Tests of internal-conversion theory with precise γ- and x-ray spectroscopy

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Internal conversion plays an important role in most nuclear decay schemes yet, until recently, the accuracy of calculated internal conversion coefficients (ICCs) was, at best, ill defined. Not only were there very few precise measurements of ICCs in existence but, for many years, there appeared to be a systematic difference between experiment and theory. In 1973 Raman compared "precisely measured" ICCs for fifteen *E*3 and *M*4 transitions with the tabulated Hager and Seltzer calculations and concluded that the theoretical values were systematically higher by 2-3%. However, even this select group of transitions included only five with measured ICCs that were known with a precision of 2% or better, so the apparent discrepancy was hardly definitive. Even so, this is where the matter remained for 30 years.

By 2002, Raman *et al.* [1] had 100 experimental ICCs to compare with tabulated values, but even at that recent date only 20 of the measured ICCs had a precision of 2% or better. Their results still indicated that all previous tables of ICCs exhibited a 3% systematic bias but the authors found much better agreement (within ~1%) for a new table by Band *et al.* [2], which was calculated in the framework of the Dirac-Fock method, with the exchange between electrons treated exactly. Yet, even though the average agreement was now much better, some of the individual ICCs disagreed significantly with the calculated values and, even more troubling, the data appeared to show a surprising preference for one particular model in which the final-state electron wave function was computed in a field that did not include the atomic subshell vacancy caused by the conversion process.

The first experiment that definitively established the need to include the atomic vacancy was our precise 2004 measurement (± 0.8%) of the *K*-shell conversion coefficient, α_K, for the 80.2-keV *M*4 transition in ^{193}Ir [3]. However, this measurement was for a single high-*Z* nucleus and certainly needed to be confirmed for lower-*Z* cases. Furthermore, among the other transitions whose ICC's had been measured with a precision claimed to be under 2%, several disagreed significantly with both types of calculations, *i.e.* whether or not the vacancy was included. Since 2004 we have addressed three of these latter cases, ^{134}Cs^m [4], ^{137}Ba [4] and ^{197}Pt^m [5], and have shown that the apparent discrepancies were due entirely to flawed experiments. With the case of ^{134}Cs^m, we also extended our experimental verification of the need to include the atomic vacancy down to $Z = 55$.

The impact of our results so far is illustrated in Fig. 1, where we plot differences between 21 experimental ICCs and two versions of the Dirac-Fock theory [1,2], one that ignores the atomic vacancy and the other that includes it via the "frozen orbital" approximation. In addition to our four results, the figure includes the twenty cases with better than 2% precision, which were listed by Raman *et al.* [1] in 2002. Note that three of the Raman results were improved and supplanted by our new measurements.

There is one more viable case that would allow us to extend our test to even lower Z, and would discriminate more definitively than ^{134}Cs^m between the vacancy and no-vacancy prescriptions. This is the 293.1-day isomeric state, ^{119}Sn^m, which decays 100% by cascade via a 66-keV *M*4 and a 24-keV *M*1/*E*2 transition. Since the latter cannot convert in the *K* shell, the *K* x rays in the measured photon spectrum from this decay scheme will be exclusively from the *M*4 transition. Consequently the *K* conversion coefficient for the *M*4 transition can be determined from the equation

$$\alpha_K \omega_K = \frac{N_K}{N_\gamma} \frac{\varepsilon_\gamma}{\varepsilon_K},$$

where ω_K is the fluorescence yield; N_K and N_γ are the total numbers of observed *K* x rays and 66-keV γ rays, respectively; and ε_K and ε_γ are the corresponding detector efficiencies. This is our standard method for making such measurements and, although our detector efficiency in the 25-29 keV *K*-x-ray energy range is not as well established as it is at higher energies, we still anticipate being able to measure the ICC to ~1% precision. Since the difference between the calculated ICC values with and without the atomic vacancy is 4.9%, this precision will be more than adequate for us to distinguish definitively between them.

These measurements are generally carried out in the summer when an REU student can be involved. The student becomes a co-author of the paper that results.

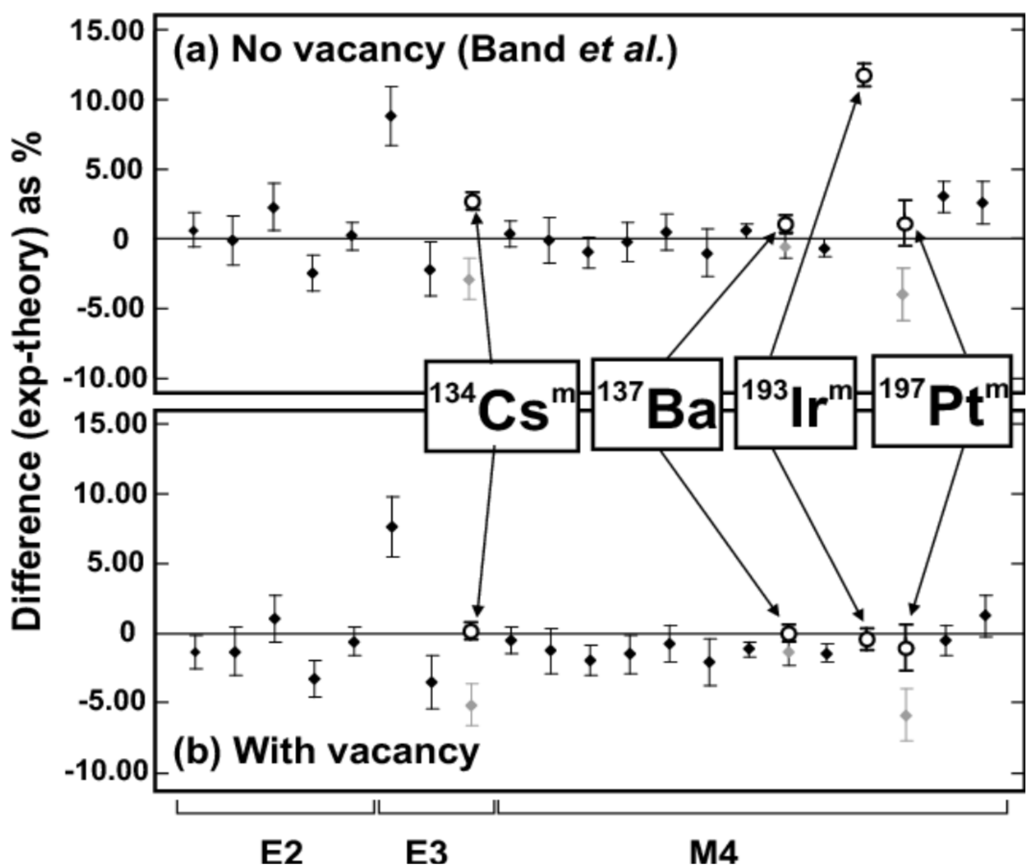

FIG. 1. Percentage differences between the measured and calculated ICCs for two Dirac-Fock calculations: one (top) is without the atomic vacancy and the other is with it included in the "frozen orbital" approximation. The points shown as solid diamonds in both plots correspond to the twenty cases that have better that 2% precision [1]; as indicated at the bottom, five are for E2 tranditions, three for E3, and the remainder are for M4 transitions. The points shown as open circles correspond to our recently measured α_K values. The grey points with error bars at the same horizontal positions are the previous α_K results, which our measurements replace.

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