Internal conversion in the field of an "electronic bridge"

V. A. Krutov
Scientific-Research Institute of Physics, Leningrad State University

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Internal conversion in the electromagnetic field set up by the current of an "electronic bridge" has been studied for the first time. At low energies of the nuclear transitions, this effect can change the ratios of the coefficients of internal conversion in high-index atomic shells.

The "electronic bridge" effect[1-4] occupies a unique position among the effects found in higher approximations in $\alpha = e^2/(\hbar c)$. This effect consists of an additional decay of an excited nucleus by γ-ray emission through an electron shell as an intermediate state (diagram 3 in Fig. 1). The effect is unique because—for certain parameter values of the physical system (at low energies ω and high multipolarities L of the nuclear transitions)—a process of third order in α may be stronger (significantly stronger) than a process of first order in α, although the final state of the system and the initial state are identical in the two processes. The electronic bridge has now been confirmed in several theoretical papers.[5-7] There have also been reports of its experimental observation,[8,9] although such experiments are extremely complicated.

There is another effect, directly related to the electronic bridge and a consequence

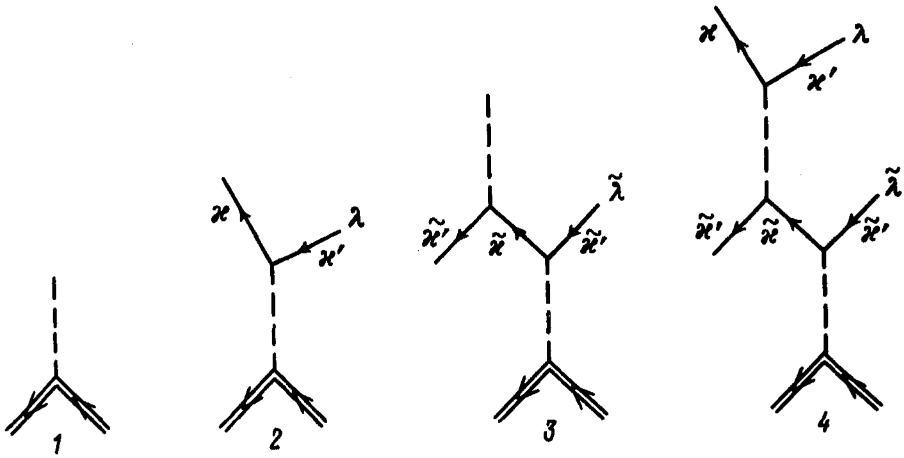

FIG. 1. Double line—Nuclear; single line—electronic, dashed line—photonic. 2) Ordinary internal conversion (and "internal photoelectric effect") for electrons λ; 3) "electronic bridge" with electron $\tilde{\lambda}$; 4) internal conversion in the field of the electronic bridge.

of it, which has not previously been studied, although an experimental test of this other effect would be a comparatively simple matter. I pointed out this effect in 1958, in the original paper on the electronic bridge.[1] In that paper, the effect was called "multiple exchange" or a "screening of multiple potentials." The effect will be called "internal conversion in the field of an electronic bridge" in the present letter, since that name better reflects the essence of the effect.

Let us look at the effect. We assume that the electronic bridge effect is large for some electronic state $\tilde{\lambda}$. A conversion transition of any other electron λ will then occur not only in the electromagnetic field set up by the current of the nuclear transition but also in the electromagnetic field set up by the electronic bridge with the electron $\tilde{\lambda}$. Diagram 4 in Fig. 1 illustrates this "internal conversion in the field of an electronic bridge." Diagram 4 has two vertices not present in ordinary conversion, as shown by diagram 2. It would seem at first glance that the probability for process 4 would be $\sim\alpha^2 \approx 10^{-4}$ of the probability for process 2. However, process 4 is unusual in that it acquires two more vertices because of the electronic bridge. If the electronic bridge effect is large in comparison with ordinary γ-ray emission, process 4 will have a much greater effect than process 2 (in principle, it could even be more important than process 2, if process 3 is more important than process 1 by a substantial amount—several orders of magnitude).

We will retain the notation of Refs. 1–4; we will simply explain the basic equations. As was shown in Refs. 1–4, the γ-ray emission from the system consisting of the nucleus and the electron shell is given in units of the γ emission of the "bare nucleus" by

$$\frac{N_q^{(3)}}{N_q^{(1)}} \approx 1 + \Big(\sum_{\tilde{\kappa}'\tilde{\kappa}} \beta_{\tilde{\kappa}\tilde{\kappa}'} \delta_{\tilde{\kappa}\tilde{\kappa}'}\Big)^2, \tag{1}$$

where the second term gives (in units of $N_q^{(1)}$) the number of γ rays emitted by the nucleus through the electronic bridge ($\beta_{\tilde{\kappa}\tilde{\kappa}'}$ is the coefficient of internal conversion in the $\tilde{\kappa}'$ shell with a $\tilde{\kappa}$ final state, $\mathrm{Re}R_{\tilde{\kappa}\tilde{\kappa}'}/\mathrm{Im}R_{\tilde{\kappa}\tilde{\kappa}'}$ and $R_{\tilde{\kappa}\tilde{\kappa}'}$ is the radial matrix element of the conversion transition).

