Fission of ^{238}U and ^{237}Np by intermediate-energy γ rays

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(Submitted 10 October 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 10, 445–447 (25 November 1984)

The average photofission cross sections and the fissility of the nuclei ^{238}U and ^{237}Np have been measured in a beam of back-scattered Compton γ rays over the energy interval $E_\gamma = 150$–710 MeV. The results are at odds with the predictions of models based on a photomeson mechanism for nuclear excitation. The discrepancy is apparently due to the excitation of nuclei in the course of the production of e^+, e^- pairs by γ rays of intermediate energy.

It has been shown in several studies (see the review by Nedorezov and Ranyuk[1]) that the cross section for photofission of ^{238}U at intermediate energies ($E_\gamma \sim 0.15$–2 GeV) is the same as the total photoabsorption cross section:

$$\sigma_{\gamma f} = \sigma_{\rm tot} = A\bar{\sigma}_{\gamma p}$$

where A is the number of nucleons in the nucleus, and $\bar{\sigma}_{\gamma p}$ is the cross section for photoproduction of π mesons at a nucleon, averaged over the momentum distribution of the nucleons in the nucleus. The fissility of ^{238}U in this energy range is thus ordinarily assumed to be unity. Data on photofission cross sections for transuranium nuclei have been found previously by only a single group.[2] It has been reported that the cross section $\sigma_{\gamma f}$ for ^{237}Np, ^{239}Pu, ^{241}Am, and ^{243}Am is 1.5 ± 0.15 times the calculated value of $A\bar{\sigma}_{\gamma p}$.

In an effort to check those results, which were obtained in a bremsstrahlung γ beam, we have carried out experiments with a beam of back-scattered Compton γ rays. The apparatus uses the VÉPP-4 e^+e^- storage complex at Novosibirsk and an LTI-701 solid-state laser. The apparatus, which is described in detail in Ref. 3, is shown in Fig. 1. A beam of laser photons (wavelength $\lambda = 514$ nm) collides with the electron beam

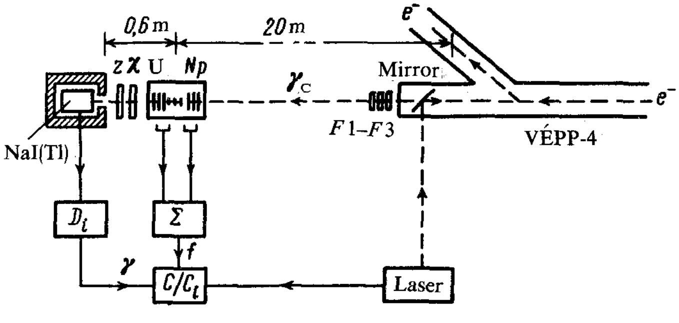

FIG. 1 The experimental layout. Z, X—Coordinate proportional chambers; NaI(Tl)—total-absorption spectrometer; $F1$-$F3$—lead filters 2, 3, and 4 mm thick, respectively; D_i—discriminator; Σ—summer; C/C_i—coincidence circuit (only one of the five channels, the i-th, is shown).

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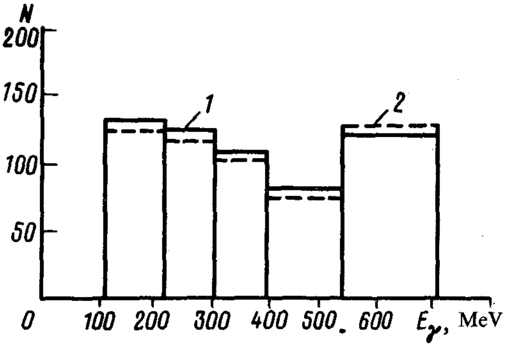

FIG. 2. 1—Spectrum of Compton γ rays incident on the samples; 2—coincidence spectrum of fission fragments with pulses from the NaI(Tl) spectrometer.

($E_e = 4.8$ GeV) of the storage ring; the maximum energy of the Compton γ rays is 710 MeV. The γ rays back-scattered into a solid angle $\sim 10^{-8}$ strike multilayer spark counters (18 with ^{238}U layers and 11 with ^{237}Np layers) at a point 20 m from the point at which the laser photons meet the electrons. The beam diameter at the targets does not exceed 2.5 cm. The spatial distributions of the γ beam are measured by (X, Z) proportional chambers with a resolution of 0.2 mm. The energy and flux density of γ rays are measured with a NaI(Tl) scintillation spectrometer with dimensions of $11 \times 11 \times 45$ cm and an energy resolution $\lesssim 8\%$. The beam intensity $I_{\gamma k}$ reached $\sim 10^4$ γ/s. The measurements were carried out in an uncollimated γ beam with a continuous Compton spectrum (Fig. 2), but since the fraction of high-energy γ rays in the Compton spectrum is ~ 10 times greater than that in a bremsstrahlung spectrum, the contribution of low-lying excitations (giant resonances) and of the quasideuteron region does not exceed 8%, according to calculations based on the available experimental data.[4] It was thus possible to obtain cross sections averaged over the region of broad baryon resonances ($E_\gamma = 150$–710 MeV) with a rather high accuracy: The values found for $\langle \sigma_{\gamma f} \rangle$ for ^{238}U and ^{237}Np are 63 ± 8 and 102 ± 11 mb, respectively (the indicated error is the total experimental error). The calculated average cross section $\langle A\bar{\sigma}_{\gamma p} \rangle$ is 57.9 mb in this energy interval. We thus find the ratio of the fissilities of ^{238}U and ^{237}Np to be 0.62 ± 0.14, in agreement with the previous measurements of Ref. 2. The photofission cross section of ^{237}Np exceeds the calculated value of $\langle A\bar{\sigma}_{\gamma p} \rangle$ apparently because excitation mechanisms other than the excitation of a nucleus through the production of pions are possible. As was mentioned by Vinogradov *et al.*,[2] $\sim 30\%$ of the cross section for the total photoabsorption in the region of the P_{33} resonance can be attributed to a quasideuteron or cluster mechanism for photoabsorption. The total cross section may also be increased by exchange meson currents, as discussed qualitatively by Lebedev.[5] However, these mechanisms should evidently cause identical increases in the fissility of the nuclei ^{238}U and ^{237}Np; the difference found in fissilities can be observed only at low excitation energies (at $E \leqslant 12$ MeV the fissility of ^{237}Np is 2.5 times that of ^{238}U, but the difference decreases rapidly with increasing excitation energy). It follows that γ rays of intermediate energy can excite a nucleus with a small transfer of momentum and energy.

