Nuclear excitation by positron annihilation: Comments on theory vs experiment

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We point out that the contribution of inelastic processes adequately explains the enormous discrepancy ($> 10^6$) observed between the measured and calculated rates for nuclear excitation by positron annihilation.

[NUCLEAR REACTIONS Nuclear excitation by positron annihilation; inelastic contributions to cross section explain enormous discrepancy between theory and experiment.]

In 1952, Present and Chen[1] first considered the process shown in Fig. 1 in which a nucleus is excited directly by absorbing a virtual photon from the annihilation in flight of a positron with a K electron of the atomic shell of the same nucleus. This process can occur when the kinetic energy T of the positron satisfies the resonance condition

$$|T+2mc^2-(\Delta E+B_K)| < \delta E/2, \qquad (1)$$

where ΔE is the energy of the excited nuclear level in question, δE its level width, mc^2 the electron rest energy, and B_K the binding energy of the K electron. Present and Chen estimated the cross section of this process for an electric-dipole-type excitation of the 1.08 MeV level of ^{115}In to be $\sigma=3\times 10^{-26}$ cm^2. The spin and parity of this level are now known to be such that only electric quadrupole ($E2$) excitation is possible and a revision of this cross section for $E2$ excitation has been given by Grechukhin and Soldatov[2] as $\sigma \simeq 6\times 10^{-31}$ cm^2.

The first experimental evidence for nuclear excitation by positron annihilation was obtained by Mukoyama and Shimizu.[3] These workers irradiated a natural In foil with positrons ($E_{\max}=540$ keV) from a ^{22}Na source. After 30 h of irradiation, the foil was removed and was found to emit internal conversion electrons corresponding to the 335 keV isomeric level ($T_{1/2}=4.5$ h) of ^{115}In. The isomer is thus used as a sensitive activation detector of the excitation of the 1.08 level of ^{115}In which has a partial decay branching to the isomeric level. Every positron with initial energy greater than $T_0=(\Delta E+B_K)-2mc^2$ has a chance to satisfy the resonance condition (1) as it slows down in the metal foil. The probability P that such a positron excites a nucleus is

$$P=(n\sigma\delta E)/(dT/dx)_{T_0}, \qquad (2)$$

where n is the number density of the nuclei and dT/dx is the positron stopping power when its kinetic energy T satisfies relation (1). Thus the effective target thickness is only that in which positrons of energy T_0 lose an energy $\sim\delta E$. Using (2), the cross section σ may be calculated from the measured induced activity of the foil, the β^+-spectrum shape, the source activity, the decay branching ratios of the 1.08 level to the ground and isomeric states, geometrical factors, etc. Small corrections for excitation of a level at 1.45 MeV were also applied.[3] Quite suprisingly, the σ thus

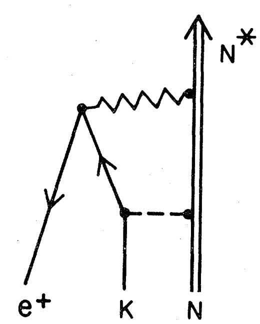

FIG. 1. The original resonant process of Present and Chen (Ref. 1) for nuclear excitation by positron annihilation. N and N^* are the nucleus and its excited state, K is a K electron, and e^+ is the incident positron. The dashed line represents a Coulomb photon and the wavy line is the virtual single quantum annihilation photon that excites the nucleus. The positron kinetic energy must be such as to conserve the total energy to a precision of 10^{-3} eV, the width of the nuclear level to be excited.

obtained was $\simeq 4\times 10^{-24}$ cm^2 indicating an activation yield some seven orders of magnitude larger than the estimate of Ref. 2 of $\simeq 6\times 10^{-31}$ cm^2 for $E2$ excitation of the 1.08 MeV level on the basis of the Present-Chen theory. The experiment has been repeated[4] and reconfirmed at another laboratory,[5] and several cases of nuclear excitation in nuclides other than ^{115}In have been observed.[5–7] The enormous discrepancy between theory and experiment, quantified by the ^{115}In case (no theoretical numbers available for the other cases) has prompted reexamination of the theoretical basis of this process.[4]

The purpose of the present note is to point out the importance of inelastic counterparts of the process shown in Fig. 1 which also contribute to nuclear excitation by positron annihilation. In these processes, shown in Fig. 2, some of the positron kinetic energy is carried away either by a photon or by the emission of a second K electron. Although of higher order than the elastic process of Fig. 1 ($\sigma' \simeq \sigma/137$), the inelastic processes relax the resonance constraint on T imposed by the inequality (1), yielding a probability of nuclear excitation per positron of

$$P' = n \int_{T_0'}^{T_1} \sigma'(T)(dT/dx)^{-1} dT. \quad (3)$$

This is constrained only the threshold condition $T_1 > T_0'$, where T_1 is the initial positron kinetic energy and, where T_0' is the threshold for the inelastic process. Thus a target thickness corresponding to the macroscopic slowing-down distance of the entire source spectrum $> T_0'$ is effective. Nuclear excitation can occur without recourse to the agency of the slowing-down processes to reduce the energy of the positrons and scan it across the microscopic thickness corresponding to the width δE. The ratio of the inelastic to the elastic probabilities is roughly

$$P'/P \simeq \left(\frac{1}{137}\right) \frac{\langle T_1 - T_0' \rangle}{\delta E} \simeq 10^6 , \quad (4)$$

since the mean available positron energy is $\langle T_1 - T_0' \rangle \simeq 10^5$ eV and $\delta E \simeq 10^{-3}$ eV. The contribution of the inelastic processes thus completely dominates the nuclear excitation and the rough estimate of (4) shows that it can explain the large difference between the observed activation yields in the case of ^{115}In and the predictions of the theory.[1,2]

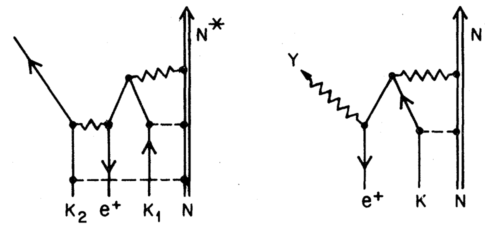

FIG. 2. Inelastic counterparts of the Present-Chen process of Fig. 1. Either the second K electron is ejected or, more probably, a real annihilation photon is emitted. The positron can have any kinetic energy above a threshold because the emitted particle takes away the excess energy. The various lines can be permuted to give other similar diagrams.

We conclude that bombarding nuclei with a broad positron energy spectrum is most likely to result in photon or K-electron emission accompanied by nuclear excitation. The dominant inelasticity of the process in the practical regime of wide-band irradiation dictates larges cross sections as has been actually observed. These conclusions indicate that the observed cross sections would scale roughly with the mean source energy $\langle T_1 - T_0' \rangle$ after accounting for the energy dependence σ' due to the phase space factors of the outgoing photon or K electron. Experiments involving sources of widely different mean energies $\langle T_1 - T_0' \rangle$ could test the validity of these conclusions.

Note added in proof. Inelastic processes analogous to those of Fig. 2 in the *photoactivation* of ^{115}In have been considered by Ljubičić *et al.* [A. Ljubičić, K. Pisk, and B. A. Logan, Phys. Rev. C 23, 2238 (1981)].

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