COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in the **Physical Review**. *Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Comment on "Double K-shell ionization in the electron capture decay of ^{55}Fe"

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The corrections made in a recent paper to the published values for double K-shell ionization in the electron capture decays of ^{54}Mn and ^{65}Zn are not applicable to the data from which these values were derived. Attention is called to a recent article that is relevant to the topic of the paper.

In a recent article [1], Campbell, Maxwell, and Teesdale (CMT) made corrections to the probabilities for double K-shell ionization (P_{KK}) in the electron capture decays of ^{54}Mn and ^{65}Zn previously published by Nagy and Schupp [2, 3]. We point out that these corrections do not apply to the data from which the P_{KK} values were derived. We also call attention to a recent relevant reference [4].

When a nucleus decays by electron capture (EC) from the K shell, there is a small probability that the second electron in the K shell is excited to an unoccupied level (shakeup) or ejected to the continuum (shakeoff). In either case, a double vacancy is created in the K shell. Experiments to measure P_{KK}, the probability of double K-shell vacancy production per K-electron capture, usually record coincidences between the hypersatellite ($K\alpha^H$) and satellite ($K\alpha^S$) x rays emitted in the transitions $1s^{-2} \rightarrow 1s^{-1}2p^{-1}$ and $1s^{-1}2p^{-1} \rightarrow 2p^{-2}$, respectively. Because the first transition is to a vacant (unshielded) orbital, the energy of the emitted $K\alpha^H$ x ray is larger than the energy of the normal x ray, $K\alpha^N$, emitted in the transition $1s^{-1} \rightarrow 2p^{-1}$. This shift in energy has been crucial to the success of experiments to measure P_{KK}. Because P_{KK} is of the order of 10^{-5}, the number of accidental $K\alpha^N$-$K\alpha^N$ coincidences is usually much higher than the number of true $K\alpha^H$-$K\alpha^S$ coincidences, even at moderate counting rates. However, because of the shift in energy of the $K\alpha^H$ x ray, the true coincidence peak in the spectrum gated by $K\alpha$ x rays is not buried underneath the accidental $K\alpha^N$ peak, but rather appears on the high energy side of the accidentals peak. If the peak width in the detector being used is less than or comparable to the hypersatellite shift, the yield of $K\alpha^H$ x rays can be extracted even in the presence of a fairly high accidental $K\alpha^N$ peak.

The P_{KK} values for ^{54}Mn and ^{65}Zn reported in Refs. [2, 3] were extracted from the areas of the $K\alpha^H$ peaks in the spectra recorded in coincidence with $K\alpha$ x rays. The measured energy shifts of the $K\alpha^H$ hypersatellite x rays were 254 ± 18 eV for ^{54}Mn and 321 ± 17 eV for ^{65}Zn. The detector resolutions at 5.9 keV were 179 and 160 eV, respectively. With these values for the shifts and resolutions it was clearly possible to differentiate between the sought-after $K\alpha^H$-$K\alpha^S$ coincidences and the interfering $K\alpha^N$-$K\alpha^N$ coincidences. CMT maintain that those P_{KK} values should be corrected for the contribution of true coincidences between the $K\alpha$ x ray that follows electron capture and the $K\alpha$ x ray that follows the K-shell internal conversion (IC) of the 835-keV transition in the case of ^{54}Mn and the 1116-keV transition in the case of ^{65}Zn. However, as mentioned in Ref. [2], the lifetime of the single hole in the K shell is much shorter than the lifetime of the excited nuclear state in both of these cases. Thus, the single hole created by electron capture will almost always be filled before the internal conversion occurs, and most of the x-ray coincidences will arise from the sequential filling of the single hole created by electron capture followed by the filling of the single hole created by internal conversion. Both of these x rays are normal, i.e., unshifted in energy, so the true coincidences between them contribute to the $K\alpha^N$-$K\alpha^N$ peak and not the $K\alpha^H$-$K\alpha^S$ peak that was used to extract P_{KK}.

