Factors responsible for the difference in the theoretical and experimental results for the probability of nuclear excitation by electron transition

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Contradictory experimental results for the probability of the formation of a long-lived ^{189m}Os isomer in the study of nuclear excitation by electron transition are explained. The importance of this process in the study of the anomalies associated with the dynamic penetration of the electron current into the nucleus is shown.

Precision experiments[1,2] on the excitation of the $5/2^-$ state (69.5 keV) in ^{189}Os nucleus (Fig. 1) have yielded values, which differ by more than an order of magnitude, for the relative probability P for the excitation of a nucleus to a given level, with the formation of a vacancy at the K shell of an osmium atom: $P=(1.7\pm0.2)\times10^{-7}$ (Ref. 1) and $(5.7\pm1.7)\times10^{-9}$ (Ref. 2). In Ref. 1, the sample which contained ^{189}Os isotope was bombarded by a beam of $\sim$100-keV electrons (the binding energy at the K shell of an osmium atom is 73.78 keV). In another experimental study,[2] a similar sample was subjected to the effect of a synchrotron radiation. In each experiment the goal was to measure the probability for the occurrence of nuclear excitation by electron transition (NEET), which was predicted by Morita.[3] This process has recently been studied extensively, both theoretically and experimentally. A bibliography of the principal studies of this process is given in the review article by Tkalya.[4]

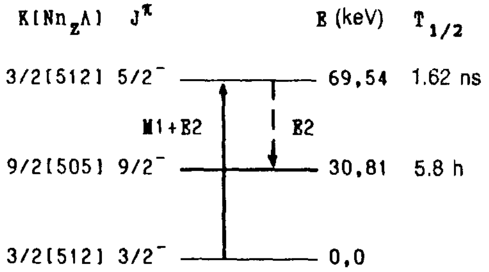

FIG. 1.

The most consistent approach to NEET was developed in Refs. 4 and 5. Using actual vacancy widths Γ_i adn Γ_f at the atomic shells, between which the electron transition occurs, we can describe the NEET, in terms of QED, on the basis of a second-order diagram, shown in Fig. 2. The relative probability for the excitation of a nucleus as a result of the decay of a vacancy at the shell $|i\rangle$ is given by

$$P = \left(1 + \frac{\Gamma_f}{\Gamma_i}\right) \frac{E^2_{int}(L;\omega_N; i \rightarrow f, I \rightarrow F)}{(\omega_N - \omega_A)^2 + (\Gamma_i + \Gamma_f)^2/4}. \tag{1}$$

Here ω_N and ω_A are the energies of respectively the nuclear transition and atomic transition (in units of $\hbar = c = 1$) with a multipolarity L, $E^2_{\rm int}$ is the square of the energy of interaction of the nuclear current, averaged over the ground states and summed over the final states, $J^\nu_{IF}(\mathbf{R}) = e\Psi^+_F(\mathbf{R})\hat{J}^\nu\Psi_I(\mathbf{R})$, and of the electron hole current $j^\mu_{if}(\mathbf{r}) = e\overline{\psi}_f(\mathbf{r})\gamma^\mu\psi_i(\mathbf{r})$:

$$H_{int} = \int d^3r d^3R j^\mu_{if}(\mathbf{r}) D_{\mu\nu}(\omega; \mathbf{r} - \mathbf{R}) J^\nu_{IF}(\mathbf{R}), \tag{2}$$

and $D_{\mu\nu}(\omega;\mathbf{r} - \mathbf{R}) = -g_{\mu\nu}\exp(\omega|\mathbf{r} - \mathbf{R}|)/|\mathbf{r} - \mathbf{R}|$ is the photon (γ-ray) propagator in the frequency coordinate representation.

In Refs. 4 and 5, the investigators used the nuclear matrix elements of $M1$ and $M2$ transitions from the ground state (g.s.) to the 5/2$^-$ state (69.5 keV), which were

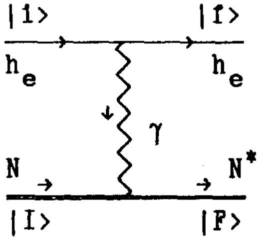

FIG. 2.

reconstructed from the experimental data on the intensities of 69.54-keV γ-ray radiation,[6] to calculate P for ^{189}Os. The transition g.s. → $5/2^-$ (69.5 keV) occurs inside the rotational band (Fig. 1) and both of its indicated components are allowed by the asymptotic quantum numbers of the Nilsson model. The use of γ-ray-emitting nuclear matrix elements in the calculation of the probability of NEET in ^{189}Os is therefore correct. The atomic part in Eqs. (1) and (2) was calculated using a tested precision program.[7] The calculated probability was found to be smaller than that determined in Refs. 1 and 2. It has the value 3.4×10^{-10}.

