Statistical calculation of fission decay probabilities of nuclear giant multipole resonances

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The statistical fission decay properties of the giant dipole, quadrupole, and monopole resonances in ^{236}U are investigated with the aid of the Hauser-Feshbach model. It is found that the giant quadrupole resonance fission decay probability is as large as that of the giant dipole resonance, at energies higher than the fission barrier. At energies close to the fission barrier, the giant quadrupole resonance fission probability is found to be appreciably larger than that of the giant dipole resonance. The giant multipole resonance fission probability follows closely that of the giant quadrupole resonance. Comparison with the more commonly employed alternative statistical fission model is made.

I. INTRODUCTION

The study of the fission decay of the giant multipole resonances for actinide nuclei is a rapidly developing field. In particular, the fission decay of the giant monopole resonance (GMR) and the giant quadrupole resonance (GQR) has been under intensive debate during the last seven years. On the one hand, from fission-fragment angular distribution data using electromagnetic probes, it was claimed that the fission decay probability of the GQR, P_f $(E2)$, in ^{238}U is about 40%. This finding[1] was later questioned by Woodworth *et al.*[2] where a much smaller P_f $(E2)$ was reported. However, quite recently, a Giessen-Heidelberg-Mainz group[3] has reported the results of an $(e,e'f)$ coincidence experiment on ^{238}U, where they found that the GQR fission probability is as large as 20% in the energy interval 8–12 MeV.

On the other hand, hadron-induced inelastic excitation of the giant resonance (GR) measured by several groups have reported similar conflicting P_f $(E2)$ and P_f $(E0)$ values for the actinide nuclei. Whereas Bertrand *et al.*[4] report a value for $P_f\,(E0)+P_f\,(E2)$ of about 20–25 %, Morsch *et al.*[5] have found 4%. The work of the Groningen group have initially reported a P_f $(E2)$ of zero,[6] which was later rectified[7,8] to about $<11\%$. The same group have recently[9] measured the fission of the GMR in ^{238}U with inelastically scattered α particles detected at 0°. They found $P_f\,(E0)=22\%$.

It is a well-known experimental fact that $P_f\,(E1)\approx P_f$ (CN)$\approx 22\%$, for ^{238}U, where CN stands for "compound nucleus."

All the above conflicting findings, which have been reviewed recently by Harakeh[10] and van der Woude,[11] gave rise to several speculations concerning the nature of the GQR fission decay in ^{238}U, namely: statistical [$P_f\,(E2)\approx P_f\,(E1)$], direct [$P_f\,(E2)>P_f\,(E1)$], or inhibited [$P_f\,(E2)\ll P_f\,(E1)$].

II. WHY A DETAILED STATISTICAL CALCULATION IS NEEDED

A widely used criterion for the evaluation of direct components participating in the decay of giant resonances, especially proton, neutron, and alpha decay, is the comparison of the experimentally determined branching ratios, and/or the measured particle-emission spectra, with those obtained from a statistical calculation. Therefore, the most exact and complete is a theoretical calculation, the more reliable are the conclusions drawn from the experimental results.

In particular, the most obvious fission calculation, namely using the statistical theory, has been partially done by several authors.[12,9] However, most of these calculations were performed with a schematic model employing rough approximations for the transmission coefficients and level densities. Owing to the important issues reviewed above a more exact and complete fission Hauser-Feshbach calculation of $P_f\,(E\lambda)$ is clearly called for in order to reach a less prejudiced conclusion. As an example of the possible erroneous conclusions that can be reached with simplified versions of the statistical model such as the one cited above for fission, we mention the recent calculation[13–15] of the neutron decay spectra of the GMR in ^{208}Pb. It was shown in these references that if a Hauser-Feshbach calculation is performed using the known levels of ^{207}Pb the measured neutron spectra can be completely accounted for by the statistical theory. This is in variance with conclusions reached through the use of the drastically more approximate Fermi level-density function which indicates appreciate direct component.

