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POSSIBLE CORRELATIONS OF ELECTROMAGNETIC TRANSITIONS IN EXOTIC ATOMS, AND THEIR IMPLICATION FOR CASCADE CALCULATIONS*)

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ABSTRACT

It is shown that if the atomic cascade is treated as a 'coherent' multi-quantum transition process, the population distribution of the atoms in the intermediate states differs significantly from results obtained by standard computations.

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When negatively charged, heavy particles are injected into matter, they are subject to Auger and radiative transitions as they cascade down, until their ultimate absorption by the host nucleus. For a proper interpretation of the X-ray spectra emitted during the cascade, and the extraction of precise answers to questions concerning strong interactions, mass determinations, and QED effects, a knowledge of the distribution of atoms in the intermediate stages of the cascade as a function of the relevant quantum numbers is necessary[1]. The standard cascade calculations[2] proceed from some initial statistical (or quasi-statistical) population distribution in a large n level ($n \geq 14$). It is then assumed that the atom cascades down either through the emission of an Auger electron or a photon according to well-established selection rules and transition probabilities. The important point in this procedure is that each electron ejection or photon emission is treated as an independent event. The purpose of this note is to explore briefly the implication, for cascade calculations, of the assumption that the passage of the exotic atom from initial state, n_i, l_i to a final state n_f, l_f, in which $n_i - n_f$ electrons and/or photons may be emitted, is a 'single' correlated event. The immediate implication of this should be the existence of angular correlations between photons and/or electrons in (multi) coincidence measurements, as is the case in nuclear physics[3].

But there is another, hitherto not emphasized, implication of such an assumption; and that is, the population distribution in the intermediate stages of the cascade. We now proceed to present a simple example to illustrate our point.

Assume that we have N exotic atoms in the 4d state. All other levels are initially unoccupied. Relativity and spin are omitted in this calculation. Dipole selection rules permit this level to decay into either the 3p or 2p state. Subsequently the 3p level can decay into the 2s or 1s state, while the 2p level decays into the 1s state. Either way, two photons are emitted in this mini-cascade. Standard computations treat each of these transitions independently; from this point of view the 4d level can branch into two directions only, with the branching ratio given by the ratio of the 4d-3p to the 4d-2p transition probability.

In contrast to this, if we consider the two-photon transition as a 'single' event, then there are three independent branches into which the 4d state can decay. Specifically, i) 4d-3p-2s, ii) 4d-3p-1s, and iii) 4d-2p-1s. The transition amplitude corresponding, for example, to the two-photon emission via branch (i) is proportional to

$$T_I \propto \sum_{m=-1}^{+1} \frac{\langle 4d0 \,|\vec{p}\cdot\vec{A}_2|\, 3pm\rangle \langle 3pm \,|\vec{p}\cdot\vec{A}_1|\, 2s\rangle}{E_4 - E_3 - \omega_2 + i(\Gamma_4 + \Gamma_3)/2} , \quad (1)$$

where A_2 and A_1 denote the vector potentials associated with photons 2 and 1, respectively; ω_2 and ω_1 stand for the respective photon energies; and Γ_4 and Γ_3 represent the widths of the 4d and 3p levels[4]; $\hbar = c = 1$. The transition probability corresponding to the above-stated amplitude is proportional to

$$R_I \propto \int \ldots \int \sum |T_I|^2 \; \delta(E_4 - E_2 - \omega_2 - \omega_1)\omega_2\omega_1 \; d\omega_2 \; d\omega_1 \; d\Omega_1 \; d\Omega_2 \; . \qquad (2)$$

The summation in the above expression is to include all possible polarizations of the two photons. The δ-function fixes the range of integration for the (photon) energy variables. Note that the integrations over the angular distribution and summation over the photon polarizations are identical for all three processes; hence they can be factored out. The rest of the computation, integrals over radial functions in Eq. (1), and integration over energy variables in Eq. (2), is elementary. We simply state the results:

$$R_I/R_{II} = 0.91 \qquad (3)$$

$$R_{II}/R_{III} = 0.28 \qquad (4)$$

Processes I and II, corresponding to decays via branc es (i) and (ii), respectively, proceed via the 3p level, hence both contribute to the population in the 3p intermediate state. In this way the 3p population is approximately 0.35N, while the 2p population is 0.65N. For comparison we include the numbers that could be obtained by the standard independent photon transition calculation. Here the 3p population would be 0.26N and the 2p population would be 0.74N.

Several simplifications were made in the above discussion. Two of them should be explicitly stated.

i) The level widths appearing in the energy denominator in Eq. (1) have been inserted 'by hand', and the values used were based on single-photon transition probabilities. This is not quite consistent with our basic assumption. A derivation of the resonant two photon transition amplitude, based on either the Weisskopf-Wigner theory[5] or the S-matrix theory[6], may alter some of the details. It is extremely unlikely, however, that the population distribution in the 3p and 2p levels will be the same as in the independent transition model.

ii) It has been known for some time that a necessary condition for observing angular correlation in a nuclear cascade is the requirement that the energy associated with the level width of the intermediate state(s) be large in comparison with the possible magnetic interaction between the external electrons and the magnetic moment of the nucleus in the intermediate state(s)[3].

We expect that similar criteria will affect the 'coherent' cascade calculation. We should emphasize, however, that while the confirmation of angular correlations in the emitted X-rays from exotic atoms would imply the correctness of our basic assumption, a negative result obtained in angular correlation measurements would still not prove the adequacy, as far as cascade calculations are concerned, of the independent transition model. We shall return to both of these points in a subsequent, detailed publication.

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