The values of P obtained in Refs. 1 and 2 are not the result of the direct measurements of the ratio of the number of nuclei excited to the $5/2^-$ (69.5-keV) state, $N_{69.5}$, to the number of nuclei created by external irradiation of the K vacancies in the osmium atoms, N_K. In each case, the efficiency of the excitation of the $5/2^-$ (69.5-keV) level was determined from the activity of the decay of the isomeric ^{189m}OS nuclei which were accumulated in a time it took to irradiate them in the long-lived $9/2^-$ (30.8-keV) state. The number of these nuclei, N_{is}, is related to $N_{69.5}$ and N_K by a relation of the type

$$N_{is} = b_0(N^{e,\gamma}_{69,5} + N^{NEET}_{69,5}) + \sum_{i\geq 1} b_i N_i^{\gamma}, \quad N^{NEET}_{69,5} = PN_K, \tag{3}$$

where $N^{\mathrm{NEET}}_{69.5}$ is the number of nuclei excited to the $5/2^-$ (69.5-keV) state as a result of NEET, $N^{e,\gamma}_{69.5}$ is the number of nuclei excited to the $5/2^-$ (69.5-keV) state as a result of other processes—the inelastic scattering of electrons by nuclei (in Ref. 1) and absorption of resonance γ-rays by nuclei (in Ref. 2), N_i^{γ} is the number of nuclei excited by synchrotron radiation to higher-lying states (in Ref. 2), and b is the branching ratio. Of greatest importance is the filling of the isomeric level in the decay of the $5/2^-$ (69.5-keV) state, b_0. In the analysis of the experimental data in Refs. 1 and 2, the authors used for the filling the value 1.2×10^{-3}, proposed in Ref. 1, as the initial estimate. For this value of b_0, the creation of isomers was *a priori* attributed principally to the NEET mechanism, since the standard cross sections of the other processes were found to be totally inadequate in explaining the observable activity of the decay of ^{189m}Os, and were therefore rejected. The parameter P, determined from a simplified relation $N_{is} = b_0PN_K$, gave probability values for NEET which differ by approximately a factor of 30. Actually, the K-forbidden, first-order $E2$ transition $5/2^-$ (69.5 keV) → 9.2^- (30.8 keV) (represented by a dashed line in Fig. 1) is yet to be observed experimentally.[6] The coefficient b_0 is not known, and hence must be a free parameter in Eq. (3).

Analyzing again the results of the experiment of Ref. 2, where the number of K vacancies formed in the osmium atoms as a result of synchrotron radiation was determined from the intensity of the characteristic x-ray emission, it is easy to see, on the basis of the probability of NEET $P=3.4\times10^{-10}$ calculated in Refs. 4 and 5, that the dominant mechanism for the excitation of osmium nuclei to the $5/2^-$ (69.5-keV) level is not the NEET mechanism, but rather the process by which $\approx$69.5-keV resonance γ rays are captured by nuclei from the synchrotron-radiation spectrum. The next three levels of the ^{189}Os nucleus, with energies of 95.2 keV, 216.6 keV, and 219.4 keV, have also contributed significantly to the production of isomers. The data of Ref. 6 can be used to determine the corresponding cross sections and the branching ratios. For the 69.5-keV level it is necessary to take into account the Compton excitation by the synchrotron radiation, whose value was determined in Ref. 8. Taking all of the aforementioned processes into account, we obtain, from the data of Ref. 2, the value $\approx 3.4\times 10^{-3}$ for the branching ratio b_0.

Analysis of the results of the experiment[1] on the basis of the new parameters P and B_0 gives quite reasonable results. First, the cross section for excitation of the $5/2^-$ (69.5-keV) level used in Ref. 1 was $\sigma_{69.5} = 3.2\times 10^{-31}$ cm^2 at electron energy of 100 keV (rather than 9.2×10^{-31} cm^2, as follows from the results of Ref. 1 for $b_0 = 1.2\times 10^{-3}$). The value of $\sigma_{69.5}$ obtained by it, however, is approximately equal to the cross section for excitation of the $5/2^-$ (69.5-keV) state, calculated in Ref. 4, in the inelastic scattering of the beam electrons by ^{189}Os nuclei: $\sigma_{69.5}^{(e,e')} = 3.1\times 10^{-31}$ cm^2. It is also in good agreement with the results of such calculations in Ref. 9. Secondly, the principal mechanism for the creation of excited nuclei in Ref. 1 was, as was assumed in Refs. 4, 5, and 9, the inelastic scattering of electrons, while the actual effect of NEET was found to be more moderate than that given above by two orders of magnitude.[4,5]