It is the purpose of this paper to supply this much needed detailed statistical model calculation of fission decay probabilities $P_f\ (E\lambda)$ of the giant multipole resonances using the Hauser-Feshbach theory with *realistic* level densities and the levels of the transition state nucleus. We take ^{236}U as an example where experimental data on $P_f\ (E2)$ is also available, and where a more reliable set of statistical calculation parameters are known. Further, a reasonably complete measurement of $P_f\ (E1)$ is also available, which we use to establish the consistency of our calculation. As it will be discussed below, the qualitative aspects of the results obtained for ^{236}U could be extrapolated for ^{238}U.

III. RELEVANT THEORY AND CALCULATION PROCEDURE

For a given $J\pi$ state, and excitation energy E, we have for the fission probability,

$$P_f\ (EJ\pi)=\frac{\Gamma_f\ (EJ\pi)}{\Gamma_f\ (EJ\pi)+\Gamma_n\ (EJ\pi)+\Gamma_\gamma\ (EJ\pi)}\ , \tag{1}$$

where Γ_f, Γ_n, and Γ_γ are the partial widths for fission, neutron emission, and gamma decay, respectively. We note that since we are calculating the fission branching ratio [Eq. (1)], the detailed information about the shape and location in energy of the giant multipole resonances considered here ($E0$, $E1$, and $E2$) is not relevant. What is relevant, however, is their angular momenta and parities, as well as the excitation energy of the compound nucleus, which we take to be the same for the three resonances supposedly completely damped.

A. Fission

To describe the fission decay modes, we have used the incomplete damping model of Back *et al.*,[16] which uses the average partial width for fission,

$$\langle \Gamma_f(EJ\pi)\rangle=\frac{D}{2\pi}\left[N_D+N_{\text{abs}}\frac{N_B}{N_A+N_B}\right]\ . \tag{2}$$

In this expression D is the average level spacing, N_D is the flux which passes directly through the two fission barriers A and B, while $N_{\text{abs}}N_B/(N_A+N_B)$ is the fraction of the absorption flux N_{abs} which is trapped in the intermediate well before passing through the second barrier B. We have used for the fission barriers and discrete transition bandheads, values consistent with the experimental ones reported in Ref. 17. As discrete transition states, we have included those members of the given rotational bands which lie within 1 MeV above the fission barrier when a rotational constant of 3.8 keV is used (see Table I). This rotational constant is approximately half of that observed in the ground-state bands, consistent with moments of inertia at the saddle points which are two times the ground-state ones. At higher energies, we have used a constant temperature density of states with $T=0.435$ MeV where the latter was fixed by adjusting $P_f\ (E1)$ to the experimental data.[18] The spin-cutoff parameter in the density of states was fixed at twice the value of that used in the description of the ^{236}U γ emission, again consistent with a moment of inertia which has doubled at the saddle points. Therefore, T is the only free parameter.

B. Neutron emission

To determine the average partial width for neutron emission, we have used transmission coefficients generated by the optical-model code SCAT2 taking for the optical potential the one reported by Haout *et al.*[19] Although this potential was obtained through a coupled-channels analysis, we justify its use in a spherical optical-model calculation with the observation that what is important in a Hauser-Feshbach calculation is a more or less correct absorption cross section, i.e., the transmission coefficients, and not the resulting elastic or reaction cross sections. We have taken for the discrete part of the emission spectrum the first 50 states given in the ENSDF library.[20] Above this energy, we have used a Gilbert-Cameron level density[22] with parameters obtained from an analysis of the known discrete states in ^{235}U and the known resolved resonances in ^{236}U (Ref. 21) (see Table II).

C. Gamma decay

As far as the partial width for gamma decay, we have used the Brink-Axel approximation for $E1$ emission and the Weisskopf approximation for $M1$ and $E2$ emission.

