Tests of internal-conversion theory

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Except for the very lightest nuclei, where internal conversion is weakest, most nuclear decay schemes depend upon calculated internal conversion coefficients (ICCs). Electromagnetic decay intensities are usually determined from gamma-ray measurements combined with calculated ICCs. Consequently, the reliability of the calculations is a matter of some importance, especially where precise decay-scheme data are required, for example in detector calibration. Until quite recently, although various tables of calculated ICCs were readily available, most ICC measurements were relatively imprecise, being aimed only at determining transition multi-polarities. Rarely were they precise enough to distinguish among different calculations or indeed to establish if any of the calculations reproduced reality. We are rectifying this deficiency.

When we began our program of precise measurements in 2004, the then-current survey of world data [1] included barely twenty ICC values measured to ±2% or better, and eighty more with up to 5% precision. They were divided 45-55 between *K*-shell ICCs (α_K) and total ICCs (α_T), respectively. Based on these data, the authors concluded that all previous tables of ICCs exhibited a 3% systematic bias, but that a table by Band *et al.* [2], which was new at the time, agreed well with the data (within ~1%). This new table was calculated in the framework of the Dirac-Fock method, with the exchange between bound electrons as well as between bound and free electrons treated exactly, an important improvement. Unfortunately, however, the best agreement with the available experimental data was achieved with a version of this calculation in which the final-state electron wave-function was computed in a field that did not include any provision for the atomic vacancy created by the conversion process. Yet the vacancy must be there, since atomic-shell-vacancy lifetimes are known generally to be much longer than the time for a conversion electron to leave the vicinity of the atom. This was an unsatisfactory paradox!

We found ourselves uniquely positioned to potentially resolve the paradox. For our program to measure branching ratios for superallowed β emitters, we had efficiency calibrated an HPGe detector to high precision over a wide range of energies. This would allow us to measure the *K* x rays and γ rays from a converted transition in the same well-calibrated detector, thus affording access to the transition's α_K value with a minimum of systematic uncertainty. For an isolated electromagnetic transition that converts in the atomic *K* shell, the observation of a *K* x ray is a signal that an electron conversion has taken place; whereas a γ ray indicates that no conversion has taken place. If both x rays and γ rays are recorded in a measurement, then the value of α_K is given by

$$\alpha_K \omega_K = \frac{N_K}{N_\gamma} \cdot \frac{\varepsilon_\gamma}{\varepsilon_K} , \qquad (1)$$

where ω_K is the *K*-shell fluorescence yield; N_K and N_γ are the respective peak areas of the *K* x rays and the γ ray; and ε_K and ε_γ are the respective detector photopeak efficiencies.

Not many nuclei feature a single isolated transition, but a number of cases have small enough interference from other converted transitions that the corrections to Eq. (1) are manageable, allowing the α_K value still to be extracted with percent precision. Since we began this program, we have published α_K values for *E*3 transitions in three nuclei, ^{103}Rh [3] ^{111}Cd [4] and ^{134}Cs [5,6], and *M*4 transitions in six nuclei, ^{119}Sn [7,8], ^{125}Te [9], ^{127}Te [10], ^{137}Ba [5,6], ^{193}Ir [11,12] and ^{197}Pt [13]. We are currently completing a measurement on an *M*4 transition, in ^{93}Nb [14].

The results from our completed measurements appear in Fig. 1, which is an updated version of a figure that first appeared in Ref. [15]. In the figure, the results are compared with two theoretical

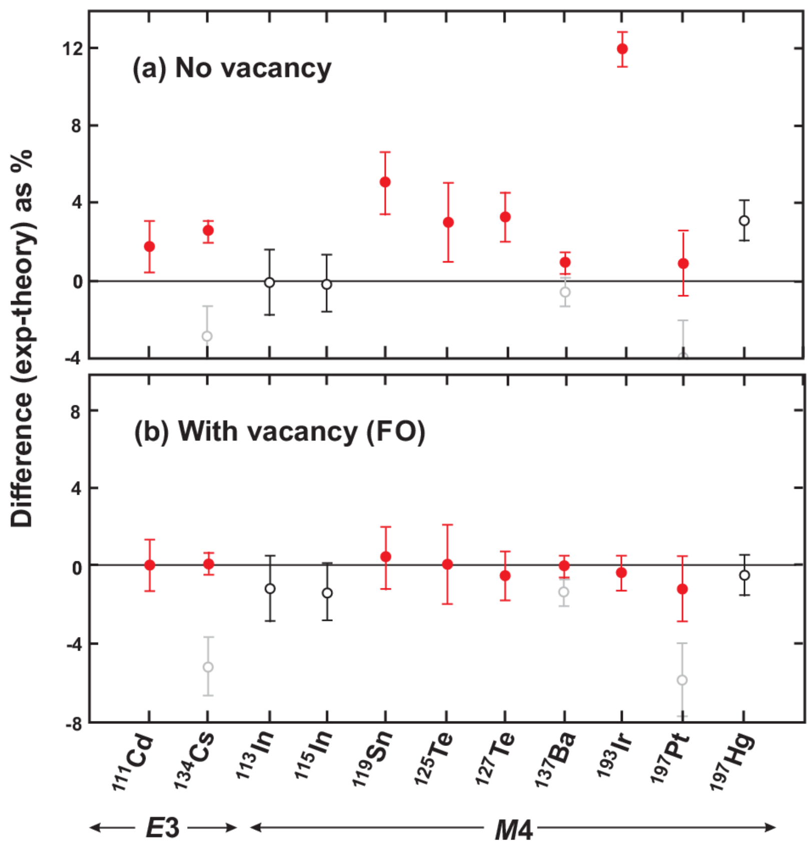

FIG. 1. Percentage differences between the measured and calculated α_K values for the Dirac-Fock calculations with and without provision for the atomic vacancy. Solid (red) circles are our measurements; open circles refer to pre-2002 results, the ones in gray having been replaced. The figure shows all α_K values for high-multiplicity transitions (E3 and above) that are known to ±2% or better.

models, one that ignores the atomic vacancy and one that includes it in the "frozen orbital" (FO) approximation. It is clearly evident that the data are completely inconsistent with the no-vacancy theory and are in remarkable agreement with the vacancy-inclusive theory. This is consistent with the known vacancy lifetimes, and resolves the earlier paradox.

A few of the cases we measured were chosen not because they were particularly sensitive to the vacancy/no-vacancy choice in the calculations, but because previous results disagreed with *both* types of calculation. These discrepancies have been removed as well. Note though that among the twelve precisely measured α_K values in Fig. 1, there are nine that statistically distinguish between the vacancy and no-vacancy calculations, and they all present a consistent picture that favors inclusion of the atomic vacancy in ICC calculations. All but one of these cases come from our work.

Note that J.C. Hardy, the Principal Investigator for this research program, officially retired at the end of August 2018. He is nevertheless committed to completing the ^{93}Nb measurement mentioned in this report, but will undertake no new initiatives.

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