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

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We point out that the large integral cross section values reported for the $^{180}Ta^m(\gamma,\gamma')^{180}Ta$ reaction by Collins *et al.* correspond to transition strengths exceeding the recommended upper limits. The small overall cross section ratio of the aforementioned and the $^{115}In(\gamma,\gamma')^{115}In^m$ reactions is shown to be an indirect piece of evidence against the enormous integral cross sections. Collins *et al.* used the $^{87}Sr(\gamma,\gamma')^{87}Sr^m$ reaction to verify their calculated photon flux, but did not identify the observed activation levels. We identify four photoactivation levels of ^{87}Sr at 1228.42 keV, $\frac{5}{2}^+$, 1770.46 keV, $\frac{5}{2}^+$, 1919.9 keV, $\frac{7}{2}^+$, 2706.5 keV, $\frac{9}{2}^+$, and deduce the existence of (at least) a further one around 2.6 MeV. These new data suggest that the calculated photon flux used by Collins *et al.* should be rechecked.

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The excitation function of the $^{180}Ta^m(\gamma,\gamma')^{180}Ta$ reaction was recently investigated by Collins *et al.* [1] in the 2–5 MeV energy region. $^{180}Ta^m$ is an especially interesting nuclide as the only naturally occurring isomer and the rarest (quasi)stable isotope. A variety of astrophysical processes have been suggested to be responsible for its nucleosynthesis but without much success (for references, see Ref. [2]). In their paper Collins *et al.* [1] drew three conclusions: (i) there are no (significant) photoactivation levels below 2.8 MeV, (ii) there are photoactivation levels at 2.8 and 3.6 MeV excitation energy with integral cross sections of $1.2(2)\times10^{-22}$ and $3.5(5)\times10^{-22}$ cm^2 eV, (iii) these photoactivation levels lie high enough to allow $^{180}Ta^m$ to survive under stellar circumstances independently of the cross sections.

We have also recently studied the $^{180}Ta^m(\gamma,\gamma')^{180}Ta$ reaction at 1.33 and 4.0 MeV [2,3]. We established an upper limit of 14 nb (95% confidence limit) for the overall cross section at 1.33 MeV and deduced a finite value of 0.52(20) mb at 4.0 MeV. We found [3] that up to 100% of the observed abundance of $^{180}Ta^m$ can be ascribed to the *s* process [4]. Our conclusions are in general agreement with (i) and (iii). We wish to point out, however, that the interpretation of the very large cross sections reported by Collins *et al.* [1] can be problematic.

We calculate the $\Gamma_m(g\Gamma_0/\Gamma)$ values of the reported photoactivation levels on the basis of the formula

$$\Gamma_m(g\Gamma_0/\Gamma)=\sigma/(\lambda^2/4)\ , \qquad (1)$$

where Γ_m is the partial width of the direct transition feeding the metastable state, Γ_0/Γ is the branching ratio for populating the ground state, σ is the integral cross section, λ is the wavelength of the exciting photons and

$$g=(2J_a+1)/(2J_m+1) \qquad (2)$$

is the statistical factor. J_a and J_m are the spin of the activation level and the metastable state concerned, respectively. We obtain 0.24 and 1.2 eV for the 2.8 and 3.6 MeV activation levels, respectively. We also calculate the Γ_m's via Weisskopf-estimation supposing $E1$, $M1$, and $E2$ transitions. By comparing the experimental and theoretical Γ_m's we obtain the transition strengths (S) multiplied by Γ_0/Γ. In the case of the dipole transitions we substitute $J_a=8$, while for the $E2$ transitions J_a is taken to be 7.

The $S(\Gamma_0/\Gamma)$ values are summarized in Table I. In order to get the real transition strengths (S) one has to estimate Γ_0/Γ. The cascades from the photoactivation levels feeding the ground state involve at least four steps since the spin differences are at least six units, and parity changes are needed. Similarly, the K value differences must be very high, most probably 5–8 units, since the K values of the ground state and the isomer are 1 and 9, respectively [5]. This means that Γ_0/Γ cannot be too large.

If $\Delta K=0$ for the 2.8 and/or 3.6 MeV transitions, these transitions can be considerably enhanced. The competing transitions, however, have far smaller energy and the cascades feeding the ground state involve a number of K-forbidden transitions ($\Delta K=8$ for the cascades). The consequence is that Γ_0/Γ cannot be larger than

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TABLE I. The $S(\Gamma_0/\Gamma)$ products for the metastable state feeding direct transitions for different possible multipolarities. For comparison, the recommended upper limits [6] of the corresponding transition strengths are also given.

Activation level energy (MeV)	$S(\Gamma_0,\Gamma)$ $E1$ (mW.u.)	$M1$ (W.u.)	$E2$ (W.u.)
2.8	5.7	0.59	36
3.6	13	1.3	50
Recommended upper limit for S (from Ref. [6])	10	2	1000

0.01–0.001, resulting in transition strengths exceeding the recommended upper limits [6] (RUL). If the 2.8 and/or 3.6 MeV transitions are K forbidden, $(\Delta K>0)$ Γ_0/Γ can be of the order of 0.1. If so, the $E2$ strengths will not exceed the RUL [6]. However, it is very improbable that a K-forbidden transition would have a strength of ~ 100 Weisskopf units. The $E1$ and $M1$ strengths exceed or are very close to the RUL [6], even for higher Γ_0/Γ, as one can see from Table I.

