Reply to "Comment on 'Resonant excitation of the reaction $^{180}Ta^{m}(\gamma,\gamma')^{180}Ta$'"

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We reply to the preceding Comment.

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The preceding Comment of Németh [1] raises three topics regarding the observation of intermediate states in the resonant $^{180}Ta^{m}(\gamma,\gamma')^{180}Ta$ reaction [2] at 2.8 and 3.6 MeV with very large integrated cross sections of 1.2 and 3.5×10^{-25} cm^2 keV, respectively. These topics are (i) Németh assumes a summed branching ratio of ground state (g.s.) transitions of 0.01–0.001, from which he calculates the transition strengths of intermediate states (IS) to the isomer and concludes that the recommended upper limits (RUL) [3] for dipole transitions in this mass region would be significantly exceeded; (ii) he suggests that the bremsstrahlung spectra used in the data analysis might be wrong because the energies and strengths of IS in the $^{87}Sr(\gamma,\gamma')^{87}Sr^{m}$ calibration reaction cannot be explained with the available nuclear structure data base; and (iii) he claims that the overall cross-section ratio of the photoactivation of $^{180}Ta^{m}$ and ^{115}In deduced from his own experiments at 1.33 and 4 MeV provides indirect evidence against the magnitude of the reported integrated cross sections.

(i) The estimates of transitions strengths to the $^{180}Ta^{m}$ isomer (Table I of Ref. [1]) are indeed very large and their interpretation is a problem of considerable interest. However, the supposition of an effective g.s. branching ratio of 0.01–0.001 which would lead to a severe contradiction with the RUL is not justified in the present case. While the ^{180}Ta low energy spectrum (≤ 1 MeV) is well characterized [4] as a rotator for which K conservation is fulfilled, there are good reasons to assume a breakdown of the K selection rule at higher energies.

Evidence for a strong admixture of different K values at energies around neutron thresholds has been derived from a statistical analysis of the widths of slow neutron capture resonances [5]. While the degree of completeness of the mixing is still a subject of discussion [6], the disappearance of K conservation at these energies is well established. Also, evidence for K mixing at excitation energies of about 3 MeV has recently emerged from nuclear resonance fluorescence (NRF) studies [7] and an investigation of the 3.312 MeV isomer in ^{174}Hf [8].

The decay of the $K=14^{+}$, 4 μs isomer at 3.312 MeV in ^{174}Hf provides a particularly impressive example of strong K mixing. Amongst the 20 transitions depopulating the state (see Table I of Ref. [8]) no relation to the final state K value can be observed. The strongest branch has $\Delta K=8$, and even $\Delta K=14$ transitions to the yrast band are seen with a probability $>1\%$. In contrast, the minimum $\Delta K=2$ transitions contribute less than 20%. It is obvious that with a comparable mixing in the IS wave functions, the $\Delta K=8$ transfer from isomer to g.s. in ^{180}Ta could be mediated very efficiently, perhaps even in a single step. The cascade from IS to g.s. needed for the spin transfer could then proceed through unhindered transitions.

The example of ^{174}Hf is an even-even nucleus, so in the doubly odd ^{180}Ta configuration mixing induced by the high level density should additionally amplify the K-transfer efficiency. A simple estimate of the level density, based on the backshifted Fermi gas model [9] and using parameters taken from the comparable ^{182}Ta nucleus, shows that within the experimental uncertainty of ±1.0 MeV for the 3.6 MeV state one finds approximately 10^3 states with $J=8$ (the IS spin assumed by Németh).

On the other hand, due to the configuration mixing a fragmentation of the principal transitions into several close lying levels is quite likely. Exactly such a behavior has been observed in a recent study [10] of the $^{115}In(\gamma,\gamma')^{115}In^{m}$ reaction. Here, the isomer excitation function was compared to NRF data that fixed the g.s. branches. Numerous transitions were observed which clustered in two groups corresponding to the IS identified from the isomer photoactivation. The model interpretation strongly favored a common excitation mechanism and qualitatively reproduced the energy clustering [10]. If a similar distribution over several states occurs in ^{180}Ta, the individual transitions would be well below the RUL and all concerns about unexpectedly large transition probabilities become unfounded.

We also note that the magnitudes of integrated cross sections reported in Ref. [2] are not singular cases. A recent investigation [11] of the photoactivation of short-lived isomers reveals two isotopes, ^{167}Er and ^{179}Hf, with similar values in the same 2.5–4 MeV excitation energy region.

(ii) Németh questions the calibration of the bremsstrahlung spectra obtained with the $^{87}Sr(\gamma,\gamma')^{87}Sr^{m}$ reaction. He extracts the information available from the nuclear structure data base [12] on energies and strengths of IS in ^{87}Sr. We agree that the available data upon branching ratios and half-lives explain neither the integrated cross

sections of the 1.88 MeV level detected by Booth and Brownson [13] and assumed in our calculation [2], nor of the 2.67 MeV level observed in both experiments. Németh's discussion indicates that the experimental cross sections might result from, respectively, three and two closely spaced levels instead of single ones. The photon spectral intensity distribution varies slowly with respect to the energy differences of the levels in question, so this would have little impact, certainly below 5%, on the overall normalization.

