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著者	大槻 勤
journal or publication title	Physical review letters
volume	92
number	11
page range	112502-1-112502-4
year	2004
URL	http://hdl.handle.net/10097/35815

doi: 10.1103/PhysRevLett.92.112502

Evidence for Multiphonon Giant Resonances in Electromagnetic Fission of ^{238}U

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(Received 7 October 2003; published 18 March 2004)

Differential cross sections for electromagnetic fission of ^{238}U projectiles (500 MeV/u) in C, Sn, and Pb targets are measured and analyzed in terms of single- and multiphonon giant resonance excitations as doorway states to fission. A novel experimental method exploits the linear relationship between neutron multiplicity and the primary ^{238}U excitation energy. Multiphonon states contribute up to 20% of the cross section; a component at high excitation energies is indicated that may arise from three-phonon dipole and two-phonon GDR $\otimes$ GQR$_{iv}$ giant resonance excitations.

DOI: 10.1103/PhysRevLett.92.112502 PACS numbers: 25.85.–w, 24.30.Cz, 25.70.De

Electromagnetic dissociation of nuclei in peripheral heavy ion collisions at relative velocities close to the speed of light is mediated through single- and multiphonon excitations of giant resonances. Dipole excitations are strongest, a fact that has earlier been exploited in studying the double-phonon giant dipole resonance (GDR) [1–3]. Giant resonances built from more than two phonons were not yet observed.

In heavy nuclei, giant resonances decay by neutron emission since charged particle emission is suppressed by the Coulomb barrier. In the nucleus ^{238}U, fission decay competes with (multiple) neutron emission according to the partial decay width's Γ_f and Γ_{xn}, respectively. Since fission probabilities increase with excitation energy, multiphonon giant resonances should appear "enhanced" in the fission channel in comparison to single-phonon states. This effect makes multiphonon studies in electromagnetic fission particularly attractive.

The experimental problem arises in reconstructing the primary excitation energy of the fissioning nucleus. Since the fission fragments are highly excited and emit a multiplicity of particles and γ rays, a complete and precise calorimetry would be required. Here, the problem is circumvented by a novel technique that exploits the experimentally known linear relationship between primary excitation energy and the prompt neutron multiplicity accompanying the fission process (see below). The neutron multiplicity is measured in coincidence with fission events and reflects the excitation energy of the nucleus prior to fission. This method is applied to determine the relative contributions of single- and multiphonon giant resonances in electromagnetic fission of ^{238}U.

Electromagnetic fission of ^{238}U beams at high bombarding energy was studied earlier in more inclusive experiments [4–8]. Somewhat conflicting results were reported as far as the role of the double-phonon GDR in electromagnetic fission is concerned. The practical interest in such studies results from the fact that "in-flight" fission of ^{238}U beams is the most effective production mode for high-energy secondary radioactive beams of medium-mass neutron-rich nuclei. In such applications, a precise understanding of the excitation mechanisms which govern the fission process is of interest.

The experiment is performed with a ^{238}U beam of 500 MeV/nucleon energy delivered by the heavy-ion synchrotron at GSI, Darmstadt, and directed onto targets of Pb (302 mg/cm^2), Sn (230 mg/cm^2), and C (274 mg/cm^2). The detector system serves both a measurement of the decay of the excited ^{238}U by neutron emission and by fission. Results for the neutron decay have already been published in [1], preliminary results in [9]. A detailed description of the various detector components and performance parameters is provided in [1]. Here, the setup is briefly described to the extent relevant for the fission measurement. A thin organic scintillation counter is installed in front of the target delivering the start signal for time-of-flight measurements. Because of the high velocity of the uranium beam, both fission fragments and accompanying neutrons are kinematically focused into narrow cones around the beam trajectory. Behind the target, two silicon diodes are placed on each side of the beam trajectory in order to measure the energy loss of the two fission fragments and thus to obtain their nuclear charges. Elemental distributions of the fission fragments are shown in Fig. 1. The fission fragments are deflected in a dipole magnet with a large aperture. A multiwire gas avalanche counter and four arrays of scintillating fibers in front or behind the magnet serve to determine the trajectory and thus the magnetic rigidity of each fission fragment. An array of 20 organic scintillators covering a total area of 2 m $\times$ 2 m and placed 12 m downstream from the target provides a precise velocity measurement for the fission fragments.