The amplitude for the conversion transition of the λ electron in fourth order is[1]

$$^{\lambda}U_{fi}^{(4)} = {}^{\lambda}U_{fi}^{(2)} - \pi^2 \; {}^{\lambda}H_{0\omega} \; {}^{\lambda}H_{\omega 0} \; {}^{\lambda}U_{fi}^{(2)} - \pi^2 \; {}^{\lambda}H_{0\omega} \sum_{\tilde{\lambda} \neq \lambda} {}^{\tilde{\lambda}}H_{\omega 0} \; {}^{\tilde{\lambda}}U_{fi}^{(2)}, \tag{2}$$

where ${}^{\lambda}U_{fi}^{(2)}$ is the amplitude of the ordinary conversion transition, and

$$^{\lambda}H_{0\omega} = \mathrm{Re}R_{\kappa\kappa'} T_{\kappa\mu\kappa'\mu'} = {}^{\lambda}H_{\omega 0}^{*}. \tag{3}$$

Here $T_{\kappa\mu\kappa'\mu'}$ is the angular part of the matrix elements (with factors of the $\sqrt{\alpha}$ type).

The third term in (2) also describes internal conversion in the field of an electronic bridge. In this case, however (in contrast with ${}^{\lambda}H_{0\omega}{}^{\lambda}H_{\omega 0}$), the ${}^{\lambda}H_{0\omega}$ conversion transition in the radiation field of the transition ${}^{\tilde{\lambda}}H_{\omega 0}$ cannot be factorized in the form $\mathrm{Re}R_{\kappa\kappa'} T_{\kappa\mu\kappa'\mu'} \cdot \mathrm{Re}R_{\tilde{\kappa}'\tilde{\kappa}} T_{\tilde{\kappa}\tilde{\mu}\tilde{\kappa}'\tilde{\mu}'}$, since in this case we are dealing with an exchange of virtual phonons between the current of the electronic transition $\psi_{\tilde{\kappa}'\tilde{\mu}'}(\mathbf{r}) \rightarrow \psi_{\kappa\mu}(\mathbf{r})$ and the current of the electronic transition $\psi_{\tilde{\kappa}\tilde{\mu}}(\mathbf{r}') \rightarrow \psi_{\tilde{\kappa}'\tilde{\mu}'}(\mathbf{r}')$ in the electronic bridge. In this case r can be either greater than or less than r'. We thus find[1)]

$$^{\lambda}H_{0\omega} \; {}^{\tilde{\lambda}}H_{\omega 0} = \mathcal{R}_{\kappa\kappa'\tilde{\kappa}'\tilde{\kappa}} T_{\kappa\mu\kappa'\mu'} T_{\tilde{\kappa}\tilde{\mu}\tilde{\kappa}'\tilde{\mu}'}, \tag{4}$$

$$\begin{aligned}\mathcal{R}_{\kappa\kappa'\tilde{\kappa}'\tilde{\kappa}} = {} & \int_0^\infty dr \varphi_{\kappa\kappa'}(r) \{ h_L(\omega r) \int_0^r dr' \varphi_{\tilde{\kappa}'\tilde{\kappa}}(r') j_L(\omega r') \\ & + j_L(\omega r) \int_r^\infty dr' \varphi_{\tilde{\kappa}'\tilde{\kappa}}(r') h_L^{*}(\omega r') \} \\ & + \int_0^\infty dr \chi_{\kappa\kappa'}(r) \{ h_{L-1}(\omega r) \int_0^r dr' \chi_{\tilde{\kappa}'\tilde{\kappa}}(r') j_{L-1}(\omega r') \\ & + j_{L-1}(\omega r) \int_r^\infty dr' \chi_{\tilde{\kappa}'\tilde{\kappa}}(r') h_{L-1}^{*}(\omega r') \},\end{aligned} \tag{5}$$

$$\varphi_{\tilde{\kappa}\tilde{\kappa}'}(r) = r^2 \{ g_{\tilde{\kappa}}(r) g_{\tilde{\kappa}'}(r) + f_{\tilde{\kappa}}(r) f_{\tilde{\kappa}'}(r) \}, \tag{6a}$$

$$\chi_{\tilde{\kappa}\tilde{\kappa}'}(r) = r^2 \left\{ \frac{\tilde{\kappa}' - \tilde{\kappa} - L}{L} f_{\tilde{\kappa}}(r) g_{\tilde{\kappa}'}(r) + \frac{\tilde{\kappa}' - \tilde{\kappa} - L}{L} g_{\tilde{\kappa}}(r) f_{\tilde{\kappa}'}(r) \right\}. \qquad (6b)$$