The finding that the IS identified by Németh cannot account for the experimental value raises the question whether all relevant states have been identified and whether the spectroscopic information on the decay branches is complete. As an example, one could conclude from unplaced γ transitions excited in the $^{86}\mathrm{Sr}(n,\gamma)^{87}\mathrm{Sr}$ study of Winter *et al.* [14] that the 1.920 MeV level was populated and that an additional weak, previously unknown branch to the 1.253 MeV levels exists. Since this state decays 100% to the isomer, the additional contribution would effectively double the integrated cross section of the 1.920 MeV level. This would bring the results into much closer agreement with Refs. [2,13]. Also, the particular selectivity of different reaction types can preclude the detection of levels which are easily excited in resonant photoexcitation. We will not pursue this kind of speculation further, but instead point out two independent results which validate our confidence that both the spectral intensity distributions and the total fluxes of the bremsstrahlung spectra are correct.

The shapes of the bremsstrahlung spectra were extensively investigated [15,16] with a setup for NRF experiments [17] installed in the same experimental area as used for the work of Ref. [2]. Utilizing precisely determined [18] calibration states in $^{27}\mathrm{Al}$ and $^{11}\mathrm{B}$ distributed over the important energy region, the spectral distribution was investigated for various electron end-point energies, and very good correspondence to the Monte Carlo calculations was observed [15,16].

The absolute normalization was checked in a study [10] of the $^{115}\mathrm{In}(\gamma,\gamma')^{115}\mathrm{In}^m$ reaction measured concurrently with $^{180}\mathrm{Ta}^m$ and $^{87}\mathrm{Sr}$. In the $^{115}\mathrm{In}$ nucleus *all* relevant IS at excitation energies below the lowest bremsstrahlung end point of 2 MeV accessed in the present experiments are known from independent spectroscopic investigations [19]. The yields calculated from these parameters describe quite well our experimental data in the region from 2 to 2.75 MeV with only an overall normalization factor of 1.17. Considering the experimental errors of the input data as well as of our own experiments, this 17% deviation provides an extremely conservative estimate of the absolute normalization error of the total photon flux.

(iii) Finally, Németh claims that indirect evidence against the integrated cross section magnitudes in Ref. [2] is provided by a ratio of overall cross sections which he deduced in his own measurements of the $^{180}\mathrm{Ta}^m(\gamma,\gamma')^{180}\mathrm{Ta}$ and $^{115}\mathrm{In}(\gamma,\gamma')^{115}\mathrm{In}^m$ reactions at 4 MeV electron energy. While it is not clear from the Comment how the overall cross sections were calculated, we conclude from the context that it corresponds to the normalized activation per unit photon flux $A_f(E_0)$ defined in Eq. (2a) of Ref. [2]. It is related to the integrated cross sections $(\sigma\Gamma)_{fj}$ by

$$A_f(E_0)\equiv\frac{N_f}{N_i\phi_0}=\sum_j(\sigma\Gamma)_{fj}F(E_j,E_0)\ , \tag{1}$$

where N_i is the number of $^{180}\mathrm{Ta}^m$ ($^{115}\mathrm{In}$) target nuclei, N_f gives the $^{180}\mathrm{Ta}$ g.s. ($^{115}\mathrm{In}^m$ isomer) decays, ϕ_0 describes the total photon flux per cm^2, $F(E,E_0)$ is the normalized spectral intensity function, and E_j gives the resonance energy of the jth intermediate state. We note that the primary flux numbers strongly depend on the model approximations in the calculation of the photon spectra, and so A_f results from different experiments cannot be compared in a useful way.

With the data presented in Refs. [2,10] one can trivially extract the Ta/In overall cross-section ratio from Eq. (1). Németh's assertion that one could draw conclusions about the magnitudes of integrated cross sections from a knowledge of the overall cross-section ratio determined in a particular experiment at a particular electron endpoint energy is simply untenable (except in the very special case in which both nuclei compared possess only one IS at nearly the same energy). It is clear from Eq. (1) that the experimental yields are proportional to the sum of products of integrated cross sections and the spectral intensities at different resonance energies. Thus, the yields obviously depend on the spectral intensity functions which differ at distinct experimental facilities. For example, in the present experiments a Ta/In cross-section ratio of ≈ 12 is deduced at 4 MeV, larger than that quoted by Németh. Due to the strong decrease of the number of photons within the bremsstrahlung spectrum as a function of energy, lower lying IS with smaller integrated cross sections can add significantly to the experimental activation. This is certainly more the case for $^{115}\mathrm{In}$ than for $^{180}\mathrm{Ta}^m$.

In summary, we have shown that the reduced isomer transition probabilities extracted from the integrated cross sections in Ref. [2] can be well understood without a violation of the RUL. It has been discussed why the simple extension of K conservation to higher energies assumed by Németh in his estimates is not justified in the present case. The discrepancies between the coinciding results of Booth and Brownson and ourselves for the $^{87}\mathrm{Sr}(\gamma,\gamma')^{87}\mathrm{Sr}^m$ calibration reaction and nuclear structure data from other reactions might be due to incomplete information about the important decay branches or due to the different selectivities of the reactions studied so far. We have presented independent experimental proof that both the total photon flux and the spectral distribution of the bremsstrahlung are well understood. The indirect evidence against the integrated cross-section magnitudes claimed by Németh is shown to be unfounded. Without a knowledge of the bremsstrahlung spectral shape and the energies of the IS, no information on possible integrated cross section values can be retrieved from the data presented by Németh.

What remains open is a microscopic understanding of the nuclear structure underlying the breakdown of K conservation and the strong coupling to the IS. The integrated cross sections deduced in recent experiments [2,11,20] for well-deformed nuclei with large ΔK between g.s. and isomer demonstrate the usefulness of resonant photoexcitation as a tool for selective population of levels with strongly K-mixed wave functions at low energies. Further experiments are clearly warranted.

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