PHYSICAL REVIEW C VOLUME 28, NUMBER 4 OCTOBER 1983

Gamma-ray energy dependence of transition probabilities in the continuum

R. M. Aasen, J. Rekstad, A. Henriquez, F. Ingebretsen,
M. Guttormsen, and T. Engeland
Institute of Physics, University of Oslo, Oslo, Norway
(Received 11 July 1983)

The multiplicites of unresolved γ rays depopulating low spin states in ^{148}Sm have been measured for excitation energies up to the neutron binding energy. The general increase in multiplicity with excitation energy is well accounted for by a Fermi gas model. The comparison with theory shows that the dipole transition probabilities are not influenced by the giant dipole resonance.

[NUCLEAR REACTIONS ^{149}Sm(^{3}He, α), $E=26$ MeV; measured $\sigma(E_\alpha)$, γ-α coinc. ^{148}Sm deduced γ-ray multiplicity. Enriched target, Ge(Li), NaI(Tl), Si detectors. Fermi gas model analysis.]

Studies of continuum γ rays from heavy-ion compound reactions[1] have revealed important information on the cooling process of nuclei. Above the $E2$ bump which appears around γ energies of 1.5 MeV, the γ intensity follows an exponential slope and is associated with statistical $E1$ transitions.[2]

The statistical part of the spectrum is usually fitted by a two-parameter formula[1]

$$N_\gamma(E_\gamma) \propto E_\gamma^n \exp(-E_\gamma/T) \quad , \tag{1}$$

where T represents the average nuclear temperature for all the levels contributing to the statistical decay, and the dependence on the γ-ray energy for the $E1$ transition probability is expressed by the exponent n. The slope of the statistical spectrum depends essentially on the set of values for n and T. An independent measurement of the two parameters should require a method to distinguish between transitions in the high and low temperature region.

Recently,[3,4] a new method to study the cooling process of nuclei from a well defined excitation energy and low spins has been presented. In the present Communication we use this method in an investigation of the dipole transition rates, as a function of excitation energy, in order to settle the value of the exponent n in Eq. (1) independent of the nuclear temperature.

Low spin states in ^{148}Sm were populated using the ^{149}Sm(^{3}He, α) pickup reaction with 26 MeV ^{3}He ions produced by the Oslo cyclotron. The target was a self-supporting foil of thickness ~ 2 mg/cm^2 enriched to 98% in ^{149}Sm. Four ~ 1 mm thick surface barrier Si detectors were placed at 60° with respect to the beam. A 12.5 cm × 12.5 cm diam NaI(Tl) detector and a Ge(Li) detector of 18% efficiency were located at 135°. The data were stored event by event on magnetic tapes and with an accumulation time of one week with ~ 0.3 nA beam current.

The α particles from the reaction were recorded in singles $[N_s(E_x)]$ and in coincidence $[N_c(E_x)]$ with the NaI(Tl) detector. The ratio, channel by channel, between these two spectra is proportional to the average number of γ rays emitted[4] when levels at the corresponding excitation energy deexcite. Hence,

$$\langle M_\gamma(E_x)\rangle \propto N_c(E_x)/N_s(E_x) \quad . \tag{2}$$

A simultaneous measurement of the average γ-ray multiplicity and the corresponding excitation energy provide a method to deduce the average γ-ray energy in the decay since the relation

$$\langle M_\gamma(E_x)\rangle \langle E_\gamma\rangle = E_x \tag{3}$$

is always fulfilled. Thus, from the analysis of the γ-ray multiplicity spectrum, it is possible to extract how the γ-ray energy varies with excitation energy in the statistical region of the nuclear excitation spectrum.

Figure 1 displays the multiplicity spectrum measured in the ^{149}Sm(^{3}He, α)^{148}Sm reaction. The multiplicity is seen to increase with increasing excitation energy up to the neu-

