Reply to "Comment on 'Observation of annual modulation induced by γ rays from (α, γ) reactions at the Soudan Underground Laboratory' "

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Annual modulation of γ rays from (α, γ) reactions induced by the α activity of radon and its daughters was reported by Tiwari, Zhang, Mei, and Cushman (TZMC). While Mohr does not contest the measurements themselves, he has commented that unrealistic (α, γ) cross sections were used in the analysis of the γ-ray flux, and thus the γ-ray fluxes calculated by TZMC are not reliable. We demonstrate that the (α, γ) cross sections obtained from TALYS include the energy-broadened cross sections for discrete states in the high-energy tail of the spectra, which are required in order to compare with the angle-integrated and double-differential spectra obtained from a liquid scintillator detector with an energy resolution of only ≈15%. A comparison with varying "elwidth" shows that cross sections indeed are reliable within the energy region (4 to 10 MeV) reported by TZMC, especially for the dominant contribution, which is the aluminum wall of the detector. Any differences in the (α, γ) cross sections for ^{16}O at the level detailed by Mohr will have negligible effect on the final flux.

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In 2017, Tiwari, Zhang, Mei, and Cushman reported the observation of annual modulation of γ rays from (α, γ) reactions in the Soudan Underground Laboratory (SUL) [1]. They demonstrated that the measured annual modulation of the event rate from (α, γ) reactions is strongly correlated with the time-varying radon concentration observed independently in SUL. In a recent study, Mohr has commented that the quantitative analysis of γ-ray flux suffers from unrealistic cross sections of the (α, γ) reactions under study in [1]. We appreciate his comments and would like to address his main points below.

His main criticisms are the application of the TALYS code [2] and the chosen parameters ("elwidth"), which result in a high energy tail distribution of (α, γ) cross sections shown in Fig. 5 of [1]. TALYS is a nuclear physics tool for the analysis and prediction of nuclear reactions [3]. In the TALYS code, the nuclear reaction models are constrained by many precise measurements. Therefore, TALYS is believed to have sufficient predictive power and can give an indication of the reliability of measurements. In calculating nuclear reaction cross sections, TALYS uses "elwidth": the width of the Gaussian spreading that takes care of the energy-broadened cross sections for discrete states in the high-energy tail of the spectra, which are realistic in order to compare with experimental angle-integrated and double-differential spectra.

To understand the impact of "elwidth" on the distribution of (α, γ) cross sections, we extract the (α, γ) cross sections for ^{27}Al and ^{16}O with different values of "elwidth" for two α energies, 5.304 and 8.784 MeV, as examples in Figs. 1 and 2. Indeed, a high-energy tail distribution exceeding the highest possible γ-ray energy (as mentioned by Mohr) is a direct result of choosing a default value of 0.5 for "elwidth" in Fig. 5 of [1]. However, in the quantitative analysis of γ-ray fluxes, the value of 0.2 was used in [1].

It is clear that the values of "elwidth" broaden the cross sections for discrete states in the high-energy tail of the spectra. A smaller value of "elwidth", 0.01, shows nearly a feature of discrete states. When the value of "elwidth," the width of the Gaussian spreading, is chosen to be larger, 0.1, 0.2, and 0.5, the cross sections for discrete states are broadened accordingly. These are realistic distributions in comparison with with experimental angle-integrated and double-differential spectra.

In response to Mohr's criticism of Fig. 8 in [1] for $^{16}\mathrm{O}(\alpha, \gamma)$ with a continuous γ-ray spectrum up to $E_{\max} \approx$ 18 MeV, it is important to point out that the reported γ-ray fluxes in [1] were obtained using a 12-liter liquid scintillation detector with an energy resolution of ≈15% [4] in the energy region of 4 to 10 MeV. The calculated γ-ray fluxes for targets of Al, Si, and O, as shown in Figs. 6, 7, and 8 in [1], are the convolution of a detector resolution function and the energy-broadened cross sections summed over $(\alpha, X\gamma)$ with $X = p, n, d, \ldots$ for discrete states in the high-energy tail of the spectra. Thus, $E_{\max} \approx 18$ MeV, which is beyond the maximum possible discrete γ-ray energy, reflects mainly the energy resolution of the detector. The detector energy resolution is also responsible for smoothing out the resonant structures of the cross sections, which are still seen in the "elwidth" = 0.2 curves as shown in Figs. 1 and 2.

In addition, we must point out that the $^{27}\mathrm{Al}(\alpha, \gamma)$ reaction is the dominant source of the observed γ-ray fluxes in the 12-liter scintillation detector, since the detector container is made

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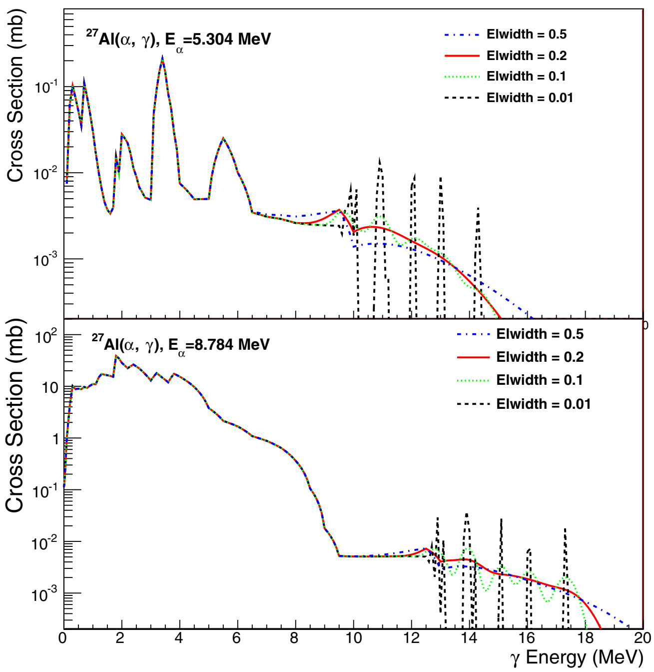

