nature portfolio

Peer Review File

Next-Generation Neutron Detection Using a ^{6}Li Glass Scintillator Composite

Corresponding Author: Dr Markus Hehlen

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I do not find this manuscript suitable for the Nature family of journals. While the device described does have some novelty, it is not clear to me that the utility of such a device is broad. In fact, I think the audience is small and very specialized. In a few instances the data analysis could be improved or, at least, the presentation improved. A modified manuscript responding to my appended comments would be suitable for NIMA.

1. The goal here is fast neutron couting, but not fast neutron spectroscopy, i.e. thermalization is employed. Therefore…

Over 70 years ago GdC_2O_4 [Gd – oxalate] loaded scintillator detectors were created for fission neutron neutrons. Neutrons are thermalized, captured (157Gd, \sig_g ~ .25Mb), and counted in the well-separated capture pulse train. Gamma are easily distinguished as they are < a few MeV and the neutron pulses are a full BE of gammas, i.e. ~ 8 MeV. If the sourse is placed inside a central well, Cd lined if desired, an accuate fast neutron count with a modest sided devise is extracted. A background should be subtracted as a devise large enough to stop most of the \gamma's (r ~ 0.5 m) would have a substantial background. While used for fission studies in the 1950, new ones crop up every few years.

The authors compare to 3He proportional counter systems. They need to compare to Gd tanks as they seem to be headed toward a 4\pi detector. A modern Gd tank could use SiPM's and would use lower flash-point scintillators than were used decades ago. See Eljin product EJ-331. If they do not want to compare to a device with dissolved the Gd, they should compare to tiny Gd cubes. in some other scintillator. BTW the decay time for an individual (capture) flash from a Gd scintillator is very fast.

In short, what is missing is a comparison to Gd loaded scintillator tanks and why this is not a suitable replacement for 3He PC's embedded in polyethylene. I suspect the answer is complex, i.e. sometimes Gd tanks can be used (fixed 4\pi uses) and other times not.

2. The manuscript reports inconsistent values of the efficiency. The abstract reports 6.7%, on line 255 one finds 7.3%. I do not know what these numbers are. Are they the efficiency at the test distance 2.3 m? (I presume there are the n efficiency, not fission detection as there are an average of 3.7n/fission for 252Cf). If these numbers are the absolute n eff at the test distance, what is the geometric fraction of 4\pi?

3. Relating to Fig. 6. The fit in (a) must have a constant. If this background is subtracted, a curve directly comparable to (b) could be plotted in (b). As I understand it, the points in (b) are MC. If this is the case, please use a different point type to (a). Perhaps solid in (a) and open in (b). You could also have (a) Experiment (b) MCNP. (At first I thought (b) was the "peal" from the data in (a).

4. Position resolution using individual pulse mode. Generate event wise scatter plot in the dispersion variable (L-R)/(L+R), calculate first and second moments and, using calibration fixed by the means at different positions, get one \sigma position resolution.

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Reviewer #2

(Remarks to the Author)
This paper discusses an alternative neutron detector based on Li-6 glass mounted in a mineral oil moderator. The detector design is novel with a number of potential applications. The paper is well written and clearly presented.

There are some revisions that I think are needed.

The detector is filled with mineral oil. This could be a problem for some applications where liquid leaks could cause criticality concerns, as well as flammable liquids not being allowed for many applications. Is there an alternate moderator material (epoxy)?

On page 5 there is a brief design section that references another paper. But, at the end of the paper there is a more complete design section. Why not combine these or at least refer to the details later in the paper?

On page six, there is a mention of the excellent n-gamma separation. The quality of this separation can be quantified better. I think there should be a figure showing the natural n-gamma background spectra (no sources present. Such a figure can show a much better representation of the n-gamma separation since the gamma ray background is about 1000 times larger than the neutron background (at sea level, though Los Alamos has a larger n background). For some applications, this large difference in background rates, and the resulting poor n-gamma separation might make this detector not usable for those applications.

