Nuclear excitation due to photon-free annihilation of positrons

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The excitation of $In^{113,115}$ and Cd^{111} nuclei in photon-free annihilation of positrons in matter was investigated experimentally by observing the isomeric γ-ray transitions. A large discrepancy between the theoretical and experimental cross sections for In^{115} is established.

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In addition to the well-known double- and single-quantum annihilation of positrons, photon-free annihilation by bound atomic electrons is possible. The energy liberated as a result of photon-free annihilation

$$E_a = E_K + 2m_o c^2 - E_b ,$$

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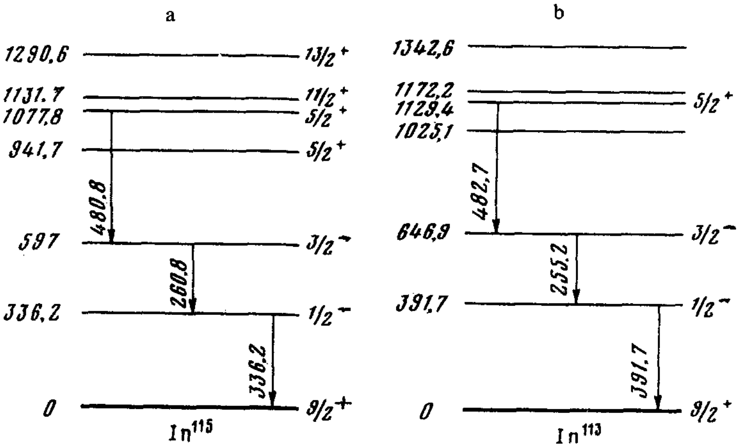

FIG. 1. Fragments of energy-level diagrams: a, In^{115}; b, In^{113}.

where E_K is the kinetic energy of the positrons, m_0c^2 is the rest energy of the electron, and E_b is the binding energy of the electron, may be transferred 1) to the electron shell or 2) to the atomic nucleus.

Nuclei having levels with energy $E_l = E_\alpha$, which are de-excited to the isomeric states, are suitable for experimental observation of nuclear excitation under the influence of radiation-free annihilation of positrons. If after positron irradiation there is evidence (under low-background conditions) of conversion transitions or γ-ray transitions from the isomeric levels, then, after allowing for all the possible accompanying nuclear- and background-excitation channels, we can conclude whether the effect is present or absent.

In this paper we investigated In^{115} and In^{113} nuclei that have, respectively, 336.2-keV ($T_{1/2} = 4.5$ h) and 391.7-keV ($T_{1/2} = 99$ min) isomeric levels which are populated as a result of de-excitation of the high-lying states (Figs. 1a and 1b) and also the Cd^{11} nucleus which is characterized by the 396-keV ($T_{1/2} = 48.7$ min) isomeric state (Fig. 2).

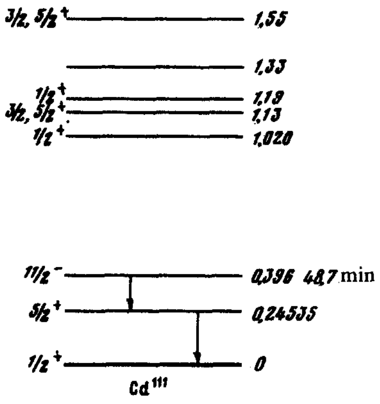

FIG. 2. A fragment of the energy-level diagram of Cd^{111}.