FIG. 1. Plot of ^{27}Al(α, γ) cross section versus γ-ray energy for two α energies, 5.304 and 8.784 MeV, with different values of "elwidth."

of Al. To understand the typical caveats about the accuracy of the cross sections from TALYS, we evaluate the percent error for different "elwidth" values between 0.2 and 0.01 for ^{27}Al, ^{16}O, and ^{28}Si with two α energies, 5.304 and 8.784 MeV. The results are shown in Table I.

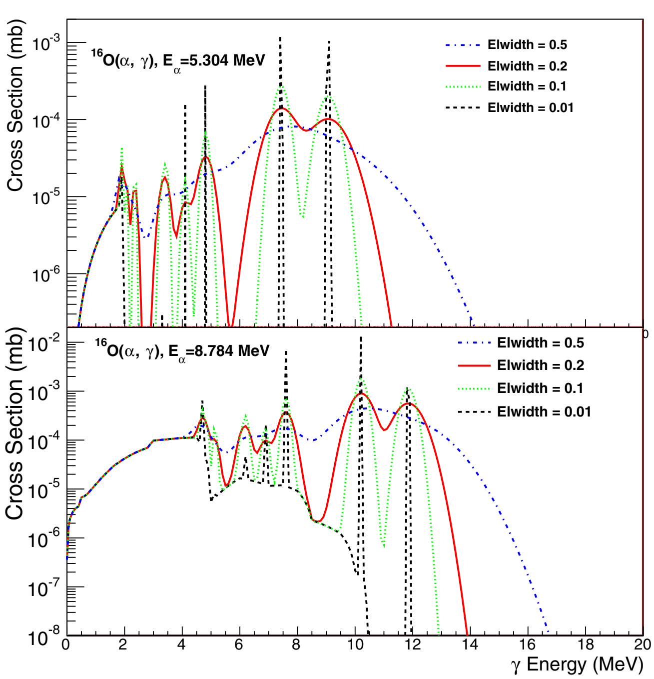

FIG. 2. Plot of ^{16}O(α, γ) cross section versus γ-ray energy for two α energies, 5.304 and 8.784 MeV, with different values of "elwidth."

TABLE I. The percent error for different "elwidth" values between 0.2 and 0.01.

Target	Percent error ($E_\alpha = 5.304$ MeV)	Percent error ($E_\alpha = 8.784$ MeV)
^{27}Al	0.11%	0.004%
^{16}O	29.46%	19.10%
^{28}Si	4.40%	0.06%

As can be seen in Table 1, the aluminum (α, γ) cross sections with α energies of 5.304 and 8.784 MeV are very similar for the energy region of 4 to 10 MeV whether discrete states ("elwidth" = 0.01) or a continuous distribution ("elwidth" = 0.2) are used. For the much smaller contributions from the rock wall, there are visible differences in the discrete and continuous distributions as shown in Table 1 for targets of O and Si (the silica composition at SUL is about ≈45% O and 24% Si). The resulting change to our overall γ-ray flux using the discrete versus continuous distribution with "elwidth" = 0.2 is within the quoted uncertainty (≈30%) stated in [1]. In any case, the discrete cross sections of ^{16}O(α, γ)^{20}Ne with α energies of 5.304 and 8.784 MeV shown as Fig. 1 of Mohr's Comment cannot be directly used to estimate the observed γ-ray flux in a given detector without taking into account the convolution of the detector energy resolution and the energy-broadened cross sections for discrete states in the high-energy tail of the spectra. However, we must point out that there are more resonant structures in Fig. 1 of Mohr's Comment compared to Fig. 2 in this Reply. This indicates that there may exist large uncertainty in the calculation of the ^{16}O(α, γ) cross sections in TALYS. Possible uncertainties may also exist in the calculation of (α, γ) cross sections when choosing different parameters for the physical ingredients, especially for the treatment of γ decay of residual nuclei ("maxlevelsbin") in TALYS. More experimental data are needed to improve the accuracy of the simulation.

The last point in the Mohr's comment is that Eq. (1) of [1] differs from the calculations by Heaton *et al.* [5]. As stated in the original work of [1], the stopping power (sum of electronic and nuclear) was obtained from the ASTAR database [6]. This does represent a slightly different way to calculate the final yield of γ rays than that by Heaton *et al.* However, the overall results are quite similar, as shown in our earlier work [7].

In conclusion, the value of the "elwidth" parameter is used to estimate the energy-broadened cross sections for discrete states in the high-energy tail of the TALYS code spectra. Our results in [1] correspond to the energy region of 4 to 10 MeV. In this energy region, the γ-ray fluxes reported in [1] are reliable. However, it is worth pointing out that the TALYS calculations may have significant uncertainties that are not completely understood, and experimental data are needed.

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