°$): (a) $5n$, (b) $4n$, before and after the discrete-line subtraction; (c) the $5n - 4n$ spectrum. The vertical spread of the line indiates the statistical error.

[Fig. 1(c)]. The results should represent quite well the differences between the yrast cascade pulse-height spectra for the two reactions, which bring in different angular momenta to the system. They were then unfolded to give the γ spectra [see Fig. 2(a)]. Similarly, for each separate reaction, γ spectra corresponding to the differences between the sums of the 30° and 45° and the 60° and 90° spectra were obtained. If the angular distribution of the yrast cascade were independent of E_γ—e.g., if all were stretched $E2$—the resulting spectrum should have the same shape as the yrast cascade, but otherwise not. Such spectra are shown in Fig. 2(b), and the angular distribution coefficients A_2 for the unmodified spectra (including statistical part) in Fig. 2(c). The data are considered to be reliable down to $E_\gamma \simeq 300$ keV.

All three cases exhibit similar features. The $5n - 4n$ spectra show a broad peak having a maximum around 0.7 MeV, and a dip near 0.45 MeV followed by a rise at lower energy. Similar be-

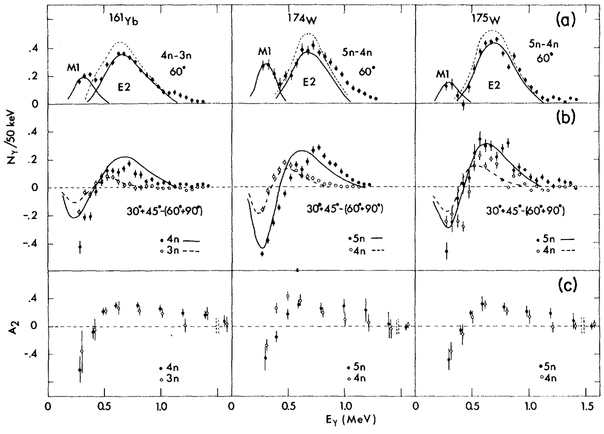

FIG. 2. (a) $(x+1)n - xn$ γ spectra for ^{161}Yb and ^{174,175}W. The dashed lines give model fits for $E2$ only and the full lines for $E2$ and $M1/E2$ components. (b) $(30° + 45°) - (60° + 90°)$ γ spectra for the $(x+1)n$ and xn reactions. The full and dashed lines are model fits to the data. (c) Angular distribution coefficients A_2 for the continuum γ-ray spectra.

havior occurs in the spectra for ^{160,162}Yb.[2] The broad peak is associated with a positive value of A_2, the angular distribution for the peak as a whole being characteristic of that for stretched $E2$ transitions and suggesting that the component transitions are of similar character. The sign of A_2 reverses through the dip, becoming large and negative at the lower energies; this is clearly reflected in the $(30° + 45°) - (60° + 90°)$ spectra. These large negative values indicate that most of the transitions have $\Delta I = 1$ and are dipole, with quadrupole admixtures $\delta^2/(1+\delta^2)$ in the range of about 0.005 to 0.16 or 0.76 to 0.97; here we have assumed a homogeneous character for the component transitions and that $I_i > I_f$, as seems most likely for the yrast region. The mixing ratio δ is negative.[7]

The precise origin of the dipole component is not clear since there is no adequate theory of the many bands which exist above the yrast line. In this region of nuclei, it is generally assumed that the states nearest to the yrast line for $I \gtrsim 16$ arise from rotation-aligned bands (which would not have in-band dipole transitions) based on the two-quasineutron $(i_{13/2})^2$ and similar configurations. However the observed discrete population within such bands is usually a very small fraction of the total population at the appropriate spin, indicating that the population is contained within many bands. Hence many of these might be deformation-aligned bands and $M1/E2$ $\Delta I = 1$ transitions within these bands could account for some or all of the dipole component. It might also arise from transitions, which could be $M1/E2$ and/or $E1/M2$, between different bands.