Prompt neutrons emitted post or prior to fission are detected in the large-area neutron detector (LAND) with an efficiency of 92%. LAND covers an area of 2 m $\times$ 2 m and was placed 11.7 m downstream from the target. It comprises 200 independent modules built from interspersed layers of iron serving as converter material and of organic scintillator material. For each detector module, the time of flight and the position of incidence can be determined. As outlined below, the multiplicity ν_d of triggered detector modules is utilized in this measurement. As known from calibration measurements, a neutron of around 500 MeV triggers about 2.5 detector modules. From these calibration data, the distribution in ν_d can be deduced using an event mixing method in case of multiple neutron hits. Its mean value relates to the neutron multiplicity as $\nu_d = 2.47\nu_n - 0.028\nu_n^2$ and the standard deviation of the approximately Gaussian distribution as $\sigma_{\nu_d} = 1.63\nu_n^{0.4}$. The small quadratic term in the mean value arises because, with increasing neutron multiplicity, the charged particle showers induced in LAND partially overlap in space. Data are taken for events requiring neutrons in coincidence with two fission fragments and are corrected for finite acceptance. Background due to fission induced in material other than the target is determined through measurements without the target. In analyzing the electromagnetic fission events, it was required that the sum of the nuclear charge of the two

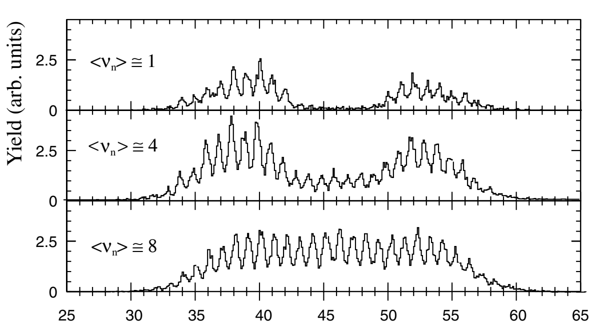

FIG. 1. Elemental distribution of fission fragments of ^{238}U projectiles (500 MeV/nucleon) in a lead target in coincidence with neutrons of a mean multiplicity $\langle \nu_n \rangle$ as indicated. The sum of the nuclear charges of the two fission fragments is required to equal 92.

fission fragments equals that of uranium, as applied in earlier measurements [5]. Charged particle evaporation of the excited neutron-rich fission fragments should be strongly suppressed by the Coulomb barrier. In nuclear processes, however, a number of protons may be removed from the ^{238}U projectile prior to fission of the residual nucleus.

The data analysis aims at having access to the excitation energy distribution prior to fission in order to enable a determination of the relative contributions due to single- and multiphonon giant resonance excitations. Since the excitation energy cannot be reconstructed directly, the electromagnetic fission cross sections are differentiated with regard to the accompanying neutron multiplicity. A nearly perfect linear dependence of the mean prompt fission neutron multiplicity ν_n from the ^{238}U excitation energy E is experimentally well established; see [10–12], and references therein. For instance, a dependence $\nu_n = 0.158E/\text{MeV} + 1.44$ is given in [10]. A slightly more elaborated parametrization is provided in [11] which we adopt. The neutron multiplicity is Gaussian distributed with a width of $\sigma_n \approx 1.0$, essentially independent of E [12]. It is also well established that, with increasing excitation energy, the distributions in nuclear charge and mass of the fission fragments shift from a more asymmetric to a more symmetric pattern. In consequence, low neutron multiplicities should go in hand with "asymmetric fission" and high neutron multiplicities with more "symmetric fission." This is clearly observed from Fig. 1 showing the elemental distribution for selected average neutron multiplicities.