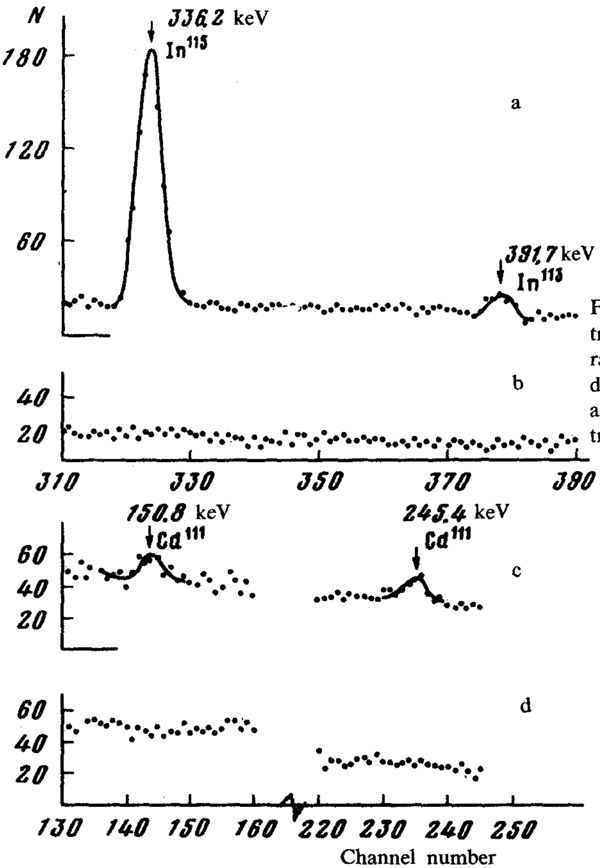

FIG. 3. Gamma-ray spectra: a, γ-ray spectrum of positron-irradiated indium; b, γ-ray spectrum of the control samples of indium; c, γ-ray spectrum of positron-irradiated cadmium; d, γ-ray spectrum of control samples of cadmium.

The Cu^{64} positron sources used in the experiment were obtained from the Cu^{63} (n,γ) Cu^{64} reaction produced as a result of irradiation in the reactor of copper samples of natural isotopic composition. The geometry of the experiment in the form of a stack of consecutively alternating indium or cadmium plates of natural isotopic composition and radioactive copper plates provided the most efficient positron irradiation of the samples-radiators. To control photoexcitation and excitation of In^{115}, In^{113}, and Cd^{111} nuclei by photo and Compton electrons, we irradiated a part of the samples-radiators by Cu^{64} γ quanta and other accompanying γ radiation only and positrons and electrons emitted by Cu^{64} were absorbed by a lead plate. The γ-ray spectra of the investigated main and control samples were measured by Ge-Li detectors. We determined from the energy and half-life whether the observed γ-ray transitions (Figs. 3a and 3c) belong to the isomeric transitions in the γ-ray spectra of the control samples (Figs. 3b and 3d).

According to our measurements and calculations using relations analogous to those of Refs. 1 and 2, we obtained the integral σ_{eff} and differential $\sigma_{\text{res exp}}$ cross sections of the given process for In^{115}, In^{113}, and Cd^{111} nuclei.

TABLE I.

Nucleus	σ_{eff}, cm^2	$\sigma_{res\ exp}$, cm^2	$\sigma_{res\ theor}$, cm^2
In^{115}	$(1.1 \pm 0.4)\times10^{-32}$	$(4.8 \pm 2.1)\times10^{-24}$	$(0.626 \div 1.49)\cdot10^{-30}$
In^{113}	$(7.3 \pm 3.7)\times10^{-33}$	$(1.9 \pm 1.0)\times10^{-24}$	–
Cd^{111}	$(3.3 \pm 2.0)\times10^{-33}$	–	–

The results are given in Table I.

In determining $\sigma_{res\ exp}$ for In^{115}, we omitted the contribution from the 1450-[3] and 1464-keV[4] levels to the populated isomeric state, which, according to our estimates (with allowance for the β^+ distributions of Cu^{64}), comprises $\sim 3\%$ of the contribution from the 1077.8-keV level.[3-6]

In the case of In^{113} we determined $\sigma_{res\ exp}$ for the 1129.4-keV level, which, according to Ref. 5, is de-excited to the 391.7-keV isomeric state (Fig. 1b).

Since, according to data of Ref. 7, Cd^{111} showed no evidence of having levels which could be de-excited to the isomeric state, we give in Table I only the integral cross section of the process. The errors in the values of σ_{eff} and $\sigma_{res\ exp}$ are due principally to the errors in determining the positron flux and the effective thickness of the indium foils rather than the measurement statistics (for example, the statistical error in the case of In^{115} is $\sim 3\%$).

The recently published paper by Watanabe *et al.*[8] confirmed the data for In^{115} obtained by us using a methodologically novel experiment[2] as compared to that of Ref. 1. The results for In^{115} of Ref. 2 and of our present work are also in satisfactory agreement with Ref. 1, whereas a comparison with the theoretical calculations[9] of the $E2$ excitation of the 1078-keV level reveals a significant discrepancy—$\sigma_{res\ exp}$ exceeds $\sigma_{res\ theor}$ by a factor of $> 10^6$ (Table I). A comparison with the theoretical calculations[10] is incorrect because these calculations are for the $E1$ excitation of the 1078-keV level in In^{115}.

The excitation of the In^{113} and Cd^{111} nuclei under the influence of photon-free positron annhilation was observed by us for the first time. The cross sections of the given process for these nuclei have not been calculated theoretically.

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