To test this possibility, we measured coincidences of fission fragments with fast interaction products emitted forward in a small solid angle corresponding to the expected kinematics of the process (for excitation of the nucleus near the fission threshold, ~6 MeV). Within the experimental errors, the spectra of the γ rays incident on the samples agree with the pulse-height spectra of pulses from the NaI(Tl) spectrometer in coincidence with fragments of the fission of ^{238}U and ^{237}Np (to increase the statistical base, we took the sum from all 29 counters), as can be seen in Fig. 2. The solid angle of the NaI(Tl) spectrometer in these measurements was 5×10^{-3}. It should be noted that NaI(Tl) spectrometer detects neutral and charged particles (γ, e^+, e^-, etc.) with an identical efficiency, near 100%. The measured probability for (γ-f) coincidences in terms of the total yield of fission fragments turned out to be $17\pm4\%$. The total experimental error indicated here is ~5 times the statistical error and is due primarily to allowance for double and triple γ rays in each pulse of Compton photons. [The LTI-701 laser used in these experiments could be operated at a repetition frequency up to 16 kHz, so that the probability for coincidence reached ~50% (according to calculations from a Poisson distribution) at the γ flux density of $(5\text{–}6)\times10^3$.] To rule out the possibility of random coincidences, we carried out measurements in a bremsstrahlung beam with an intensity of $(3\text{–}5)\times10^3$ γ/s at a repetition frequency of 818 kHz (the orbiting frequency of the electrons in the storage ring). (In the experiments with the laser, the bremsstrahlung background could be ignored because of the temporal strobing of the laser pulse.) The probability for (γ-f) coincidences, measured in a bremsstrahlung beam at $E_{\gamma\max}=4.8$ GeV, was found to be $18\pm3\%$.

Among the systematic checks, we should mention a study of the shower particles produced by the high-energy γ rays in lead filters (Fig. 1) installed at the exit from the vacuum chamber to shield against synchrotron radiation. For this purpose, 0.5-cm-thick plate scintillators, which could distinguish between charged and neutral particles, were placed ahead and behind the spark counters (Fig. 1). Varying the thickness of the lead filters from $0.5X_0$ to $3X_0$ (X_0 is the radiation length) increased the number of charged particles at the target by a factor ~4.5 but did not affect the coincidence probability. (The total thickness of the spark counters along the beam axis was $0.5X_0$.) The probability for coincidences of the pulses from the fragments of the first and second plates and the NaI(Tl) spectrometer was $10\pm1.5\%$ of the observed total number of (γ-f) coincidences. The presence of charged particles in the shower thus did not have any important effect on the results. The probability for coincidences of pulses from the second plate, the fission fragments, and the NaI(Tl) spectrometer was $28\pm4\%$ of the total number of coincidences.

These results apparently imply that one of the most probable mechanisms for the excitation of nuclei by intermediate-energy γ rays, aside from the photoproduction of pions, is the production of e^+e^- pairs in the nuclear field (Fig. 3). In the energy range of interest here, the wavelength of the γ ray becomes comparable to the size of a nucleon, so that collective nuclear excitations are strongly suppressed. The pair-production probability is three orders of magnitude greater than the nuclear cross section for total absorption, and the excitation energy transferred to the nucleus by the virtual photon may be sufficient to split the nucleus. According to the data obtained in the present study, the cross section for the excitation of a nucleus in pair production is ~0.02% of the total (atomic) photoabsorption cross section.

In summary, the previous observation that the cross sections $\sigma_{\gamma f}$ for transuran-

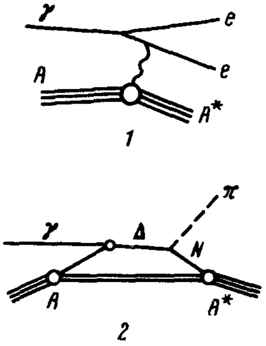

FIG. 3. 1—Diagram corresponding to the excitation of a nucleus through the production of an e^+e^- pair; 2—excitation of a nucleus through the production of a π meson.

ium nuclei are greater than the theoretical predictions may be a consequence of a variety of mechanisms, including a purely electromagnetic mechanism, which must be taken into account in determining the total nuclear photoabsorption. That such excitations might occur at low energies was first pointed out some time ago,[6] and it has recently come under discussion in the literature.[7]

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Translated by Dave Parsons
Edited by S. J. Amoretty