In principle, the neutron multiplicity (ν_n) distribution could be obtained from the measured LAND detector multiplicity ν_d (see above) by a deconvolution using the experimentally known ν_d distribution for a given number of incident neutrons. Since a deconvolution enlarges statistical fluctuations, we refrain from it and differentiate cross sections with respect to ν_d. Such spectra are shown in Fig. 2. Figure 2(a) compares the spectrum obtained with the Pb target to that with the C target. On the average, larger neutron multiplicities are observed for the C target, for which fission is induced by nuclear processes. The spectrum with the Pb target shows a component peaked at a relatively low neutron multiplicity around $\nu_n \approx 4$ that is assigned to the electromagnetic excitation. The spectrum with the C target was scaled to that with Pb and Sn targets for $\nu_d > 20$ and subtracted in order to eliminate the nuclear fission cross section. Multiplicities $\nu_d > 20$ correspond to average excitation energies above 50 MeV at which electromagnetic excitations are negligible (see Table II). Choosing different intervals above $\nu_d > 20$ resulted in fluctuations of the scaling factor on a level of a few percent only, taken into account in the estimate of the systematic errors. The nuclear background arises from few-nucleon removal reactions, the cross sections of which scale with the radii of the interacting nuclei; see [13], and references therein.

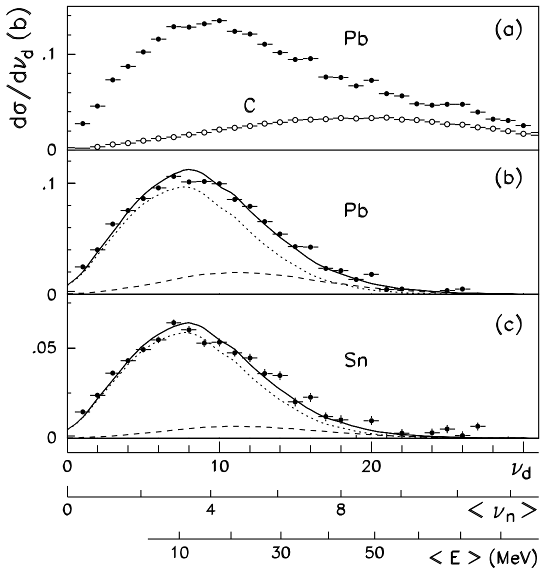

FIG. 2. Fission cross sections $d\sigma/d\nu_d$ for ^{238}U (500 MeV/nucleon). The axis labels refer to detector multiplicity ν_d, associated mean neutron multiplicity $\langle\nu_n\rangle$, and mean excitation energy $\langle E\rangle$. (a) Measured values for Pb and C targets. (b) Measured electromagnetic fission cross sections for Pb target and calculated values (solid line). Calculated cross sections for the sum of single-phonon (multiphonon) components is shown as a dotted (dashed) curve. (c) Same as (b) but for the Sn target.

Nevertheless, we performed calculations using the intranuclear cascade code ISABEL [14] exploring the assumption that the shape of the nuclear-induced excitation energy distribution remains unchanged when going from the carbon to the heavy targets. The calculations performed for the targets used here indeed show that the shape of the nuclear excitation energy distribution is independent on target over the range of excitation energies considered here. Coulomb-nuclear interferences are negligible as discussed in [15].

The background subtracted spectra are shown in Figs. 2(b) and 2(c), from which quantities such as the integrated electromagnetic cross section, mean neutron multiplicity, and mean excitation energy are derived. The results are given in Table I. The electromagnetic fission cross section of 1.24(25) b for the Pb target is in agreement with the value of 1.30(23) b measured earlier at the same bombarding energy [4]; see also the systematics of electromagnetic fission cross sections collected in [5]. A mean excitation energy of 19 MeV was deduced from the peak-to-valley ratio of the elemental distribution observed for electromagnetic fission of ^{238}U in a Pb target at 750 MeV/nucleon [8]. Here, a value of 15.4(5) MeV is obtained.

