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COMPOUND AND PRECOMPOUND γ -RAY ENTRY LINES FROM MEASURED MULTIPLICITIES AND ENERGIES IN α -INDUCED REACTIONS

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Multiplicities of quasi-continuum γ -rays have been measured for the $^{160}\text{Gd}(\alpha, xn\gamma)$ reactions as a function of bombarding energy and for the $4n$ exit channel also as a function of γ -ray energy. Increase of beam energy causes initially an increase of the energy and angular momentum of the entry line in the residual nucleus until the neutron "drip line" is reached. This can be understood in terms of competing compound and precompound processes.

The entry line in the excitation energy versus angular momentum plane at which the quasi-continuum γ -ray cascades originate can be deduced from multiplicity measurements. Quasi-continuum γ -ray spectra are observed in α and heavy-ion (H.I.) induced reactions. Their gross structure has been established by measured γ -ray intensities [1] and multiplicities [2] which indicated the existence of two main components: a high-energy exponential tail and a low-energy bump. It has been shown earlier [3] for the $^{58}\text{Ni}(^{16}\text{O}, xp\gamma)$ reactions that the energies of the entry lines can be retrieved from the product of the average γ -ray energy and the average multiplicity.

In this letter we report on a determination of the entry line as a function of bombarding energy for the reaction $^{160}\text{Gd}(\alpha, 4n\gamma)^{160}\text{Dy}$. The energy and angular momentum of the entry line are seen to increase with beam energy until the neutron "drip line" is reached. We thus located the drip line in the residual nucleus which is the neutron instability line with zero binding energy for the neutrons to decay. Multiplicities are also reported as a function of bombarding energy for $^{160}\text{Gd}(\alpha, xn)$ reactions with $x = 4-8$.

The reactions $^{160}\text{Gd}(\alpha, xn\gamma)$ were induced by 40–110 MeV α -particles from the Groningen 280 cm AVF-cyclotron. The γ -ray cascades were detected with a set-up consisting of a 110 cm³ Ge(Li) detector in combina-

tion with 16 "3 × 2" diam. NaI(Tl) crystals in lead shieldings at a distance of 15 cm from the target. The full information was stored event by event on magnetic tape. The 0 to 6 fold coincidence Ge(Li) energy spectra, the Ge(Li) time spectrum and the 1-fold coincidence energy spectra of the 16 NaI detectors were simultaneously updated in the computer memory during the experiment. Using a new and faster converging algorithm [4] the multiplicity shape parameters were deduced from the measured multifold coincidence probabilities. These were obtained from the 0 to 6 fold coincidence Ge(Li) spectra for all relevant γ -ray transitions in the various final Dy isotopes. Multiplicities were also deduced from the same set data with different lower thresholds introduced off-line in the NaI energy spectra. The efficiency of the NaI detectors used in the extraction of the multiplicity was corrected for the cut off effects of the thresholds such as the Compton efficiency for γ -ray energies above the thresholds. Subtraction of multiplicities obtained with different thresholds yielded multiplicities within various γ -ray energy intervals. The related γ -ray energies were deduced from peeled and efficiency (thresholds included) corrected NaI spectra.

Fig. 1 shows the systematic behaviour of the average multiplicity $\langle M \rangle$ and multiplicity width σ_M as a function of bombarding energy. All exit channels but especially the $(\alpha, 4n)$ and $(\alpha, 6n)$ reactions show a steep increase of the multiplicity with increasing bombarding

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Fig. 1. Average multiplicities $\langle \bar{M} \rangle$ and widths σ_M determined for various reaction channels (top) which are cross-section averaged over all relevant (g.s.b.) transitions. The error bars are taken from the strongest transition in each reaction. The corresponding reaction cross sections (bottom) are determined from previous [5] and the present experimental data.

energy up to about 10 MeV above the energy where the cross section of that reaction reaches its maximum. At still higher beam energies the multiplicities and widths at least for the 4n and 6n exit channels remain approximately constant. A similar behaviour of the multiplicity has also been observed [6] previously for (α, xn) reactions on neutron deficient Sm isotopes. This saturation of the multiplicity for the individual reaction channels is apparently in contrast with a previously suggested [7] linear relationship between the average multiplicity and the average initial angular momentum brought into the compound nucleus by protons and H.I. projectiles. However, such a relationship can also be derived from the present data if one considers the multiplicity of the total reaction, thus

taking the cross-section averaged multiplicity of all exit channels as a function of input angular momentum. The contrasting behaviour of the multiplicity of the total reaction and of the individual exit channels indicates that the reaction mechanism should be considered in the interpretation of the relation between γ -ray multiplicity and angular momentum.

