
Report of the First Referee -- CY10771/Sun

****** Data Checking Report from the Nuclear Data Review Group ******

The present manuscript has been reviewed for data consistency.

Below are comments the authors may wish to consider prior to publication.

We greatly appreciate the referee's time and effort in checking the data in our manuscript! Their comments and suggestions have been invaluable in improving the quality of the manuscript. Our point-by-point responses (in blue) to the referee's comments (in black) are listed as follows. The revisions made to the manuscript are highlighted in red in the revised PDF.

Figure 2:

Caption states: "The proton spectrum is adapted from Ref. [41]." For completeness, perhaps this could be expanded to "The proton spectrum and beta-delayed proton and alpha branchings are adapted from Ref. [41]"

Thanks for the suggestion. We have revised the caption of Fig. 2 accordingly.

The figure itself presents an up-to-date 60Ga decay data evaluation. There is not much detail on the evaluation, apart from a few sentences on page 4. It might be worth mentioning, either in the text or in the figure caption, that the decay scheme of 60Ga to 60Zn is rather incomplete, with summed beta feedings less than 100 by several sigma and a number of unplaced gamma transitions with large intensities.

Thanks for pointing this out. We have noted the incompleteness of the decay scheme in Sec. II on pages 3-4. We acknowledge that the manuscript primarily focuses on instrumentation, which has limited the amount of detail provided regarding the evaluation. Additional information can be found at: https://wikihost.frib.msu.edu/pxct/lib/exe/fetch.php?media=zn60_ec_decay_69.4_ms.pdf

We welcome any advice or suggestions you may have.

Table III:

We believe that the column labeled E_Kalpha is E_Kalpha1.

In our case study, it is necessary to distinguish the 8.046-keV $K_{\alpha1}$ and 8.027-keV $K_{\alpha2}$ for Cu from the 8.637-keV $K_{\alpha1}$ and 8.614-keV $K_{\alpha2}$ for Zn so that we can obtain the Cu/Zn count ratio and effectively utilize the PXCT. $K_{\alpha1}$ and $K_{\alpha2}$ are experimentally indistinguishable, and we usually round the energies to one decimal place and collectively refer to them as K_{α}. A clarification has been added to Sec. III on page 6 and the caption of Table III.

Figure 6:

For the Sm K_beta2 energy, we obtain 46.578, compared with 46.568 given in the figure.

We have checked the X-ray energies that we quoted from Ref. [124], a database developed by the University of Chicago: https://xraydb.xrayabsorption.org/element/Sm and the Sm $K_{\beta2}$ energy value is confirmed to be 46568.4 eV.

Figure 8:

In subsequent figures, the peak at 444-keV is labeled by both components of the doublet 152Sm 443.96/444.01 but in the top and bottom panel here, only the 443.96 transition is indicated.

Thanks for pointing this out. We have corrected the labeling of the ^{152}Sm 444-keV doublet peak in Fig. 8.

Page 15, right column, Section F:

Authors list recent measurements of the 59.5-keV level in 237Np. They could consider also including NPA 1040, 122745 (2023).

Thanks for bringing that measurement to our attention. We have included the reference 2023SA13 in Sec. V F: "*The results obtained from both Si detectors are consistent with recent precision measurements of 67.86(9) ns [139], 67.60(25) ns [140], and 67.60(20) ns [141].*"

Figure 16:

A reader would benefit if the authors would include the nucleus that the authors are analyzing in this figure.

Thanks for the suggestion. We have specified the nuclei in the caption of Fig. 16.

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Report of the Second Referee -- CY10771/Sun

See Attachment: cy10771_report_1_2.pdf

The article reports on the development of the LIBRA apparatus, which was designed for forthcoming experiments at FRIB. LIBRA can measure protons and X-rays in coincidence, together with nuclear gamma rays. Proton unbound states created by electron capture or beta+ decay of proton-rich nuclei can be studied. Explosive hydrogen burning often involves such states. The rp-process relevant to X-ray bursts is an example The properties as lifetimes and p/gamma decay branching ratios of these unbound dates are crucial in evaluating the astrophysical reaction rate of the relevant (p,gamma) process.

LIBRA can extract average lifetimes and branching ratios. Experimental access to nuclei in explosive burning is rather limited, and thus more efforts are needed to clarify the roles of proton-rich nuclei in astrophysical scenarios. Due to the expected unique and high performance, LIBRA should open new opportunities in nuclear astrophysics research. Thus the study meets the requirements for instrumentation papers in PRC.