The differential cross sections assigned to electromagnetic fission are analyzed in terms of electromagnetic giant resonance excitations facilitated by the following steps:

TABLE I. Experimental and calculated values for electromagnetic fission cross sections σ^{emf} and mean neutron multiplicities $\langle\nu_n\rangle$ and excitation energies $\langle E\rangle$ of ^{238}U (500 MeV/nucleon) in Pb and Sn targets. Single- and multiphonon cross sections are denoted as σ^{sph} and σ^{mph}, respectively. Systematic errors are quoted; statistical errors are negligible.

	Pb target		Sn target	
Observable	Exp.	Calc.	Exp.	Calc.
σ^{emf} (b)	1.24(25)	1.34	0.68(12)	0.59
$\langle\nu_n\rangle$	3.9(2)		3.7(2)	
$\langle E\rangle$ (MeV)	15.4(7)	15.3	14.6(7)	14.3
$\sigma^{\mathrm{sph}}/\sigma^{\mathrm{emf}}$	0.80(4)	0.78	0.89(5)	0.89
$\sigma^{\mathrm{mph}}/\sigma^{\mathrm{emf}}$	0.20(4)	0.22	0.11(5)	0.11

(i) Electromagnetic excitation cross sections for single- and multiphonon giant resonances in ^{238}U are calculated treating the reaction dynamics in semiclassical approximation [16]. The isovector GDR and the isoscalar and isovector giant quadrupole resonances (GQR$_{\mathrm{is}}$ and GQR$_{\mathrm{iv}}$) are taken into account. The excitation of multiphonon states built from these phonons are described in harmonic approximation, i.e., adopting that the phonons are excited independently from each other. Single- and two-phonon states from the GDR and the GQR$_{\mathrm{is,iv}}$ as well the triple-phonon GDR are considered; other multiphonon states would be of considerably lower cross sections. The width of the giant resonances is incorporated adopting the folding model [17] formulated for the excitation of identical phonons; it is straightforward to extend it for non-identical phonons such as GDR $\otimes$ GQR. The calculation of cross sections is performed in the same manner as for the analysis of the neutron decay channels from the same experiment reported earlier [1].

(ii) The cross sections were multiplied with the partial fission decay width $\Gamma_f/(\Gamma_f + \Gamma_{xn})$, adopting the values given in [18]. These fission probabilities increase with excitation energy and, within the relevant domain, range from about 0.2 to 0.8. The peak energies and partial fission cross sections as calculated for the various phonon states are given in Table II for orientation.

(iii) The calculated fission cross sections were then transformed into cross sections $d\sigma/d\nu_n$ and finally into $d\sigma/d\nu_d$ by successively convoluting the cross section at a given excitation energy E with the distributions $\nu_n(E)$ and $\nu_d(\nu_n)$ as given above.

These cross sections $d\sigma/d\nu_d$ are compared to the experimental ones. In a first step, the experimental multiplicity distribution is compared to a calculation with only single-phonon states. The measured cross section is not well reproduced and is underestimated towards higher multiplicities, i.e., higher excitation energies.

In a second step, multiphonon states are taken into account and the normalizations of the group of single- and the group of multiphonon states are adjusted in a χ^2 minimization. The measured multiplicity distribution is

TABLE II. Calculated partial electromagnetic fission cross sections $\sigma/\sigma^{\mathrm{emf}}$ and their peak energies E_p for single- and multiphonon giant resonances in ^{238}U (500 MeV/nucleon) on Pb and Sn targets.