TABLE I. The parameters used in the statistical fission calculation. A and B refer to the first and second barriers, respectively. An imaginary parabolic potential was employed in the second well, with a strength of 2.2 MeV and curvature of 0.9 MeV. For the "direct" fission calculation we have employed the following transition nucleus states bandheads: 0^+ (0.0 MeV), 0^- (0.8 MeV), 0^+ (0.92 MeV), and 0^+ (0.94 MeV).

A				B			
V (MeV)	$\hbar\omega$ (MeV)	Band heads $J\pi$	Band heads E (MeV)	V (MeV)	$\hbar\omega$ (MeV)	Band heads $J\pi$	Band heads E (MeV)
5.6	0.9	0^+ (g.s.)	0.0	5.55	0.5	0^+	0.0
		0^- (oct)	0.8			0^-	0.2
		0^+ (β)	0.92			1^-	0.65
		0^+ (γ)	0.94			0^+	0.92
						0^+	0.94

TABLE II. Gilbert-Cameron level-density parameters for ^{235}U (neutron channels) and ^{236}U (gamma channels).

	^{235}U	^{236}U
a	29.88	29.71
Δ	0.69	1.18
E	0.7	1.16
σ	3.54	3.46
T	0.43	0.41

For the discrete part of the spectrum we have used the first 31 states—up to 1.16 MeV, taken from the ENDSF library. Above this energy, we have again used the Gilbert-Cameron level density with parameters obtained from an analysis of the ^{236}U discrete states and the resolved resonances in the $n+{}^{235}$U system. In the calculation, we have utilized the Hauser-Feshbach code STAPRE.[23]

IV. RESULTS AND DISCUSSION

The result of our calculation is presented in Fig. 1 by the full curve [P_f ($E2$)], dashed curve [P_f ($E1$)], and dashed-dotted curve [P_f ($E0$)]. In the same figure we also present the available data on P_f ($E1$).[18]

The important message conveyed by Fig. 1 is that: (a) at energies well above the fission barrier ($B_f \cong 6$ MeV) namely at $\omega > 9$ MeV, the three calculated fission probabilities are practically all equal, and (b) the GQR and GMR statistical fission probabilities become larger than that of the giant dipole resonance (GDR) at low energies. Such *qualitative* features of ^{236}U fission decay could be extrapolated to ^{238}U, since transmission coefficients, level densities, and other relevant quantities needed in a statistical calculation, are quite similar for these two nuclei. Quantitative differences, on the other hand, arise mostly from the discrete part of the emission spectrum and the discrete transition fission bandheads.

Therefore, it would be expected on statistical grounds, for ^{238}U at energies around the peaks of the giant resonances (9–12 MeV), that

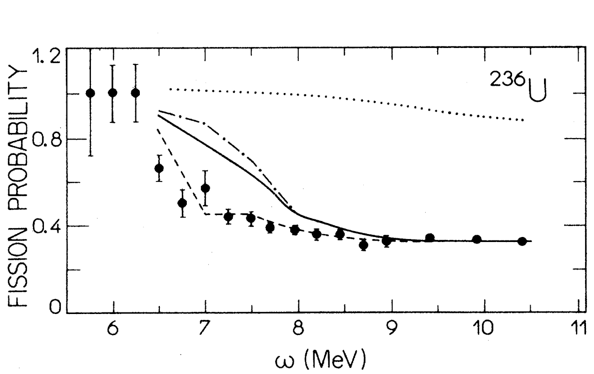

FIG. 1. Calculated fission probabilities of the GMR (dashed dotted curve), GDR (dashed curve), and GQR (full curve). See text for details. Also shown is the experimental data for the GDR fission decay. The dotted curve represents the results of $P_f(E\lambda)$ (equal for all λ's) obtained from the approximate Vandenbosch-Huizenga expression (see text for details).

$$P_f\,(E1) \approx P_f\,(E0) \approx P_f\,(E2) \approx 22\%\ .$$

It should be noted that the results from the Giessen-Heidelberg-Mainz group,[3] Bertrand *et al.*,[4] and De Leo *et al.*[9] (for the GMR), are quite compatible with a statistical model picture for the fission decay of the GQR and GMR.