It is, of course, possible to get a double vacancy associated with the internal conversion decay of the excited nuclear state. One way is to have the nuclear state decay by internal conversion *before* the vacancy created by electron capture is filled. The probability for this process is calculated as follows: the rate $R_{KK}(t)$ of double vacancy production (per K hole) a time t after K capture is given by

$$R_{KK}(t) = e^{-t/\tau_a} \frac{1}{\tau_n} e^{-t/\tau_n} \frac{\alpha_K}{1+\alpha}, \tag{1}$$

where τ_a is the lifetime of the K hole, α and α_K are the total and K-shell internal conversion coefficients, respectively, and τ_n is the lifetime of the nuclear state. The factor e^{-t/τ_a} is the probability that a hole created at $t = 0$ is still present at time t, $(1/\tau_n)e^{-t/\tau_n}$ is the decay rate of the nuclear state a time t after its creation, and $\alpha_K/(1+\alpha)$ is the probability that the decay is by internal conversion. Thus the probability P_{KK}(EC,IC) of double vacancy production per K capture due to this successive ionization of the K shell is

$$P_{KK}(\text{EC,IC}) = \int_0^\infty R_{KK}\, dt = \frac{\alpha_K}{1+\alpha}\left(\frac{\tau_a}{\tau_a+\tau_n}\right). \tag{2}$$

Using the values $\tau_a = 6.09 \times 10^{-16}$ s [5] for the Cr K hole, $\tau_n = 11.8$ ps, $\alpha = 2.5 \times 10^{-4}$, and $\alpha_K = 2.2 \times 10^{-4}$ for the 835-keV state in ^{54}Cr [6], we get P_{KK}(EC,IC) $= 1.13 \times 10^{-8}$, which is clearly negligible compared to the P_{KK} value of $(3.6 \pm 0.3) \times 10^{-4}$ for ^{54}Mn [2]. For the EC decay of ^{65}Zn the relevant numbers are $\tau_a = 4.25 \times 10^{-16}$ s [5] for the Cu K hole, $\tau_n = 0.411$ ps, $\alpha = 1.85 \times 10^{-4}$, and $\alpha_K = 1.66 \times 10^{-4}$ [7] for the 1116-keV state in ^{65}Cu; using these values we get P_{KK}(EC,IC) $= 1.71 \times 10^{-7}$, which is again negligible compared to the P_{KK} value of $(2.2 \pm 0.2) \times 10^{-4}$ for ^{65}Zn [3].

Double ionization of the K shell may also occur by the internal conversion process alone, i.e., *both* vacancies may be created during the K-shell internal conversion, *after* the hole created by electron capture has been filled. The probability P_{KK}(IC) of double K-shell vacancy production *per K conversion* has been measured for several isotopes [8] and is on the order of 10^{-5}–10^{-4}. Therefore the probability of double K-shell vacancy production resulting from internal conversion *per K capture* to the excited state is $[\alpha_K/(1+\alpha)]\, P_{KK}$(IC). For the ^{54}Mn and ^{65}Zn decays under consideration this gives a probability on the order of 10^{-8} per K capture, which again is clearly negligible compared to the measured P_{KK}(EC).

Thus, contrary to the claim by CMT, x rays contributed by internal conversion cannot account for the P_{KK}(EC) values of ^{54}Mn and ^{65}Zn being higher than the general trend.

CMT also state that there were no other reported measurements of P_{KK}(EC) for isotopes that decay to nonisomeric excited states. We would like to point out that there was such a measurement reported for ^{139}Ce [4]. The P_{KK} value for ^{139}Ce [$(2.0 \pm 1.6) \times 10^{-6}$] does *not* follow the smooth decreasing trend (with atomic number) of the previously measured P_{KK} values. Like the cases of ^{109}Cd and ^{181}W, which were cited by CMT as the only exceptions to the smooth general trend, the ^{139}Ce measurement further confirms that decays with Q values comparable to the K-shell binding energy have lower P_{KK}'s than the general trend.

In summary, the corrections that CMT make to the ^{54}Mn and ^{65}Zn P_{KK} values are not valid and these values remain anomalously higher than the general trend. A recent reference, apparently overlooked by CMT, confirms that decays with low Q values have smaller P_{KK}'s than the general trend.

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