The results for coincidence and multiplicity counters are impressive. Here, the use of liquids could be problematic.

Can you estimate the cost of such detectors as compared to He-3 detectors?

On page 14, what is the purpose of the Cd to eliminate thermal neutrons? For some applications, that could be limiting.

It seems there should be a Conclusions section at the end of the paper.

Reviewer #3

(Remarks to the Author)
The manuscript Next-Generation Neutron Detection Using a 6Li Glass Scintillator Composite by Favalli and collaborators presents a demonstration of an innovative new idea for neutron detection.

Authors developed a working prototype of a neutron counter, which presents a viable alternative to a 3He-based detector. The need for 3He replacement in neutron detection has been identified as very important due to the price and availability of this isotope. The authors use an idea, which has been tried several times in this field, of combining the material with high-neutron capture cross section with sensitive distributed readout. Their original idea was published in 2015 by the same team. This paper shows an implementation of the concept as a fully evolved working detector with high neutron detection efficiency and excellent suppression of gamma rays. The design is very clever; it uses the high-detection efficiency for thermal neutrons for a 6Li-glass scintillator but overcomes the biggest problem of all the scintillators, which is their gamma-ray sensitivity. The use of transparent mineral oil acts as a moderator and optical medium at the same time. The description of the detector properties is complete, includes an evaluation of detection efficiency, and quantifies suppression of the gamma-rays, two critical components of a potential 3He-based counter successor. This work is critical; the current detector has superior qualities to the 3He-based assemblies. The authors focus on examples of applications in well logging or detection of nuclear materials. I also see excellent potential in neutron counting that is relevant to fundamental science, where neutron counting is essential. The new design may suggest a new detector concept and may overcome the geometrical limitations of 3He counters, which always require
a large moderator volume, making the systems relatively cumbersome. The manuscript is well-written and gives an excellent introduction to the subject, and the description of the detector design and test measurement is complete. The data is supported by extensive simulation efforts. The referencing to literature is extensive.The manuscript presents a summary of a very creative effort. The implications of this work are broad e.g. in nonproliferation and safeguards applications but also in fundamental research where efficient neutron counting is essential.
I would like to recommend this manuscript for publication in Nature Communications Physics.

Version 1:

Reviewer comments:

Reviewer #1

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The authors did not take my first review seriously. A discussion/comparison between their design and possible Gd loaded, mineral-oil-based liquid scintillator detectors should be presented. If the 8 MeV of released energy from the n capture is captured in the Gd doped detector the capture pulse height is far removed from that from single gamma and the device is highly efficient. Over the past 50+ years there have been many such designs that that been employed. (The added reference

to water based Gd systems is strange as most Gd applications employ trimethylbenzene (pseudocumene) or a closely related aromatic organic liquid.)

I suspect that the bottom line is this: For a Gd/scint detector to be have the PH separation mentioned above and be high efficiency, it must be large - perhaps too large and geometrically constrained, i.e. close to spherical. Before I can recommend accepting this work, at the very least, the present work needs a discussion of the value of having the scintillation local in the Li glass rather than distributed in a scintillator. I suspect that if the Gd/scint detector is large enough it becomes more efficient. If this is the case, the argument for the present detector is the desire/requirement is for a small device.

As a side point, in both the detector described in the work and in Gd/scintillator systems, the time response is fast AFTER thermalization.

Reviewer #2

(Remarks to the Author)
I think the revised paper is acceptable for publication.