To get some insight into the yrast cascade decay we have made calculations with a simple model, the details of which will be reported later. Decay is assumed to occur through a large number of roughly parallel deformation-aligned collective rotational bands having definite K and with $\mathcal{J}$ tending smoothly to the rigid-body value $\mathcal{J}_{\text{rig}}$ at high angular momentum. The angular-momentum distribution of population to the yrast region is assumed to be that for the compound nucleus, deduced from the Bass model as modified by Broda *et al.*,[8] modified by allowing for the spreading and reduction in angular momentum due to neutron and statistical γ-ray emission. The yrast region is depopulated by the dumping transitions, which have been taken to be of I to $I-1$ type, though the results are not very sensitive to this assumption. The $E2$ part of the yrast cascade arises from the crossover transitions within the bands, and the mixed dipole ($M1/E2$) from the cascade transitions. The branching ratio was chosen to give the experimental "dipole" intensity in the $(x+1)n - xn$ spectrum at a spin corresponding to $E_\gamma \simeq 300$ keV, where the crossover component is negligible. Other branching ratios are then obtained from formulas such as $B(M1, I \to I-1)/B(E2, I \to I-2) \propto Q_0^{-2}K^2(g_K - g_R)^2 f(I,K)$ for branching ratios within rotational bands.[9] In calculating the curves in Fig. 2(b) we took the whole of the "dipole" continuum to have the same angular distribution, with $A_2 = -0.6$ [see Fig. 2(c)].

The agreement between the results shown in Fig. 2 and the data is surprisingly good considering the simplicity of the model and the fact that we have not varied parameters after the initial choice. The model fit determines the parameter $K^2(g_K - g_R)^2$ and, since typically $|g_K - g_R| \lesssim 1$, we find that $K \geq 3$ is required. It also gives a value for $\delta^2/(1+\delta^2) \simeq 0.01$ which is consistent with the range required by the angular distributions. The negative sign for δ would be given if the bands were based on quasineutron states.[10] The value suggested for K, which should be taken as an "average," seems in reasonable accordance with expectation since bands with lower K values are probably mostly too high in energy to be in the yrast region. The real situation must involve rotation-aligned bands ($\bar{K} \simeq 1$) as well. It is unlikely that the good qualitative agreement with the $E2$ part of the spectrum would be changed by different assumptions for the dipole part.

These results show, for the first time, that there is a substantial dipole component in the *yrast* cascade. The general shape of the spectrum for these cases can be well described by a model involving few adjustable parameters together with the assumption that the average moment of inertia of the collective bands tends to $\mathcal{J}_{\text{rig}}$ at large I. Further experimental and theoretical work is required to elucidate the origin of the dipole component, a first step being to determine whether it is $M1$ or $E1$, and to explain the negative sign of δ, if it proves to be a general feature.

We are indebted to J. R. Leigh for considerable help in the data collection.

[1] G. B. Hagemann, R. Broda, B. Herskind, M. Ishihara, S. Ogaza, and H. Ryde, Nucl. Phys. A245, 166 (1975).

[2] J. O. Newton, J. C. Lisle, G. D. Dracoulis, J. R. Leigh, and D. C. Weisser, Phys. Rev. Lett. 34, 99 (1975).

[3] R. S. Simon, M. V. Banaschik, P. Colombani, D. P. Soroka, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 36, 359 (1976), and references therein.

[4] J. O. Newton, I. Y. Lee, R. S. Simon, M. M. Aleonard, Y. El-Masri, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 38, 810 (1977).

[5] R. S. Simon, M. V. Banaschik, R. M. Diamond, J. O. Newton, and F. S. Stephens, Nucl. Phys. A290, 253 (1977).

[6] J. O. Newton, F. S. Stephens, R. M. Diamond, W. H. Kelly, and D. Ward, Nucl. Phys. A141, 631 (1970).

[7] T. Yamazaki, Nucl. Data, Sect. A 3, 1–25 (1967).

[8] R. Bass, Nucl. Phys. A231, 45 (1974); R. Broda, M. Ishihara, B. Herskind, H. Oeschler, and S. Ogaza, Nucl. Phys. A248, 356 (1975).

[9] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin Inc., Reading, Mass., 1975), Vol. II, Chaps. 4.3b and 4.3c.

[10] J. O. Newton, Nucl. Phys. A108, 353 (1968).