Intensity and Multipolarity of Low-Energy Components in the Quasicontinuum γ-Ray Spectrum Following α- and ^{12}C-Induced Reactions

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(Received 27 April 1979)

Measurements of K-shell ionization yields for (α, xn) and $(^{12}\mathrm{C}, xn)$ evaporation residues exclude the existence of a large $M1$ component in the quasicontinuum spectrum of well-deformed Dy nuclei below 500 keV. Upper intensity limits are deduced for $M1$, $E1$, and $E2$ components.

Conflicting experimental results concerning the multipole composition of the quasicontinuum γ-ray spectrum associated with α- and heavy-ion-induced reactions have recently been published. Angular-distribution experiments[1,2] as well as measured electron-conversion coefficients[3-5] established the existence of an intense $E2$ component in the relatively low-energy region (typically up to about 800–1000 keV) in deformed medium-heavy nuclides. For higher γ-ray energies a predominant $E1$ character was deduced from conversion-electron experiments in which care was taken to determine the specific reaction exit channels in α- (Ref. 3) and ^{20}Ne-induced (Ref. 4) reactions. A 30–50% $E2$ admixture to this high-energy $E1$ component was reported[5] on the basis of a similar experiment in which the exit channel was not specifically identified.

The conversion-electron data of Ref. 5 also indicated an increasing $M1$ contribution at low energies, with the conversion coefficients corresponding to practically pure $M1$ radiation at $E_\gamma = 500$ keV. This result seemed to confirm the earlier findings of Newton, Sie, and Dracoulis[6] of a "substantial dipole component" in the yrast cascade around $E_\gamma = 300$ keV for ^{16}O-induced reactions. The latter result was based on angular-distribution measurements in which the data handling involved subtraction of spectra obtained at various bombarding energies in order to enhance particular reaction exit channels. It was suggested that the dipole component was of a magnetic character and a simple physical model explaining this $M1$ radiation was proposed.[6] Deleplanque *et al.*[2] have reported intense, low-energy, stretched dipole transitions for ^{40}Ca- and ^{40}Ar-induced reactions leading to nuclei near closed shells.

It should be noted that in the work of Ref. 4, where the exit channel was identified by coincidence requirements with discrete γ rays, the results for the low-energy region (about 440–680 keV) were consistent with pure $E2$ multipolarity, with $M1$ contributions limited to less than 40%. The question of the existence of such an $M1$ component is important for understanding of the nuclear properties at high angular momenta, since such a component might be the signature for a specific high-spin band structure. Thus, e.g., the yrast cascades might be conceived as proceeding along several deformation-aligned bands with $E2$ interband and $M1/E2$, $\Delta I = 1$, intraband transitions. In the K-band deexcitation model[7] the $M1$ cascade transitions are expected to be dominant in the low-energy region. The findings of Refs. 5 and 6 have stimulated theoretical work[8] which explains the $M1$ radiation as evidence for oblate shape at high spin.

The discrepancies between the various experimental results quoted above might be due to the unfolding and background-subtraction procedures, which are particularly difficult at low energies. In addition, the interpretation of angular-distribution data for quasicontinuum γ rays is ambiguous and involves several *a priori* assumptions. This paper presents strong evidence that the intensity of a low-energy $M1$ component is not large. The evidence is based on K-shell ionization measurements for the evaporation residues. This new technique is rather simple and does not suffer from the above-mentioned shortcomings. It allows us to obtain upper limits for the intensity of $M1$, $E1$, and $E2$ components in the quasicontinuum below about 500 keV.

The experiment consisted of simultaneously measuring the characteristic K x-ray spectra and the γ-ray spectra emitted from 1–2-mg/cm^2 metallic targets of $^{154-160}$Gd bombarded with 47–130-MeV α particles, of ^{150}Nd irradiated with 65- and

90-MeV ^{12}C ions, and of ^{148}Nd bombarded with 65-MeV ^{12}C ions. The x-rays and the low-energy γ rays were observed with a hyperpure germanium detector of high resolution, placed at 55° with respect to the beam direction, while the higher-energy γ rays were detected with a large Ge(Li) spectrometer located at 125°. The angles were chosen to average out the first-order angular dependence of the γ rays. The detectors were placed at large distances from the target to minimize the true-coincidence summing. Special care was taken of dead-time corrections and absolute efficiency calibrations. Details of the experimental procedure are described elsewhere[9] in connection with a systematic study of (α,xn) reaction cross sections by in-beam γ-ray spectrometric techniques.

Figure 1 shows examples of the characteristic x-ray spectra for $^{160}Gd+\alpha$ at $E(\alpha)=56$ MeV and for $^{148}Nd+{}^{12}C$ at $E({}^{12}C)=65$ MeV. For a given bombarding energy, the direct observables of the present work are the relative intensities of the dysprosium K x rays and of the γ transitions pertaining to the various final dysprosium nuclides. Absolute determination of the respective cross sections can be made by relating the observed yields to those of the characteristic x rays of the target atoms and making use of the ionization cross sections known from the literature. For the purpose of this work, however, only the γ-ray yields per reaction and the x-ray–to–γ-ray cross-section ratios are needed.