From this point on, the calculations are similar to those in Refs. 1 and 2. As a result of the calculations, we find the following expression for the coefficient of internal conversion in the κ' subshell of the atom, in which we have retained in the numerator only the internal conversion in the field of the electronic bridge, and in the denominator only the electronic bridge (the other higher-order approximation effects are always small):

$$\beta_{\kappa'} = \sum_{\kappa} \beta_{\kappa\kappa'} \frac{\left| 1 - \sum\limits_{\tilde{\kappa}\tilde{\kappa}'} \beta_{\tilde{\kappa}\tilde{\kappa}'} \frac{\mathcal{R}_{\kappa\kappa'\tilde{\kappa}'\tilde{\kappa}}}{R_{\kappa\kappa'} R^*_{\tilde{\kappa}\tilde{\kappa}'}} \right|^2}{1 + \left(\sum\limits_{\tilde{\kappa}'\tilde{\kappa}} \beta_{\tilde{\kappa}\tilde{\kappa}'} \delta_{\tilde{\kappa}\tilde{\kappa}'} \right)^2}. \qquad (7)$$

The electronic bridge reduces all the internal-conversion coefficients proportionately; i.e., it does not alter the ratios of the coefficients of internal conversion in the various electron shells and subshells. However, the internal conversion in the field of an electronic bridge depends on κ', as can be seen from (7), and may change these ratios. This possibility can be tested experimentally if the effect is large enough. There is the further possibility, in principle, of a change in the lifetime of the nuclear state as a result of a change in the probability for conversion due to the electronic bridge, although the probability for the electronic bridge is itself very small in comparison with probability for an ordinary conversion transition.

The electronic bridge effect may be large at small values of ω and at $EL \geqslant 2$, as was shown in Refs. 1–7. However, could internal conversion in the field of such an electronic bridge be a large effect? It is our opinion that a large internal conversion effect can be expected. This opinion is based on the relation

$$|\mathcal{R}_{\kappa\kappa'\tilde{\kappa}'\tilde{\kappa}} / R_{\kappa\kappa'} R^*_{\tilde{\kappa}\tilde{\kappa}'}| \gg \delta_{\kappa\kappa'} \delta_{\tilde{\kappa}'\tilde{\kappa}}.$$

This relation is in turn clear from (5), which contains Hankel functions. However, a final resolution of this question will have to await accurate numerical calculations. Screening for the electron wave functions must be taken into account, since approximate calculations may distort the magnitude of the electronic bridge by several orders of magnitude (since $\mathrm{Re}R_{\tilde{\kappa}\tilde{\kappa}'}$ is small) and thus distort the magnitude of the conversion in the field of the electronic bridge. I am addressing this letter primarily to those theoreticians who have access to programs for accurately calculating the coefficients for internal conversion in high subshells (beginning with L_{III}) at small values of ω, with a correct account of screening. It is of course important to know just which particular cases warrant calculations. I recommend a calculation on internal conversion in the field of an electronic bridge [a calculation of the ratios of internal-conversion coefficients from (7) and (5)] primarily for P shells in an $E3$ transition with $\omega = 75$ eV in ^{235}U and for N subshells in an $E2$ transition with $\omega = 2.4$ keV in ^{205}Pb. The electronic bridge will be a large effect for these or nearby transitions, as has been shown by accurate calculations.[4,5,10] On the other hand, the ratios of internal-conversion coefficients calculated for these subshells, with a correct account of screening, are significantly different from the experimental values (see Ref. 10 for the values of the ratios and for references to experiments). I therefore feel it is reasonable to test the hypothesis of a large value of the internal-conversion effect in the field of an electronic bridge in specifically these cases.

(1) For brevity, we have restricted the discussion to EL transitions everywhere, especially since the electronic-bridge effect is considerably larger for these transitions than for ML transitions. To simplify the equations, we are not singling out the finite dimensions of the nucleus in the conversion matrix elements. These dimensions can easily be dealt with by standard methods. Finally, we are ignoring the exchange matrix elements for the λ and $\tilde{\lambda}$ electrons. Incorporating exchange makes the equations far more complicated without introducing anything fundamentally new.

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