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ABSTRACT

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, contrary to several recent claims, that the GQR fission decay probability is as large as that of the GDR, at energies higher than the fission barrier. At energies close to the f.b., the GQR fission probability is found to be appreciably larger than that of the GDR. The GMR fission probability follows closely that of the GQR.

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The study of the fission decay of the giant multipole resonances for actinide nuclei is a rapidly developing field. Fission-fragment angular distribution data, using electromagnetic probes, have demonstrated unambiguously the existence of a substantial E2 component in the photofission of even-even actinide nuclei at least at excitation energies just above the fission barrier$^{1-4)}$ where one might expect to find the low-energy tail of the isoscalar giant quadrupole resonance (GQR). At somewhat higher energies the fission decay of the giant monopole (E0) resonance (GMR) for ^{238}U has been observed$^{5)}$. The fission of 1^+ states (populated by M1 photoabsorption) has been observed in the even-even uranium isotopes$^{6)}$. The fission decay of the GQR in actinide nuclei has been investigated by means of both electromagnetic and hadronic probes, particularly for ^{238}U. The results of Arruda-Neto et al.$^{2)}$, Shotter et al.$^{7)}$ and Bertrand et al.$^{8)}$ are in qualitative agreement with respect to the fact that the GQR does fission, but the branching ratios so far deduced are contradictory$^{2)}$. Other electron and hadron-induced fission experiments, on ^{232}Th and ^{238}U$^{9,11)}$, yielded results compatible with a GQR fission branching ratio equal to the apparently unphysical value of zero. However, kinematically complete (e,e'f) coincidence measurements alone are not decisive because of the lack of fission angular correlations for excitation energies ≥ 8 MeV$^{12,13)}$. Then, in an (e,e'f) experiment the disentangling of the E0 from the E2 strength cannot be accomplished, as

demonstrated recently for the reaction ^{238}U(e,e'f)$^{12,13)}$ and extensively discussed elsewhere$^{14)}$.

It is the purpose of this letter to supply a much needed statistical model calculation of fission decay probabilities of the giant multipole resonances, $P_f(E\lambda)$, using 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.

To describe the fission decay modes, we have used the incomplete damping model of Back et al.$^{15)}$, which uses for the average partial width for fission,

$$\langle \Gamma_f(EJ\pi) \rangle = \frac{D}{2\pi}\left(N_D + N_{ABS}\frac{N_B}{N_A + N_B}\right) \qquad (1)$$

In this expression the first term accounts for the flux which passes directly through the two barriers while the second accounts for the fraction of the flux which is trapped in the intermediate well before passing through the second barrier. We have used for the fission barriers and discrete transition band heads, values consistent with the experimental ones reported in reference 16. 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 moment of inertia of $3.8\times10^6\ \frac{\mathrm{MeV}}{e^2}\ \mathrm{fm}^2$ is used (see table I).

Above the above energy we have used a constant temperature density of states with T=0.435 MeV.

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.[17]. 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[18]. Above this energy, we have used a Gilbert-Cameron level density with parameters obtained from an analysis of the known discrete states in ^{235}U and the known resolved resonances in ^{234}U[19] (see table II).

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. For the discrete part of the spectrum we have used the 1st 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.

For a given Jπ resonance, we then have for the fission probability,

$$P_f(EJ\pi) = \frac{\Gamma_f(EJ\pi)}{\Gamma_f(EJ\pi) + \Gamma_n(EJ\pi) + \Gamma_\gamma(EJ\pi)} \qquad (2)$$

We note that since we are calculating the fission branching ratio Eq. (2), 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. In the calculation, we have utilized the Hauser-Feshbach code STAPRE[20].

The result of our calculation is presented in figure 1, together with available data on P_f(E1)[20] and P_f(E2)[2]. We also show the fission probability of the GMR, P_f(E0), for the purpose of comparison. It is clear from the figure 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 reproduce by our statistical calculation, thus indicating a very small "direct" fission component in the GDR fission decay. In fact, this behaviour of $P_f(E1)$ seems to hold even at lower energies as figure 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[21]. The agreement between the data and the statistical model calculation for $P_f(E2)$ seems to hold reasonably well at $\omega \leq 8$ MeV, indicating a similar behaviour as that of $P_f(E1)$ referred to above. However, at $\omega > 8$ MeV the statistical model calculation underestimated the data by as much as 30%. This may indicate that, at these above-barrier energies, pre-equilibrium fission of the GQR becomes appreciable, in clear contrast to the E1 case. Such a possibility could be understood in terms of the simple two-fluid model of the nucleus discussed in reference 22. The above conclusions concerning $P_f(E2)$ for ^{236}U, which we feel quite comfortable to extrapolate to ^{238}U, obviously contradict the several recent claims concerning the inhibition of the fission decay of the GQR in the actinide nuclei[9-13]. It is interesting to note that $P_f(E0)$ shown in figure 1, follows closely the trend of $P_f(E2)$, being practically equal at $\omega \geq 8$ MeV and slightly higher below this energy. Therefore, the recent analysis of the $^{238}U(\alpha,\alpha'f)$ reaction reported by Morsch et al.[5], where it was assumed that $P_f(E0) \cong P_f(E1)$ even at energies below the GMR peak, might be questionable.

In conclusion, we have demonstrated in this letter that the fission decay probability of the giant quadrupole resonance in the actinide nuclei is quite important and becomes even larger than that of the GDR at energies close to the fission barrier, contrary to recent claims based on electron - and hadron-induced reactions. We reached the above conclusion by comparing a detailed and realistic statistical model calculation with the available data for ^{236}U. It is interesting to remark at this point that such a large fission probability of the GQR, near the fission barrier, is also shared by ^{232}Th[24].

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FIGURE CAPTIONS

Figure 1. Calculated fission probabilities of the GMR (dashed dotted curve), GDR (dashed curve) and GQR (full curve). See text for details. Also shown are the experimental data for the GDR fission decay and the GQR (shown as the hatched band). The data were collected from Refs. (2) and (20).

TABLE CAPTIONS

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 band heads: 0^+ (0.0 MeV), 0^- (0.8 MeV), 0^+ (0.92 MeV) and 0^+ (0.94 MeV).

TABLE II – Gilbert-Cameron level density parameters for ^{235}U (neutron channels) and ^{236}U (gamma channels) (see A. Gilbert and A.G.W. Cameron – Can.J. Phys. 43 (1965) 1446).

TABLE I

A				B			
V (MeV)	$\hbar\omega$ (MeV)	Band heads		V (MeV)	$\hbar\omega$ (MeV)	Band heads	
		$J\pi$	E (MeV)			$J\pi$	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

	^{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