Reviewer #3

(Remarks to the Author)
I want to reiterate support for the publication of the manuscript by A. Favalli et al., with the added corrections resulting from the review process. For completeness, I would like the authors to mention the use of 3He-based counters in fundamental nuclear physics research. These include early work at ISOLDE at CERN by Kratz et al., measurement with NERO array at NSCL, 3Hen array at ORNL, and most recent results, which use BRIKEN array at RIKEN facility, to name a few. These devices measured beta-delayed neutron emission branching ratios and provided data for astrophysical applications. In other applications, neutron counting is used for nuclear reaction-type experiments to precisely measure neutron emission probabilities in the presence of large gamma-ray and particle backgrounds. Mentioning these efforts will help broaden the manuscript's scope and generate more interest in their work. The field of neutron counting for fundamental nuclear physics will likely grow in the future, and the technique that the authors of this manuscript worked out may interest researchers working in this area of physics.

Response to Reviewer Comments:

Reviewer #1 (Remarks to the Author):
I do not find this manuscript suitable for the Nature family of journals. While the device described does have some novelty, it is not clear to me that the utility of such a device is broad. In fact, I think the audience is small and very specialized. In a few instances the data analysis could be improved or, at least, the presentation improved. A modified manuscript responding to my appended comments would be suitable for NIMA.
Response: We have carefully considered your comments and aim to address them in detail in our responses below and in the revised version of the manuscript.

1. The goal here is fast neutron couting, but not fast neutron spectroscopy, i.e. thermalization is employed. Therefore…

Over 70 years ago GdC_2O_4 [Gd – oxalate] loaded scintillator detectors were created for fission neutron neutrons. Neutrons are thermalized, captured (157Gd, \sig_g ~ .25Mb), and counted in the well-separated capture pulse train. Gamma are easily distinguished as they are < a few MeV and the neutron pulses are a full BE of gammas, i.e. ~ 8 MeV. If the sourse is placed inside a central well, Cd lined if desired, an accuate fast neutron count with a modest sided devise is extracted. A background should be subtracted as a devise large enough to stop most of the \gamma's (r ~ 0.5 m) would have a substantial background. While used for fission studies in the 1950, new ones crop up every few years.

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In short, what is missing is a comparison to Gd loaded scintillator tanks and why this is not a suitable replacement for 3He PC's embedded in polyethylene. I suspect the answer is complex, i.e. sometimes Gd tanks can be used (fixed 4\pi uses) and other times not.
Response: Our novel neutron detection technology, based on ^{6}Li scintillator glass particles suspended in a non-scintillating matrix that serves as both a moderator and a light transport medium, features high efficiency, short time response, neutron/gamma discrimination, and robustness to high count rates. This new technology development offers several additional benefits. Our novel detector design's unique combination of features, portability, and modularity provides many advantages for a broad range of applications. For example, it can be optimized for a large-array format, such as a ring surrounding a plutonium item to assay the mass via multiplicity counting, or used as individual modules for fundamental science needs, such as in pulsed neutron applications or emergency response situations.

^{3}He-based neutron detection systems are considered the "gold standard" for neutron detection in fundamental science, security, and civil applications [see ref. 11 of the manuscript on the DOE-Euratom/European Commission international effort]. In the manuscript, our technology is compared with ^{3}He-based systems as a performance metric Water-based detectors with Gd dispersed inside are another alternative approach for specialized neutron detection applications. Neutron multiplicity counting using such technology is presented in Dazeley, S., et al. "A water-based neutron detector as a well multiplicity counter." Nucl. Instrum. Methods Phys. Res. A 771, (2015). We acknowledge this work in our revised manuscript, adding a reference to it. It may be worth noting that the neutron detection efficiency of the reported system is around 25%, whereas our approach can achieve more than double the neutron efficiency in a similar form factor.

As reflected in our manuscript, we believe that comparing our technology to ^{3}He-based systems is the most appropriate approach. Based on the results presented in the manuscript, our ^{6}Li-based glass scintillator composite neutron detection technology stands as a viable alternative to ^{3}He-based detectors across a broad range of applications. We believe this will be of interest to the extended readership readers of Nature Communications Physics.