The measured dysprosium x-ray yield at each bombarding energy can be compared with that obtained as a sum of contributions due to K-shell internal conversion of all the discrete γ-ray transitions between states populated in the various xn channels. The dysprosium nuclides are especially suited for such a procedure because of the very extensive knowledge of their spectra and level schemes, available in the literature and supplemented in course of the cross-section work.[9]

Table I gives the measured ionization cross sections, $\sigma_{\mathrm{meas}}{}^{K}$, and the corresponding yields per dysprosium-producing reaction, $\sigma_{\mathrm{meas}}{}^{K}/\sum_x \sigma(\mathrm{HI},xn)$, for one of the Gd targets and several α-particle energies and for the three Nd + ^{12}C reactions. Also listed are the ratios of these yields to those derived from the analysis of discrete γ-ray spectra, $\sigma_{\mathrm{meas}}{}^{K}/\sigma_{\mathrm{derived}}{}^{K}$. Here, $\sigma_{\mathrm{derived}}{}^{K}=\sum \sigma_{\gamma i}\alpha_K{}^{i}$, where $\sigma_{\gamma i}$ are the cross sections for production of individual γ rays and $\alpha_K{}^{i}$ are the corresponding K-shell internal-conversion coefficients.

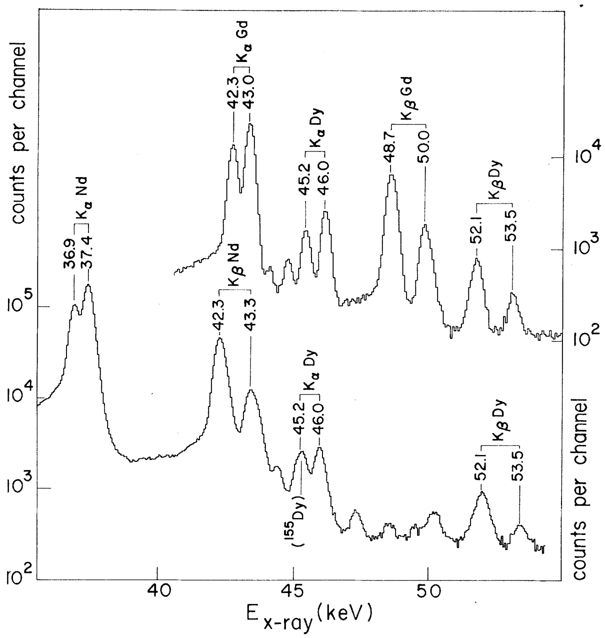

FIG. 1. Examples of the characteristic x-ray spectra following bombardment of a ^{160}Gd target with 56-MeV α particles (upper curve) and of a ^{148}Nd target with 65-MeV ^{12}C ions.

The measured K-shell ionization yields are to within the experimental errors completely accounted for by the electron conversion of known discrete γ transitions. From the data of Table I the limiting values can be obtained for ionization yields due to processes other than the internal conversion of observed discrete γ transitions. These limits, defined as the difference between the measured and derived ionization yields, per xn reaction, enlarged by two standard deviations, are listed in the last line of Table I as n_{limit}. Each such entry signified an independent determination of an upper intensity limit for any unobserved highly converted γ radiation, such as the low-energy $M1$ quasicontinuum transitions. The magnitude of the limits depends mostly on the uncertainties in the derived values of the ionization yields. The largest uncertainties occur in cases where the dominating reaction channel leads to an odd-A product. This is due to poorer knowledge of the complex level schemes of the odd-A nuclides as well as to the fact that the partial ionization yields per reaction are several times larger for these nuclides than for the adjacent even ones.[9]

The limits for the ionization yields due to unknown processes may be transformed into limit-

TABLE I. The measured and derived values of ionization yields and the resulting limits for ionization yields per dysprosium-producing reaction due to unobserved processes.

E (MeV)	$\sigma_{\text{meas}}{}^K$ (mb)	$\sigma_{\text{meas}}{}^K/\Sigma_x\sigma(\text{HI},xn)$	$\sigma_{\text{meas}}{}^K/\sigma_{\text{derived}}$	n_{limit}
		^{158}Gd + α		
47	1240 ± 50	0.90 ± 0.08	1.04 ± 0.06	0.15
64	1850 ± 50	1.12 ± 0.10	1.12 ± 0.07	0.26
80	1000 ± 40	0.62 ± 0.08	0.99 ± 0.08	0.11
90	730 ± 30	0.47 ± 0.05	0.98 ± 0.11	0.12
100	570 ± 60	0.44 ± 0.05	1.17 ± 0.17	0.20
110	380 ± 30	0.32 ± 0.03	0.93 ± 0.09	0.09
130	300 ± 30	0.44 ± 0.06	1.58 ± 0.23	0.30
		^{150}Nd + ^{12}C		
65	630 ± 30	1.05 ± 0.14	1.04 ± 0.09	0.22
90	330 ± 20	0.41 ± 0.04	1.03 ± 0.07	0.06
		^{148}Nd + ^{12}C		
65	270 ± 20	0.46 ± 0.04	1.05 ± 0.09	0.10