Our results for $\omega \leq 9$ MeV are quite revealing too, since they show that $P_f\,(E2) > P_f\,(E1)$ does not necessarily indicate the presence of a direct fission component in the GQR fission decay. Therefore, we are tempted to conclude that the extracted P_f ($E2$) near the barrier from inclusive electrofission experiments,[1] which comes out conspicuously larger than P_f ($E1$), is predominantly statistical.

A. Comparison with other statistical calculations

In this section we compare our results with an alternative model widely employed in data analysis namely the Vandenbosch-Huizenga model.[12]

Within this model, the branching ratio Γ_n/Γ_f is given by the expression

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4a_f A^{2/3}(E-B_n)}{a_n K_0[2a_f^{1/2}(E-B_f)^{1/2}-1]} \times \exp[2a_n^{1/2}(E-B_n)^{1/2} - 2a_f^{1/2}(E-B_f)^{1/2}]\ , \quad (3)$$

where $K_0 = \hbar^2/(2MR_0^2) = 15.8$ MeV for $R_0 = 1.15$ fm, B_n and B_f are the neutron-emission threshold and the fission-barrier height, respectively; a_n and a_f are the nuclear level-density parameters, and E is the excitation energy. The fission probability is calculated using Eq. (1) but neglecting the γ decay width Γ_γ.

The dotted line in Fig. 1 represents the result of the calculation of P_f with the Vandenbosch-Huizenga model (VH model), Eq. (3), using the *same* values for the parameters B_n and B_f of our calculation. However, a good reproduction of the $E1$ data can be achieved with the VH model if B_f were increased by about 20%.

It would be quite instructive to discuss the origin of the differences between our results and those obtained from the Vandenbosch-Huizenga model[12] (VH model), whereas we employ *all the available experimentally determined discrete levels.* The VH model, on the other hand, uses a J-independent parametrized density of states which necessarily overestimates the number of levels and, thus, overestimates P_f (λL), irrespective of λL, as shown in Fig. 1 (dotted curve). The second important difference is related to the use by the VH model of sharp cutoff transmission coefficients, in contrast with our optical-model generated ones.

Notwithstanding these differences, the simplicity of the VH expression is understandably very appealing and, therefore, it would be of great value to investigate the question of how its parameters are related to those entering the Hauser-Feshbach calculation.

V. CONCLUDING REMARKS

It is clear from Fig. 1 that at energies well above the fission barrier ($B_f \cong 6$ MeV) namely at $\omega \geq 9$ MeV, the three calculated fission probabilities are practically all equal. It is interesting to observe that the experimental $P_f\ (E1)$ in this energy region is very well reproduced by our statistical calculation, thus indicating a very small "direct" fission component in the GDR fission decay. In fact, this behavior of $P_f\ (E1)$ seems to hold even at lower energies as Fig. 1 clearly shows. We consider the above finding a clear demonstration of the correctness of our calculation since most authors appear to agree that the fission decay of the GDR, in this energy range, is predominantly statistical.[18]

The important message conveyed by Fig. 1 is that: (a) the GQR and GMR statistical fission probabilities become larger than that of the GDR at low energies and (b) the alternative statistical calculation using the Vandenbosch-Huizenga expression, Eq. (3), which is quite commonly employed in data analysis, though insensitive to the multipolarity of the giant resonance, does reproduce the $P_f\ (E1)$ as long as B_f is increased by about 20%.

The above calculation gives upper bounds on statistical fission decays of GR which attain when the mixing of GR with CN is complete. If direct fission is present as a competing process,[24] the Hauser-Feshbach calculation is reduced by an amount which is measured by the mixing parameter μ, introduced recently by Dias, Hussein, and Adhikari[25] in their theoretical description of the decay of GR which was motivated by the apparent importance of both direct and compound γ decay of the GQR in ^{208}Pb discussed by Beene *et al.*[26] and Dias *et al.*[27]

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