Resonance	E_p (MeV)	$\sigma/\sigma^{\mathrm{emf}}$ (Pb)	$\sigma/\sigma^{\mathrm{emf}}$ (Sn)
GDR	13.5	0.66	0.75
$\mathrm{GQR_{is}}$	9.5	0.07	0.07
$\mathrm{GQR_{iv}}$	21.0	0.06	0.07
GDR ⊗ GDR	23.0	0.15	0.09
GDR ⊗ $\mathrm{GQR_{is}}$	21.0	0.02	0.01
GDR ⊗ $\mathrm{GQR_{iv}}$	32.0	0.013	0.008
GDR ⊗ GDR ⊗ GDR	35.5	0.023	0.006

fairly well described, both for the Pb and the Sn targets; see Figs. 2(b) and 2(c). The fraction of fission cross section contributed by the multiphonon states amounts to 0.20(4) and 0.11(5) for the Pb and the Sn targets, respectively. These values should be compared to the ones obtained from the calculation in harmonic approximation (see Table I) which amount to 0.22 (Pb target) and 0.11 (Sn target) in accord with the experimental ones. Consistency of the cross section for the double dipole giant resonance, which should provide the strongest contribution, with the harmonic approximation was reported in [18] and was found in our own analysis of the ^{238}U neutron decay data [1].

Finally, the statistical significance of the multiphonon components located at excitation energies above that of the double giant dipole is explored. Since the distribution in excitation energy of triple-phonon giant dipole and of the GDR ⊗ $\mathrm{GQR_{iv}}$ are rather close in mean excitation energy, see Table II, these two components were added. In an attempt to determine its cross section from the data, a strong correlation with that of the remaining two-phonon states is observed. If the cross section for the double dipole giant resonance is constrained according to the result from the analysis of the neutron decay data obtained in the same experiment [1], the component at higher excitation energy is found to contribute 25–90 mb in case of the Pb target. According to the harmonic approximation a value of 50 mb would be expected, most of this cross section arising from the triple giant dipole resonance (see Table II). In the case of the Sn target, this component at higher energies was not significant; from the harmonic approximation, a cross section of less than 10 mb would be expected.

In [8], the peak-to-valley (P/V) ratio in the elemental distribution observed for electromagnetic fission of ^{238}U (750 MeV/nucleon) in a Pb target was analyzed. From the known almost exponential decrease of the P/V ratio with increasing excitation energy an average excitation energy of 19 MeV was deduced. The calculated P/V ratio, taking into account only single-phonon states and the double dipole giant resonance, was larger than observed, thus indicative of components at higher excitation energies. It was stated that the discrepancy could be cured adopting an enhanced (by about a factor 2) cross section of the double-phonon dipole resonance. A similar discrepancy between measured and calculated P/V ratios was also reported in [19]. From the present data, an average excitation energy of 15.4 MeV is deduced. This value and, moreover, the differential cross section distributions can be reproduced without invoking an enhanced double dipole giant resonance cross section if triple GDR and GDR ⊗ GQR excitations are incorporated. Such components at excitation energies above the double GDR may be responsible for the filling of the valley in the elemental distribution observed in [8,19].

In summary, it appears that heavy-ion induced electromagnetic fission cross sections for ^{238}U can be described reliably by taking multiphonon giant resonances into account. Depending on target and beam energy, multiphonon states at energies above that of the double dipole giant resonance may contribute significantly. Since the excitation energy distribution determines the charge and mass distributions of the fission fragments, it thus concerns the production yields of secondary beams from ^{238}U in-flight fission which is the richest source for very neutron-rich medium-mass nuclei.

We thank P. Armbruster, A. Kelic, and K. H. Schmidt for valuable discussions. This work was supported by the German Federal Minister for Education and Research (BMBF) under Contracts No. 06 OF 933 and No. 06 MZ 963 and by GSI via Hochschulzusammenarbeitsvereinbarungen under Contracts No. OF ELZK, No. MZ KRAK, and by the Polish Committee of Scientific Research under Contract No. PB2/P03B/113/09.

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