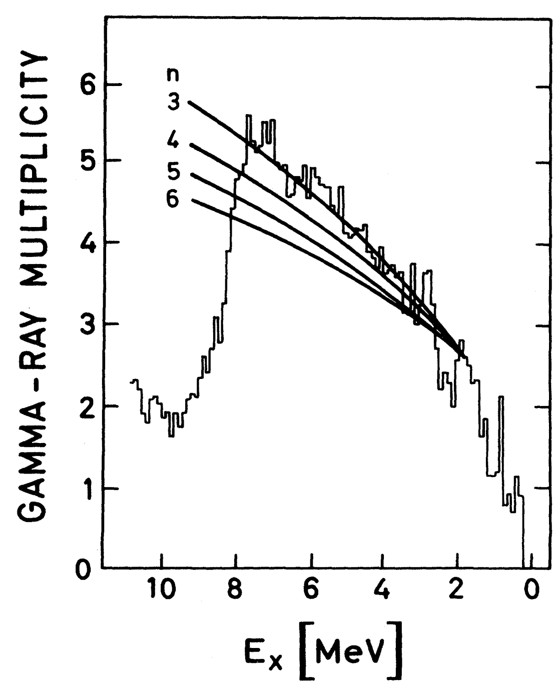

FIG. 1. Gamma-ray multiplicity spectrum from the ^{149}Sm(^{3}He, α)^{148}Sm reaction. The theoretical curves are calculated for $n=3$, 4, 5, and 6 with $a=19.0$ MeV^{-1}.

tron binding energy of $B_n = 8.1$ MeV. Above this energy the cooling process is dominated by the evaporation of one neutron with following γ emission in the neighboring ^{147}Sm nucleus.

The multiplicity spectrum was normalized by means of two separate methods: (i) For certain E_x the multiplicity can be estimated since the reaction selectively populates states with known decay paths, and (ii) by unfolding the NaI(Tl) spectrum for certain E_x and evaluating the average γ energy $\langle E_\gamma \rangle$. The average multiplicity is then given by Eq. (3). The two methods gave consistent results, and a normalization within $\pm 6\%$ in the multiplicity was obtained.

The increase in γ-ray multiplicity with excitation energy below 8.1 MeV is interpreted as an increase in the number of statistical γ rays in the cascades. By means of the Ge(Li) detector the contribution to the multiplicity from $E2$ transitions along or parallel to the yrast line was measured to be independent of the excitation energy of the entry level.

The shape of the γ-ray multiplicity spectrum has been calculated by means of a computer code simulating the total decay process. The decay of highly excited low spin states is assumed to go by the emission of dipole γ rays. The distribution of γ rays depopulating states at E_x is given by[5]

$$P(E_\gamma) \propto E_\gamma^n \rho(U - E_\gamma, I, \pi) \quad , \tag{4}$$

where $\rho(U - E_\gamma, I, \pi)$ is the density of levels with spin I^π at the excitation energy $E_x - E_\gamma$. For even-even nuclei the intrinsic excitation energy is approximated by

$$U = E_x - 2\Delta - (\hbar^2/2\mathcal{J})_{\rm rig} I(I+1) \quad ,$$

where Δ is the pairing gap parameter and $(\hbar^2/2\mathcal{J})_{\rm rig}$ the rotational moment of inertia parameter.

Alternatively, Eq. (4) could be formulated in terms of nuclear temperature, since $1/T = (\partial/\partial U)\ln\rho$. It is interesting to notice that the shape of the multiplicity spectrum reflects the variation in nuclear level density or temperature with excitation energy, provided that the exponent n is independent of the excitation energy.

In this analysis, the level density ρ is described within the Fermi gas model by[5]

$$\rho(E, I, \pi) = \frac{2I+1}{24} a^{1/2} (\hbar^2/2\mathcal{J})_{\rm rig}^{3/2} E^{-2} \exp[2(aE)^{1/2}] \quad , \tag{5}$$

where a is the level density parameter. The expression for the level density corresponds roughly to a nuclear temperature proportional to the square root of the intrinsic excitation energy U.

The theoretical multiplicity curves calculated from Eqs. (4) and (5) depend strongly on the a and n parameters. Previously,[6] the level spacing of 3^- and 4^- states in ^{148}Sm has been measured to be $D = (5.7 \pm 0.5)$ eV at $E_x \sim B_n$. This value can be related to the level density parameter a by $\rho(3^-) + \rho(4^-) = D^{-1}$, which gives $a = (19.0 \pm 1.0)$ MeV^{-1}. The error limits are determined mainly by the uncertainty in the experimental D and Δ values. The result is consistent with values[5] found in the $A \sim 150$ mass region [$a = (20 \pm 5)$ MeV^{-1}]. The precise value for the level density in ^{148}Sm at the neutron binding energy obtained in Ref. 6 provides an excellent opportunity to determine the parameter n.