2. The manuscript reports inconsistent values of the efficiency. The abstract reports 6.7%, on line 255 one finds 7.3%. I do not know what these numbers are. Are they the efficiency at the test distance 2.3 m? (I presume there are the n efficiency, not fission detection as there are an average of 3.7n/fission for 252Cf). If these numbers are the absolute n eff at the test distance, what is the geometric fraction of 4\pi?

Response: The 6.7% is the intrinsic neutron capture efficiency we determined experimentally, while the 7.3% is the intrinsic neutron capture efficiency we obtained by simulation. We have clarified this in the revised manuscript by adding the term "intrinsic" (so, no need to comment on the geometry) and adding "by simulations" for the second efficiency.

3. Relating to Fig. 6. The fit in (a) must have a constant. If this background is subtracted, a curve directly comparable to (b) could be plotted in (b). As I understand it, the points in (b) are MC. If this is the case, please use a different point type to (a). Perhaps solid in (a) and open in (b). You could also have (a) Experiment (b) MCNP. (At first I thought (b) was the "peal" from the data in (a).

Response: Referring to Fig. 6a in the original manuscript, the time distribution obtained by a Rossi-α measurement has a constant contribution due to uncorrelated neutron detection events. This constant contribution was determined to have an average value of 2998.9 at long times (800-1000 µs). We agree with the reviewer that the presence of this constant background makes a side-to-side comparison with the calculated die-away (Fig. 6b) visually awkward. Therefore, in the revised Fig. 6a, we have subtracted this constant contribution and subsequently re-calculated the single-exponential fit to the data in the 8-60 µs time window. This has slightly changed the experimental die away time from 10.5 ± 0.1 µs to 10.3 ± 0.1 µs. We have also represented the measured data in Fig. 6a by solid circles to more clearly distinguish them from the calculated data in Fig. 6b represented by open circles, as suggested by the reviewer. The fundamental conclusions from this die-away analysis, however, remain unchanged.

4. Position resolution using individual pulse mode. Generate event wise scatter plot in the dispersion variable (L-R)/(L+R), calculate first and second moments and, using calibration fixed by the means at different positions, get one \sigma position resolution.

Response: First, we emphasize that we did not claim that position determination on the basis of single pulses was feasible. Instead, in the original manuscript, the pulse-height spectra (Fig. 7) we used to generate the position calibration curve (Fig. 8) each are the result of acquiring 100,000 neutron capture events for a fixed source position, as indicated in the Materials and Methods section.

We appreciate the reviewer's suggestion that the position error quantification in our analysis should be improved. To do so, we adopted the simpler and more intuitive "dispersion variable" $\xi = (A - B)/(A + B)$ suggested by the reviewer, rather than the quantity defined in Eqs. (1) and (2) of the original manuscript. For each source position, we calculated the histogram of 100,000 single-event ξ values and then performed a least-squares fit of a normal distribution to this histogram to obtain the $\bar{\xi}$ (first moment). The revised Fig. 8 plots source positions, z, versus this mean dispersion variable, $\bar{\xi}$. As indicated by the least squares fit $z = a\bar{\xi} + b$ (dashed red line), there is a strong linear relationship (R^2 =0.9934) between the Cf-252 source position, z, and the mean dispersion variable, $\bar{\xi}$. The respective fit parameters have standard errors in the slope ($\sigma_a = 1.902$) and the z-axis intercept ($\sigma_b = 0.3590$), see inset of Fig. 8. From these, we calculate the 1σ error in position to be ±0.36 cm for the source located in the center along the composite (z=0 cm) and ±0.61 cm for the source located at either end of the composite (z=±11 cm).

We have revised Fig.8 and its caption as well as updated the respective section in the manuscript to incorporate this improved analysis and conclusions.

5. Pg 17: F5 is not defined but probably not necessary.
Response: We have updated the text with the definition of F5 and its unit, and we have added citations to the relevant references on the MCNP code.