The paper contains motivation with a case study for the target experiment at FRIB (60Ga decay), the basic principle of the experimental method, details of the devices, performance tests, and simulations of the experiment based on theoretical prediction of the relevant process. They appropriately cover the author's study, and the manuscripts are well-written. There are, however, a few points that should be improved for publication.

We appreciate the thorough and insightful feedback provided by the referee. Their comments and suggestions have been invaluable in improving the quality of the manuscript. We have carefully considered each point and revised the manuscript accordingly. Our point-by-point responses (in blue) to the referee's comments (in black) are listed as follows. The revisions made to the manuscript are highlighted in red in the revised PDF.

Generally, the descriptions are detailed, starting from basic principles and presenting, in some cases, actual procedures for providing results. They are good for nonspecialists, while some readers with experience may feel too trivial. Some of them could be shortened.

We appreciate the referee's point regarding the level of detail provided. Given that this manuscript serves as the initial comprehensive publication describing the newly-built LIBRA system, we intended to present a balanced amount of information appropriate for a broad audience, including non-specialists and potential general purpose users of the LIBRA system.

On the other hand, the last part of each section should have statements on the outcome of the studies described in the relevant section, which are sometimes missing especially in sections V and VI:

In most of the subsections in Section V, the measurements of the resolutions and efficiencies of detectors are described. Are they better or worse compared with expectations or requirements?

We appreciate the referee's suggestion and have included concluding assessments on detector resolutions and efficiencies reported in subsections of Sec. V.

In summary, every detector we chose for our setup features minimal or no dead layers in front of its active region. The mechanical assembly is designed to be as compact as possible. We minimize the materials in the radiation path to mitigate attenuation, thereby maximizing detection efficiencies. The detection efficiencies obtained from source tests align well with those derived from our Geant4 simulations. The resolutions achieved in our lab testing environment meet or exceed the manufacturers' specifications. Furthermore, the design also allows for the flexible combination of individual detectors. We have the option to engineer the integration of LEGe and the central chamber with larger germanium detector arrays to further enhance the γ detection efficiency.

Section VI ends with an explanation of Fig. 18 and related issues. What are the outcomes of this simulation? Is the target experiment evaluated to be feasible with a good performance as expected? Note that the experiment may give a Cu-Zn ratio different from the simulated one.

We appreciate the referee raising this important point regarding the outcomes and feasibility. As we explained in the Introduction, the key resonances impacting thermonuclear $^{59}Cu(p,\gamma)^{60}Zn$ and

$^{59}Cu(p,\alpha)^{56}Ni$ reactions are currently unknown. To assess the feasibility of the proposed case study using LIBRA, we have developed Monte Carlo simulations incorporating the ^{60}Ga decay scheme. To complete the largely unknown decay scheme, we have performed shell-model calculations and statistical-model calculations.

As we clarified in Sec. IV, the theoretically important resonances are not necessarily the specific resonances that our experiment aims to identify but rather represent a plausible scenario that we may encounter. Any ^{60}Zn resonances that we are able to discover through the ^{60}Ga decay experiment using LIBRA will impose direct constraints on the currently unknown $^{59}Cu(p,\gamma)^{60}Zn$ and $^{59}Cu(p,\alpha)^{56}Ni$ reaction rates.

Then, we developed Geant4 simulations incorporating both theoretical decay properties of ^{60}Ga and realistic detector resolutions and efficiencies. The outcomes of this simulation are demonstrated in Fig. 18. First, the individual proton and α branches can be identified through the charged-particle ΔE-E spectrum, from which we obtain their respective decay branching ratios, as standard practice in decay spectroscopy experiments. Second, we obtain the proton-gated X-ray spectrum — the most important observable of the Particle X-ray Coincidence Technique. It shows a clear separation of the characteristic Cu and Zn K_α peaks on top of an acceptable background level. Third, by extracting the Cu/Zn X-ray count ratios in coincidence with protons, we have derived an average lifetime for proton-emitting resonances within specific proton-energy intervals. All necessary atomic corrections for extracting the lifetimes are detailed in Sec. VII.