The main result of the present data concerns the relation between the multiplicity and the γ -ray energy deduced for the reaction $^{160}\text{Gd}(\alpha, 4n\gamma)^{160}\text{Dy}$ in the range of $E_\alpha = 40$ –70 MeV. From the total multiplicity for each g.s.b. member up to $J^\pi = 14^+$ “side-feeding” multiplicities were deduced for γ -rays within various energy intervals. These multiplicities were averaged with the intensities of the corresponding g.s.b. transitions as weight factors and the results are presented in fig. 2. The side-feeding γ -rays appear to have significantly higher energies than those of the g.s.b. and their energy averaged multiplicities increase with beam energy in the region of 40–50 MeV. From fig. 2 it is seen that mainly the high-energy ($E_\gamma > 1400$ keV) γ -rays are responsible for this multiplicity increase.

The γ -ray entry excitation energies have been retrieved for each g.s.b. member by adding the partial

Fig. 2. Side-feeding multiplicities which are cross-section averaged over the g.s.b. transitions for different γ -ray energy intervals, indicated on the right.

products of the side-feeding multiplicities and corresponding average energies within the energy bins indicated in fig. 2. These results can be compared with those obtained with the more commonly [3] employed method of taking the product of the total average multiplicity and average γ -ray energy ($\bar{E}_\gamma \approx 930$ keV at $E_\alpha = 49$ MeV). We find that the entry lines obtained with the two different methods agree within 10%. This agreement indicates that possible correlations between γ -ray multiplicity and γ -ray energy are of minor importance. This also implies that all quasi-continuum cascades have about the same γ -ray multiplicity and energy distributions.

The corresponding angular momenta of the γ -ray entry lines have been determined by assuming that the γ -rays carry away on the average two units of angular momentum for $E_\gamma < 600$ keV (yrast transitions), one unit for $E_\gamma = 600$ –1000 keV (mixed E1 and E2 transitions) and half a unit for $E_\gamma > 1000$ keV (mixed stretched and non-stretched E1 transitions). These assumptions are based on the measured angular distributions of the low-energy ($E_\gamma < 600$ keV) component which were found to be consistent with stretched E2 transitions while those of the high-energy exponential tail were nearly isotropic. This finding has also been reported earlier [1] for H.I. induced reactions. Combination of this information with the recently established [8] predominant E1 character of the high-energy γ -ray component for the same reaction and residual nucleus indicates a mixed stretched and non-stretched E1 character of this radiation. The deduced entry lines and the schematic γ -ray decay for the reaction $^{160}\text{Gd}(\alpha, 4n)^{160}\text{Dy}$ are presented in fig. 3. The measured widths of the multiplicity distributions (see fig. 1) are probably related to a spreading of the entry points in the excitation energy versus angular momentum plane. The entry lines thus merely represent the centroids of entry clouds. Therefore the relatively small variations in the positions of the entry lines seen in fig. 3 in the beam energy range of $E_\alpha = 50$ –70 MeV may be of minor significance. It should also be stated that reasonable changes in the above spin assumptions do not affect the positions of the entry lines significantly.

The data can be interpreted in terms of competing compound and precompound processes. The reactions appear to be dominated by compound nucleus processes in the region where the γ -ray multiplicity and the energy of the entry line increase with beam energy.

Fig. 3. Energy-spin entry lines or centroids of entry clouds of quasi-continuum γ -ray cascades following evaporation of neutrons at various bombarding energies. Energy values were obtained from average multiplicities and γ -ray energies and corresponding spin values by assuming certain spin releases per γ -ray transition (see text). M^s and E_γ represent average quantities of the γ -ray cascades connecting entry lines and g.s.b. members. The upper numbers are averaged over the results obtained at 49, 56 and 65 MeV. The upper four entry lines locate the neutron drip line.

Additional energy and angular momentum brought into the system are largely carried away by the γ -ray cascades. As is seen from fig. 1 this is the case up to beam energies of about 10 MeV above the energy at which the cross section for that reaction channel peaks. At even higher beam energies the emission of the next neutron becomes significant and a saturation of multiplicity and excitation energy occurs which is retained up to the highest applied beam energy. Competing precompound processes become then important in which neutrons carry off most of the additional angular momentum and energy. The entry lines remain located near the neutron drip line for all higher beam energies. This drip line is found about 8 MeV above and nearly parallel to the yrast line. This value is very close to the neutron binding energy ($E_n = -8.6$ MeV) in ^{160}Dy .

Additional evidence for the importance of precompound processes has recently been obtained [9] from measured neutron energy spectra in $\text{Dy}(\alpha, xn\gamma)\text{Er}$ reactions and from measured multiplicities in α and H.I. induced reactions [10]. The present data, particularly for the $(\alpha, 4n)$ and $(\alpha, 6n)$ reactions, in turn indicate that in the region where precompound processes are expected to dominate the system after neutron evaporation is left with excitation energy and angular momentum which are nearly independent of bombarding energy.

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