Collins *et al.* [1] used the ^{87}Sr$(\gamma,\gamma')^{87}$Sr^m reaction to verify their calculated photon flux. They found both their energy and cross-section data in full agreement with those of Booth and Brownson [7]. The quotation of the energy uncertainties, however, is missing from both papers [1,7]. Moreover, Collins *et al.* [1] did not identify the observed activation levels. (Booth and Brownson [7] had no real possibility to do this.) We feel that such identification is necessary since the reaction is used for calibration purposes.

The large body of available spectroscopic data [8–14] allows identification of several activation levels. The lowest-lying one, found at 1.22 MeV [1,7] is undoubtedly the 1228.42 keV, $\frac{5}{2}^+$ state [8–14]. The integral cross section measured by Collins *et al.* [1] corresponds to a level half-life of 1.7(4) ps and a ground state transition strength of 10(3) W.u. These values are in agreement with those of Ekström *et al.* [10], which are 1.0(4) ps and 8(3) W.u., respectively.

The second activation level was reported to be at 1.88 MeV [1,7]. The spectroscopic studies [8–11] revealed two activation levels in the vicinity of this energy, viz. the 1770.46 keV, $\frac{5}{2}^+$ and the 1919.9 keV, $\frac{7}{2}^+$ states. We calculate their integrated cross sections to be $1.0(4)\times10^{-26}$ and $7(3)\times10^{-26}$ cm^2 eV, respectively. The half-life and branching ratio data are taken from Refs. [9] and [10]. These integrated cross sections are smaller than that of Collins *et al.* [1], which is $16(4)\times10^{-26}$ cm^2 eV.

Collins *et al.* [1] and Booth and Brownson [7] found a further activation level around 2.67 MeV. If the 2704.3(20) keV transition observed by Arnell *et al.* [11], deexcites the 2706.5(7) keV, $\frac{9}{2}^+$ state populated in various experiments [8,10–12,14] (which seems to be very likely), this is also an activation level. We calculate its integral cross section to be $41(16)\times10^{-26}$ cm^2 eV on the basis of the data of Ekström *et al.* [10]. This value is an order of magnitude smaller than those measured in the (γ,γ') investigations [1,7] for the "2.67 MeV activation level." It means that at least one activation level is yet hidden around 2.6 MeV. The incomplete nuclear data prevent us from identifying it, as well as the 4.3(1) MeV state discovered by Collins *et al.* [1]. We note that until now nobody has carried out a Coulomb excitation study on ^{87}Sr, which would populate selectively the positive-parity activation levels and would allow determination of their halflife. Nevertheless, identification of the four activation levels suggests that the calculated photon flux used in the experiment of Collins *et al.* [1] should be rechecked, especially around 1.9 MeV.

Returning to ^{180}Ta^m, there is an indirect piece of experimental evidence against the high integral cross section values reported by Collins *et al.* [1]. In our 4 MeV experiments we found that the overall cross-section ratio of the ^{180}Ta$^m(\gamma,\gamma')^{180}$Ta and ^{115}In$(\gamma,\gamma')^{115}$In^m reactions is 7.4 ± 1.1 [2,3]. Considering that the excitation function of ^{115}In is quite flat below 4 MeV [15,16], this relatively small overall cross-section ratio does not support the large integral cross section values of Collins *et al.* [1]. We emphasize that this evidence is only indirect, since the integral and overall cross sections are different physical quantities. Nevertheless, because of their close connection the knowledge of one allows one to draw some conclusions concerning the other.

The ^{180}Ta$^m(\gamma,\gamma')^{180}$Ta excitation function can be compared also to the ^{167}Er$(\gamma,\gamma')^{167}$Er^m, ^{179}Hf$(\gamma,\gamma')^{179}$Hf^m, ^{191}Ir$(\gamma,\gamma')^{191}$Ir^m, and ^{197}Au$(\gamma,\gamma')^{197}$Au^m excitation functions. The shapes of the excitation function reported by Johnson *et al.* [17] for the above four odd-A nuclides in the 2.3–3.6 MeV energy interval, in spite of the similar mass numbers, are different from that found by Collins *et al.* [1] for the ^{180}Ta$^m(\gamma,\gamma')^{180}$Ta reaction. The former authors observed very pronounced excitation functions with 5–14 activation levels and with moderate overall cross sections, in contrast to the two activation levels and huge integral cross sections reported by the latter authors in the same energy range. These contrasted features confirm that the findings of Collins *et al.* [1] are very unusual.

We conclude that the reasons for the observed enormous integral cross section of the ^{180}Ta$^m(\gamma,\gamma')^{180}$Ta reaction are not clear. The supposition of neither smaller clusters of activation levels around 2.8 ad 3.6 MeV nor K-mixing can unambiguously resolve the problem. The simplest possibility is to accept that this particular nuclide has transitions with particular strengths. Considering that the deduced transition strengths are the least extreme when the transitions feeding the isomer are supposed to be $E2$, we propose 7^- spin for the 2.8 and 3.6 MeV photoactivation levels. Further investigations are needed to confirm the reported high integral cross sections and interpret the structure of the photoactivation levels.

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