ing values, M_{limit}, for yields of unobserved γ rays of a given multipolarity and energy as $M_{\text{limit}} = n_{\text{limit}}\,\alpha_K$. Figure 2 shows the latter γ-ray multiplicity limits for $M1$, $E1$, and $E2$ multipoles as functions of γ-ray energy for a particular case of $n_{\text{limit}} = 0.1$, which corresponds to the reaction ^{148}Nd + 65-MeV ^{12}C. It is seen that the observed ionization yields are very sensitive to the presence of low-energy magnetic dipole transitions. Thus, e.g., the number of such transitions with $E_\gamma = 100$ keV is at most 0.05 per reaction, at most 1 with $E_\gamma = 300$ keV, at most 4 with $E_\gamma = 500$ keV, etc. The limits for other reactions studied in this work may be obtained by multiplying the values from Fig. 2 by the proper ratios of the n_{limit} values of Table I. Thus, e.g., for the case of the reaction ^{150}Nd + 90-MeV ^{12}C the above-quoted limits should be lowered by a factor 0.6.

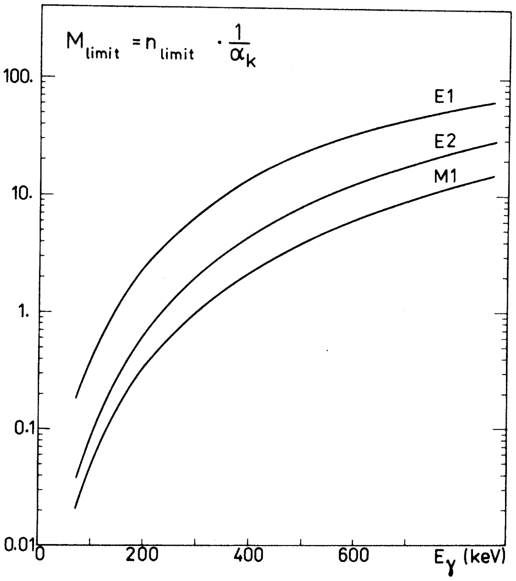

FIG. 2. Maximum allowed number of unobserved γ rays of a given multipolarity per dysprosium-producing reaction as a function of γ-ray energy. The limiting value of ionization yield, $n_{\text{limit}} = 0.1$, corresponds to the reaction ^{148}Nd + ^{12}C at $E_{^{12}\text{C}} = 65$ MeV (cf. Table I).

It should be noted that the derived values of the ionization yields should, in fact, be somewhat enlarged if one takes into account the contributions due to the higher-energy quasicontinuum radiation. The multiplicities of this radiation have been measured[10] as functions of γ-ray energy for several of the reactions studied in this work. With some plausible assumptions about the multipolarities involved, the estimated conversion of this radiation leads to ionization which is not negligible compared with the limits deduced here. This means that the actual limits for low-energy $M1$ transitions are even lower than the values presented. While the amount of this lowering is necessarily imprecise, we estimate that it typically changes n_{limit} by 0.02 to 0.04.

It is concluded that the occurrence of a *strong*, low-energy, quasicontinuum of $M1$ transitions is highly unlikely at least for the nuclear systems and reactions studied in this work. This finding is at variance with the interpretation that has been made of the results of Refs. 5 and 6 (e.g., in Ref. 8). The nuclides studied in this work and in Refs. 5 and 6 have similar structure at low excitation energies: They are all characterized by well-developed rotational bands with backbending in the even systems and with strongly populated partly decoupled positive-parity bands in the odd ones. Also the input angular momenta in all these works are similar. As far as the deformed rare-earth nuclides are concerned, the present result implies that there is no solid experimental evidence for "the existence of a small-deformation oblate region" at high spin values, as inferred from intense low-energy $M1$ transitions in a semiphenomenological theoretical approach.[8] No such statement can be made about the results of Ref. 2, which concerned lighter nuclei near closed shells studied at significantly higher angular-momentum input than in this work. Such nuclei are expected to acquire oblate deformed shapes at high spins and therefore to exhibit quite a different pattern of electromagnetic radiation than that characteristic for the prolate deformed nuclei.

This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (ZWO).

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Evidence for Rotational Structure at High Spins in ^{154,155}Er

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(Received 22 May 1979)

Erbium nuclei around $N=86$, which are weakly collective at spins below about $40\hbar$, have been studied at higher spin using techniques recently developed for studying continuum γ rays. A strong collective structure appears to develop above spins around $40\hbar$, which can explain why no discrete lines have been observed beyond $36\hbar$. The similarity of the spectra for heavier and lighter erbium nuclei at spins $(40-60)\hbar$ suggests the same shape (prolate) for both.

Recently, the level schemes of several nuclei[1] just above the $N=82$ shell have been determined up to very high spins (about $40\hbar$). All these nuclei are characterized by an irregular weakly collective yrast band which is heavily populated. No discrete lines due to transitions above spin $36\hbar$ are seen, probably because many parallel cascades are here involved in the γ-ray deexcita-