Reviewer #2 (Remarks to the Author):
This paper discusses an alternative neutron detector based on Li-6 glass mounted in a mineral oil moderator. The detector design is novel with a number of potential applications. The paper is well written and clearly presented.
Response: We would like to thank you for your positive feedback on our paper. We appreciate your recognition of our neutron detector design's novelty and potential applications.

There are some revisions that I think are needed.

The detector is filled with mineral oil. This could be a problem for some applications where liquid leaks could cause criticality concerns, as well as flammable liquids not being allowed for many applications. Is there an alternate moderator material (epoxy)?
Response: Using mineral oil offers several advantages: it allows for easy customization of detector form factors and dimensions, ensuring the scalability of our prototype for various applications. Moreover, the fabrication process is well-defined and cost-effective. While these benefits highlight the advantages of the oil solution, we acknowledge that it presents limitations in certain applications. Therefore, we have been developing a solid version of the detector, which we intend to report on in future communications. This remark was included in the "Future Directions" section at the end of the paper.

On page 5 there is a brief design section that references another paper. But, at the end of the paper there is a more complete design section. Why not combine these or at least refer to the details later in the paper?
Response: Yes, the reference did not provide additional information, as the fabrication of the actual detector is described and explained in full detail in the Materials and Methods section of the manuscript. We have now referenced the “Detector Fabrication” in the Materials and Methods section of the manuscript.

On page six, there is a mention of the excellent n-gamma separation. The quality of this separation can be quantified better. I think there should be a figure showing the natural n-gamma background spectra (no sources present. Such a figure can show a much better representation of the n-gamma separation since the gamma ray background is about 1000 times larger than the neutron background (at sea level, though Los Alamos has a larger n background). For some applications, this large difference in

background rates, and the resulting poor n-gamma separation might make this detector not usable for those applications.
Response: We agree with the reviewer that the natural neutron/gamma background spectrum measured at the experiment location is important. We have added Fig. 3a to show the natural background at Los Alamos National Laboratory (2198 m above sea level). It shows a gamma-tail and a well-resolved neutron capture peak. In the original manuscript, this backround spectrum was already subtracted from all the raw spectra recorded when sources were present (Fig. 3b and 3c), and therefore our discussion and conclusions regarding the gamma misidentification probability remain unchanged. For completeness, in the caption of Fig. 3, we have also included the measurement durations for all spectra shown in Fig. 3; these durations were used to calculate count rates.

The results for coincidence and multiplicity counters are impressive. Here, the use of liquids could be problematic.
Response: The detector is engineered for easy implementation and field measurements, which is an integral part of the design process tailored to specific applications. As mentioned earlier, the oil detector's modularity, design flexibility, and straightforward construction process are key advantages. We also recognize the importance of developing a solid version of the detector, that is part of our ongoing research activities.

Can you estimate the cost of such detectors as compared to He-3 detectors?
Response: The detector cost is not constrained by the limited availability of 3He gas but rather relies on readily available ^{6}Li glass. We have learned many of the fabrication intricacies during the assembly of this first prototype, and the respective information gained will be useful in evaluating various future high-volume fabrication methods. However, we have not yet developed a quantitative cost model that would allow for a fair comparison with the quoted price of a comparable ^{3}He detector.

On page 14, what is the purpose of the Cd to eliminate thermal neutrons? For some applications, that could be limiting.
Response: The Cd sheet can be removed if necessary. However, for accurate performance measurements, it was important to have the Cd foil in place to minimize low-energy scattered neutrons entering the detector.

It seems there should be a Conclusions section at the end of the paper.
Response: We agree with the referee that a paper's traditional structure typically ends with the conclusion section. However, for the required formatting style of Communication Physics, the last section of the body of the manuscript should be titled “Discussion.” We updated the last subsection, “Future directions,” to serve as a conclusion, de facto, providing the outlook on the applicability of the neutron detector in various applications, including Fundamental Science.

Reviewer #3 (Remarks to the Author):
The manuscript Next-Generation Neutron Detection Using a 6Li Glass Scintillator Composite by Favalli and collaborators presents a demonstration of an innovative new idea for neutron detection.