Notably, the sensitivity range of the inferred lifetimes extends approximately one order of magnitude above and below the Zn K-shell vacancy lifetime, i.e., ~0.04 to 4 fs, a timescale very challenging for traditional lifetime techniques. Before the actual experiment, it is worth demonstrating simulated results that integrate theoretical inputs with measured detector responses in an instrumentation paper. We acknowledge that our calculations and simulations provide a representative Cu/Zn ratio, and the actual experimental outcome may differ. Measuring the true Cu/Zn ratio is precisely the goal of our future ^{60}Ga experiment using LIBRA. Please see the revised Sec. VII for details.

Section VII (Summary and outlook) should also contain more specific statements concluding the work, referring to the purpose of the study presented in the introduction. To what extent do experiments with LIBRA improve our knowledge?

We thank the referee for the suggestion. We have clarified how future LIBRA experiments can enhance our knowledge, as initially motivated in the introduction. Please see the revised Summary and Outlook (Sec. VIII).

To this day, the ^{59}Cu(p,γ)^{60}Zn and ^{59}Cu(p,α)^{56}Ni reaction rates remain unknown and have thus far relied on statistical model calculations, lacking experimental data. This limitation hinders a precise understanding of the NiCu cycle and its broader impact on observables in Type I X-ray bursts.

In this instrumentation paper, we have rigorously tested and validated the performance of LIBRA. The simulation results presented in this manuscript require the nominal operational beam power of 400 kW at FRIB, a benchmark expected but not yet realized as of 2025. Nevertheless, our tests confirm that LIBRA is well-prepared to measure the essential nuclear physics inputs, including resonance energies, lifetimes, and decay branching ratios. This readiness positions us to submit the beam proposal to future FRIB PACs as soon as the expected beam intensities become available.

Typically, these inputs have to be gleaned from various experiments conducted in different labs with different methodologies, each with its own systematic uncertainties. For instance, scientists often encounter confusion and discrepancy with level matching when trying to piece together the results obtained from multiple experiments. Even in cases where LIBRA provides only upper or lower limits on lifetimes and branching ratios due to experimental statistics, these measurements will still yield valuable constraints, establishing firm experimental bounds on the reaction channels.

If everything goes well, we will establish the ratio of the two competing reaction rates through a future PAC-approved experiment with LIBRA. Then, we can collaborate with theoretical astrophysicists on XRB modeling. They will use our newly measured reaction rates as model inputs, and the results will help us address the long-standing question of to what extent the reaction flows in X-ray bursts break out toward heavier elements or remain confined in a closed cycle. Ultimately, this could reduce the nuclear physics uncertainties in XRB model predictions of light curves and facilitate the model-observation comparisons of XRB observables to infer neutron star properties.

Detailed comments:

Section I

- The first sentences discuss the difficulties of measuring reaction rates. The one related to the cases where LIBBRA is applied could be highlighted.

Thanks for this suggestion. We would like to begin our general introduction by highlighting the challenges of directly measuring charged-particle reactions involving unstable reactants that are of astrophysical interest. Due to these challenges, researchers often rely on indirect methods to determine resonant and statistical reaction rates. Typically, each experiment only provides a portion of the information needed for a comprehensive understanding. Therefore, it is desirable to develop an indirect method that can, in principle, provide all necessary information. In Sec. II, we introduce one of the most critical questions in XRB — the NiCu cycle, as a case study and discuss it in detail. This narrative allows us to avoid making LIBRA to only a narrow range of applications. In the concluding paragraphs of Sec. I, II, and III, we highlight LIBRA from three different perspectives.

- p.2 for eq. (4) The transmission coefficient should be defined or explained.

We have revised the paragraph following Eq. (4). Please refer to Sec. I on the left-hand side of page 2 for details.

Section III

- Table III should be placed closer to the relevant text, if possible.

We have moved Table III to page 6, following the relevant text at the bottom of page 5.

- In the last paragraph (p. 6), the probabilities of X-ray production are examined (1st sentence). The resultant numbers may be discussed in connection with the purpose of the experiment.

We have revised the last paragraph of Sec. III, after introducing the Particle X-ray Coincidence Technique to provide readers with a clearer sense of the order of magnitude. All the probabilities of X-ray production have been incorporated into our simulation, along with the detector resolution and efficiencies based on tests conducted with radioactive sources (Sec. V), to inform our expected experimental sensitivity and feasibility of lifetime measurements that are discussed in Sec. VII.

Section IV

- Last sentence of subsection A The comparison becomes clearer if the case with 130MeV/u 60Ga is described. Is it for a previous experiment?