The consistent description of the two experiments given above shows that the NEET process does indeed exist, and that its "traces" ($\approx 10\%$ of the produced isomers) were detected experimentally.[2] It turned out, however, that this mechanism has a much smaller effect, than that predicted in Ref. 3 and in other theoretical studies, in the excitation of the $5/2^-$ (69.5-keV) state in ^{189}Os. The refinement of the filling factor b_0 is yet another very important consequence of the measurements of Refs. 1 and 2. This factor is related to the radiative width of the transition represented by the dashed line in Fig. 2, $\Gamma_\gamma(E2)$, to the internal electron conversion coefficient $\alpha(\approx 357.6$—calculated in Refs. 4 and 5 on the basis of a program obtained from Ref. 7), and to the total width of the nuclear level with an energy of 69.5 keV, $\Gamma(5/2^-)$, by the relation

$$b_0 = (1+\alpha)\Gamma_\gamma(E2; 5/2^- \to 9/2^-)/\Gamma(5/2^-) = 5,7\times 10^{-3} \cdot F_{E2}. \tag{4}$$

This relation can be used to determine $F_{E2} = B(E2;\, 5/2^- \to 9/2^-)/B(E2;\, W)$—the attenuation of the intensity of the $E2$ transition in question relative to the single-particle Weisskopf model [here the $B(E2)$ are the reduced nuclear transition probabilities]. Substituting in (4) the value of b_0 found above, we obtain $F_{E2} = 0.6$ for the attenuation factor.

A highly intriguing situation involving NEET in ^{197}Au and ^{237}Np nuclei has developed. Values of the probability which were much higher than all of the published theoretical estimates (Ref. 4) were obtained in the experimental studies which were reported in Refs. 10 and 11: $(2.2 \pm 1.8)\times 10^{-4}$ for ^{197}Au and $(2.1 \pm 0.6)\times 10^{-4}$ for ^{237}Np. These results have, in our view, only two reasonable explanations: either the values reported in Refs. 10 and 11 have systematic experimental errors or the anomalies similar to those found in the internal electron conversion coefficients have a strong effect in the corresponding nuclear matrix elements.

In all of the theoretical NEET models it was assumed that (first) the regions in which the nuclear current, $J_\nu(\mathbf{R})$, and the electron current, $j_\mu(\mathbf{r})$, are localized satisfy the condition $R \ll r$ in Eq. (2) and (second) the influence of the static effects is negligible when $r \ll R_0$ (R_0 is the nuclear radius). When the lower atomic shells participate in the process, however, the dynamic effects associated with the penetration of the electron current into the nucleus can have a considerable effect, as is well known (see, e.g., Refs. 12 and 13), on the forbidden nuclear transitions. Such a transition is an l-forbidden $M1$ transition $3/2^+$ (g.s.) → $1/2^+$ (77.35 keV) between the $2d_{3/2}$ and $3s_{1/2}$ subshells, with an attenuation factor $F_{M1} = 2.12 \times 10^{-3}$ in a ^{197}Au nucleus, and a proton $E1$ transition $5/2^+$ (g.s.) → $7/2^-$ (102.96 keV) between $K^\pi [Nn_z\Lambda] = 5/2^+$ [642] and $5/2^-$ [523] bands, with an attenuation factor $F_{E1} = 4.27 \times 10^{-6}$ in a ^{237}Np nucleus, which is forbidden in the asymptotic quantum numbers of the Nilsson model. Note that the large anomalies of the internal conversion coefficients in the ^{237}Np nucleus in the transitions between the indicated bands have been reported by Kramer and Nilsson.[13] It is difficult to believe that the difference between the theoretical and experimental values of P can be explained strictly in terms of the anomalies observed in NEET. Only one experiment was carried out for each nucleus, which clearly is not enough, considering that the measurements are extremely difficult to perform. Both factors probably play a role. It is important to note, however, that exact measurements of the probability of NEET may yield new information on the anomalies, which cannot be obtained by measuring the internal conversion coefficients, since conversion in the transitions which we have considered can occur only in the L shell or in higher shells of the atom, while NEET involves the K shell, which has the strongest anomalies. This circumstance makes the NEET process highly promising for experimental study.

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