Authors developed a working prototype of a neutron counter, which presents a viable alternative to a 3He-based detector. The need for 3He replacement in neutron detection has been identified as very important due to the price and availability of this isotope. The authors use an idea, which has been tried several times in this field, of combining the material with high-neutron capture cross section with *sensitive distributed readout. Their original idea was published in 2015 by the same team. This paper shows an implementation of the concept as a fully evolved working detector with high neutron detection efficiency and excellent suppression of gamma rays. The design is very clever; it uses the high-detection efficiency for thermal neutrons for a 6Li-glass scintillator but overcomes the biggest problem of all the scintillators, which is their gamma-ray sensitivity. The use of transparent mineral oil acts as a moderator and optical medium at the same time. The description of the detector properties is complete, includes an evaluation of detection efficiency, and quantifies suppression of the gamma-rays, two critical components of a potential 3He-based counter successor. This work is critical; the current detector has superior qualities to the 3He-based assemblies. The authors focus on examples of applications in well logging or detection of nuclear materials. I also see excellent potential in neutron counting that is relevant to fundamental science, where neutron counting is essential. The new design may suggest a new detector concept and may overcome the geometrical limitations of 3He counters, which always require a large moderator volume, making the systems relatively cumbersome. The manuscript is well-written and gives an excellent introduction to the subject, and the description of the detector design and test measurement is complete. The data is supported by extensive simulation efforts. The referencing to literature is extensive.The manuscript presents a summary of a very creative effort. The implications of this work are broad e.g. in nonproliferation and safeguards applications but also in fundamental research where efficient neutron counting is essential. I would like to recommend this manuscript for publication in Nature Communications.*

Response: We sincerely appreciate your positive feedback and recognition of the innovation and potential impact of our work in the field of neutron detection. Your detailed comments on various aspects of the detector's design, efficiency, and gamma-ray suppression, as well as its broad implications for different applications, are highly encouraging. We have further expanded on the value of the developed detector technology for fundamental science in the "Future directions" section of the manuscript.

Reviewers' comments:

Reviewer #1:
The authors did not take my first review seriously. A discussion/comparison between their design and possible Gd loaded, mineral-oil-based liquid scintillator detectors should be presented. If the 8 MeV of released energy from the n capture is captured in the Gd doped detector the capture pulse height is far removed from that from single gamma and the device is highly efficient. Over the past 50+ years there have been many such designs that that been employed. (The added reference to water based Gd systems is strange as most Gd applications employ trimethylbenzene (pseudocumene) or a closely related aromatic organic liquid.)

I suspect that the bottom line is this: For a Gd/scint detector to be have the PH separation mentioned above and be high efficiency, it must be large - perhaps too large and geometrically constrained, i.e. close to spherical. Before I can recommend accepting this work, at the very least, the present work needs a discussion of the value of having the scintillation local in the Li glass rather than distributed in a scintillator. I suspect that if the Gd/scint detector is large enough it becomes more efficient. If this is the case, the argument for the present detector is the desire/requirement is for a small device.

As a side point, in both the detector described in the work and in Gd/scintillator systems, the time response is fast AFTER thermalization.

Response: The reviewer's question about the value of localized neutron capture and scintillation is very important, and it has been investigated in detail in our previous study. Monte Carlo analysis of the interplay of the key design parameters of this type of detector is reported in *Wiggins, B. W., Favalli, A., Iliev, M., Ianakiev, K. D., & Hehlen, M. P. (2019). "Computational investigation of arranged scintillating particle composites for fast neutron detection," NIM A, 915, 17-23 (2019),* where we reported on an investigation using the MCNP Monte Carlo code to explore the design criteria for the 6Li glass scintillator composite. The 6Li glass scintillator composite detector is designed to confine energy deposition from the 6Li neutron capture events within individual scintillator particles dispersed in a non-scintillating organic matrix, thus providing low sensitivity to gamma rays (resulting in a very low gamma misidentification probability because of the good separation of the gamma and neutron capture pulse height distributions) while maintaining high neutron capture efficiency. The particle size and the distance between particles, referred to in the above paper as pitch, are two key design parameters for the detector.