We have provided clarification in Sec. IV A on page 6. We have also added Ref. [33] to this sentence, which is another ^{60}Ga decay experiment proposal using a Time Projection Chamber at the FRIB fast beamline. The goal is to search for resonances in ^{60}Zn and measure the branching ratios for proton, α, and γ decays, but lifetimes will not be measured. Also, a typical fast beam at ~130 MeV/u would penetrate deeply into materials, making it impossible for X rays to reach the detectors. As a result, LIBRA is designed to use a stopped beam instead of a fast beam to effectively utilize the Particle X-ray Coincidence Technique.

Section V

- The live time is estimated for a few cases. For example, the difference between the GEANT4 simulations and measurements is attributed to the live time reduction (p. 12).

Can the data acquisition system provide the live time when the events are read and recorded? While the live time depends on the counting rate, other possible sources of difference may not. Separation of the live-time influence may be useful for actual measurements.

We thank the referee for raising this point. The FRIB Digital Data Acquisition System provides online count rate monitoring and recording for each channel. An example from a high count rate test is shown below.

Numerator	Denominator	Rate(s)	Total(s)
mod2.ch0.in		14176.50	17697902
mod2.ch0.out		11805.00	14830336
mod2.ch4.in		16279.50	20494734
mod2.ch4.out		13327.00	16914737
mod2.ch8.in		15700.50	19544938
mod2.ch8.out		12893.50	16325436
mod2.ch12.in		16104.50	20196748
mod2.ch12.out		13310.50	16899630

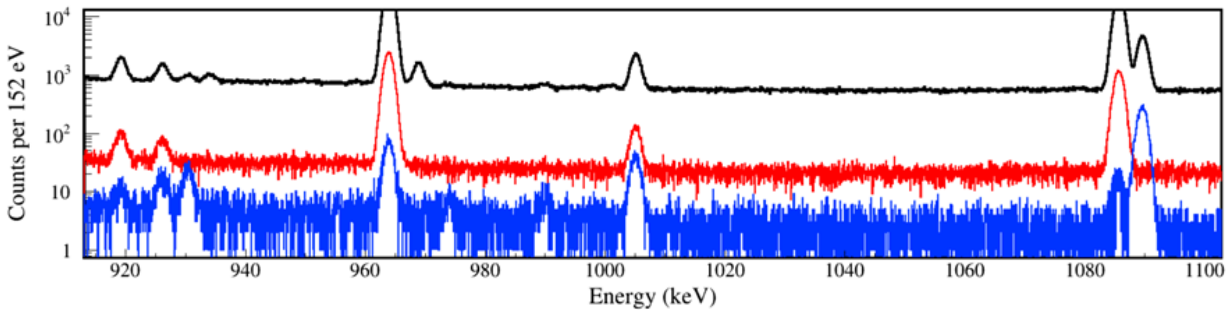
- the last sentence of subsection D

What is the definition of the efficiency for MSD26? Better to clarify.

We have clarified the observed efficiency of MSD26 for internal conversion electrons. See Sec. V E for details.

- Fig. 14 clearly shows the reduction of the background. That should be stated in the text. The amount of the reduction may be described for the two conditions, if possible.

The red spectrum in Fig. 14 represents the XtRa1 γ-ray spectrum gated by the Sm K_α and K_β X rays measured by LEGe. The observed reduction is attributed to the X ray emission probabilities of ^{152}Eu EC to ^{152}Sm, the deexcitation of ^{152}Sm states via internal conversions, and the LEGe efficiencies for detecting X rays in the energy range of 38-41 and 45-47 keV. The blue spectrum represents the XtRa1 γ-ray spectrum gated by the electrons measured by MSD26. The reduction is associated with the ^{152}Eu β^- decay probabilities to ^{152}Gd, the deexcitation of ^{152}Gd states via internal conversions, and the MSD26 efficiencies for detecting electrons. In this test, electrons within an energy range of 100–1400 keV were selected for gating. Overall, the amount of reduction is energy dependent and nuclear-structure dependent. For a quantitative illustration, we provide a zoomed-in portion of Fig. 14 below, where the background levels at 1 MeV are approximately 625: 21: 3 for the raw spectrum, X-ray-gated spectrum, and electron-gated spectrum per 152 eV bin, respectively.



All authors sincerely thank the referees for their dedicated time and effort in reviewing our manuscript!