In literature, great confusion is associated with the energy dependence E_γ^n of Eq. (1). Values of the parameter n have been suggested[7-9] ranging from $n = 3$ to 6. The lower limit of n $(2\lambda + 1 = 3)$ is based on general radiation theory for dipole transitions. The appearance of higher n values is predicted due to structural overlap factors originating from the tail of the giant dipole resonance. Experimentally, indications of $n \sim 5$ have been found in average resonance neutron capture work[10] for γ rays with $E_\gamma = 5$–7 MeV. The theoretical multiplicity curves with $a = 19.0$ MeV^{-1} are also shown in Fig. 1 for $n = 3$, 4, 5, and 6. The curves are normalized at $E_x = 1.9$ MeV, where $\langle M_\gamma \rangle \sim 2.7$. The comparison with the experimental data clearly favors the $n = 3$ alternative.

A more systematic analysis is shown in Fig. 2. Here, the theoretical multiplicity curves are fitted to data from $E_x = 4.0$–7.8 MeV, where one can assume that the Fermi gas conditions are reasonably well fulfilled. For each value of n the corresponding a parameter has been fitted (solid curve of Fig. 2). The upper and lower dashed curves represent one standard deviation. They include statistical fluctuations as well as the uncertainties in the normalization of $\langle M_\gamma(E_x) \rangle$. By taking into account the constraints[6] $a = (19.0 \pm 1.0)$ MeV^{-1} (hatched area), we find $n = 2.8 \pm 0.7$. It should be emphasized that the value of n deduced in the present experiment is an effective value for the whole γ spectrum. Previous investigations[10] reporting $n \sim 5$ are limited to the highest part of the γ spectrum only, representing a very small fraction of the total γ-ray yield ($< 3\%$). Our experiment does not necessarily contradict the earlier findings, since the high energy γ tail contributes negligibly to the effective n value.

In summary, the γ-ray energy distribution was found

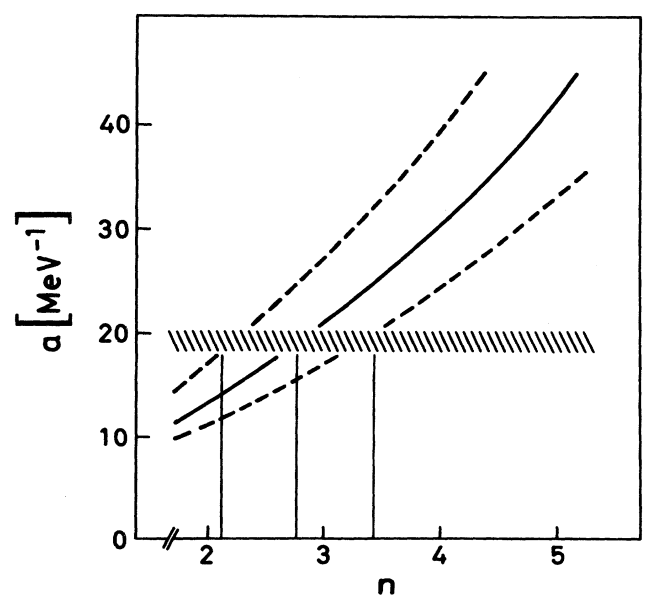

FIG. 2. The results of fits to the experimental multiplicity spectrum. The best fit (solid curve) is shown with one standard deviation (dashed curves). The hatched area represents the region (Ref. 6) $a = 18.0$–20.0 MeV^{-1}.

roughly proportional to $E_\gamma^3 \rho(U - E_\gamma, I, \pi)$, where the level density is based on a Fermi gas description. This result indicates that, at least in ^{148}Sm, the giant dipole resonance has only minor influence, if any, on the statistical γ-transition probabilities below 8 MeV excitation energy.

The authors wish to express their appreciation to Professor B. Mottelson for stimulating discussions.

[1]R. M. Lieder and H. Ryde, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1978),Vol. 10, p. 1.

[2]R. M. Diamond and F. S. Stephens, Annu. Rev. Nucl. Part. Sci. 30, 85 (1980).

[3]J. Rekstad *et al.,* Phys. Scr. (in press).

[4]J. Rekstad *et al.,* Phys. Lett. 117B, 384 (1982).

[5]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, MA, 1969), Vol. 1.

[6]M. Mizumoto, Nucl. Phys. A357, 90 (1981).

[7]S. M. Sie *et al.,* Nucl. Phys. A367, 176 (1981), and references therein.

[8]J. M. Blatt and V. F. Weisskopt, *Theoretical Nuclear Physics* (Wiley, New York, 1967), p. 583.

[9]R. J. Liotta and R. A. Sørensen, Nucl. Phys. A297, 136 (1978).

[10]D. J. Buss and R. K. Smither, Phys. Rev. C 2, 1513 (1970).