The simulations reported in the cited paper show that to achieve high neutron capture efficiency while maintaining a low gamma misidentification rate, the optimal particle size ranges between approximately 0.01 and 0.05 cm, with the pitch (spacing between scintillator particles) between 0.4 and 0.6 cm. For particle sizes in this range, more than 90% of the alphas and tritons from the 6Li capture reactions are contained within the scintillator while gamma interactions are relatively inefficient. The interspace between particles is also crucial in minimizing the possibility that electrons (from gamma interactions) deposit energy in more than one scintillator particle (reducing the separation of neutron/gamma in the pulse height distribution) while maintaining high neutron capture efficiency. Finally, having a non-scintillating organic matrix avoids any gamma-induced scintillation in the matrix that would degrade the neutron/gamma separation.

The performance of our developed composite neutron detector thus depends on the geometric parameters size and pitch, which ensure low gamma misidentification while maintaining neutron detection efficiency (detectors up to 30 cm long and 6 cm radius were studied). They have a defined range of values to guarantee neutron efficiency and neutron/gamma separation, so they are the design parameters.

We have updated the manuscript by adding: "An initial computational investigation provided directions on the design parameters (particle size, spacing between scintillator particles) to minimize gamma misidentification while maintaining high neutron detection efficiency [18]."

Reviewer #2:
no further comments.

Reviewer #3 (Remarks to the Author):
I want to reiterate support for the publication of the manuscript by A. Favalli et al., with the added corrections resulting from the review process. For completeness, I would like the authors to mention the use of 3He-based counters in fundamental nuclear physics research. These include early work at ISOLDE at CERN by Kratz et al., measurement with NERO array at NSCL, 3He array at ORNL, and most recent results, which use BRIKEN array at RIKEN facility, to name a few. These devices measured beta-delayed neutron emission branching ratios and provided data for astrophysical applications. In other applications, neutron counting is used for nuclear reaction-type experiments to precisely measure neutron emission probabilities in the presence of large gamma-ray and particle backgrounds. Mentioning these efforts will help broaden the manuscript's scope and generate more interest in their work. The field of neutron counting for fundamental nuclear physics will likely grow in the future, and the technique that the authors of this manuscript worked out may interest researchers working in this area of physics.

Response: We sincerely appreciate your positive feedback and suggestions on expanding on the applications of fundamental nuclear physics. In the "Future directions" section of the manuscript, we expanded the manuscript with more references to applications in fundamental nuclear physics (such as nuclear reactions and β-delayed neutron emission measurements, experiments in neutrino physics).

Dear Prof. Rogachev,

We are pleased to inform you that we have carefully addressed the Editor's comments and suggestions in this new round of review. We have also addressed the publisher's list of editorial requests.

The manuscript has been updated to reflect the required changes.

We appreciate your time, comments, and consideration.

Sincerely,

Drs. A.Favalli and M.P. Hehlen on behalf of all co-authors

EDITORS' COMMENTS:

Editor. While we interested in publishing this paper, we did not find your answer to the referee #1 questions detailed and direct enough. We appreciate that a direct quantitative comparison may be to some extent outside the scope of this study, but we believe that addressing the question of why the proposed design is superior to the Gd-based scintillators is essential for the readers and would increase significantly the impact of your work, even if this remains qualitative. It is an important point to make for the future interest to this detector system in the community. In particular, outline the conditions under which the proposed design is advantageous. It may be a high gamma-ray flux, or detector size limitations, or some other considerations.

Response: Reviewer 1's enthusiasm for Gd-loaded scintillator tanks is evident. They are indeed an important class of detectors for some applications, and we have recognized that fact by adding Ref. [19] in a preceding revision of our manuscript. However, such Gd-loaded scintillator tanks are not a general-purpose solution or panacea for all applications. We also emphasize that the development described in this manuscript was not conceived and is not presented as an alternative or competitor to large Gd-loaded scintillators. Therefore, it seems odd to single out the Gd-loaded tank as the basis for comparison. There exist many neutron detector types. Some fill niche applications. Others form the basis for more broadly used general-purpose solutions. Gd-loaded scintillator tanks are a specialized type of detector, and they are neither used for radioactive waste assay applications nor for international nuclear safeguards domains where arrays of moderated ^{3}He proportional counters have been dominant for decades. For these broad applications, simplicity, stability, reliability, flexibility, the wide dynamic range of efficiency, compactness, scalability, non-toxicity, non-liquid, ease of modeling, availability, and exceptional gamma-to-neutron discrimination are all critical factors. This is why the community widely considers ^{3}He proportional counter-based systems as the gold standard for neutron detection. The detector approach described in the present manuscript emerged from an effort to imagine an alternative to ^{3}He-based detector systems for the demanding application space of nuclear materials measurement across the fuel cycle at a time when ^{3}He supply continues to be challenged, the price is high, and the demand is expected to grow dramatically to meet homeland security needs.

It is important to remember that the flux of gamma rays is many orders of magnitude greater than that of neutrons in typical waste assay and safeguard applications. A bulk scintillator detector is intrinsically sensitive to gammas and would be overwhelmed by this gamma background. This is why in our approach, (1) the ^{6}Li scintillator glass particles are embedded in a non-scintillating matrix, and (2) the particles are too small to absorb much energy from the electron field created by gamma interactions, whereas the neutron-induced charged particles created inside the glass particle can deposit relatively larger amounts of energy, producing large light pulses. As a result, the gamma-to-neutron discrimination is achieved physically. The other feature is that the hydrogenous matrix becomes an intrinsic part of the moderator. Whereas moderated ^{3}He proportional counter arrays are inherently heterogeneous, the proposed more integrated approach can be inherently more compact (the migration distance from the point of thermalization to the point of capture is reduced), the die-away time is shortened, and the detector can be formed or cast, extending the range of applications. So, for example, while Gd-loaded tanks have not been used as structural components, e.g., in drones, in hand-held applications, in phantoms, etc., the proposed concept immediately suggests itself as a contender as a general-purpose neutron detector in a way that Gd-loaded scintillator tank technology does not. One can envision designs on a scale of the order of a few mm diameter probes to >1 m^2 panels. The solution space overlaps with that covered by conventional cylindrical ^{3}He-filled proportional counters and is also expanded. The new approach also has other potential advantages, such as higher count rate capability. Of course, it could be used with other light-sensor types and configurations, but that is not germane to the present discussion.

Note that we make no claim that the present concept and demonstration are superior to large Gd-doped scintillation tanks for the applications they have been successfully applied to, such as neutrino physics and neutron multiplicity distribution measurements in basic physics experiments. As explained, we began searching for a general-purpose alternative to ^{3}He-based neutron counting systems for a broad range of demanding field applications. Nor are we suggesting that the present approach is a potential replacement for every neutron detector; for example, we are not doing spectroscopy (although one could build a Bonner sphere spectrometer around such devices) or usurp neutron time-of-flight arrays.

Given this context, we sense that comparing our detector design to Gd-loaded scintillator tanks is inappropriate and too restrictive. Nor do we want the article to become a review: that is not the purpose of this manuscript, and there are other excellent accounts to turn to for that. We feel that the range of applications, users, and variants for this nascent technology is vast and will be of interest to a broad audience engaged in cutting-edge research and innovation beyond narrow or traditional confines. We contend that using the widely accepted and wellknown ^{3}He-based neutron detector as a basis for comparison for our detector is, therefore, most appropriate for the present manuscript.