

Novel Approach to Investigate ATOMKI Anomaly Using Coherent CAPTAIN-Mills Detectors

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ATOMKI nuclear anomaly has suggested a new BSM (beyond the standard model) boson with mass ~ 17 MeV emitted from excited nuclei and quickly decays into a pair of e^+e^- . In order to search for the new particle, we propose a new approach that utilizes the ongoing coherent CAPTAIN-Mills (CCM) ten-ton LAr (liquid argon) detectors. The neutrons from the Lujan target can scatter inelastically, but the PMT glass in the CCM detector can produce the new boson which solves the ATOMKI anomaly. The new boson can be detected from its decay to a e^+e^- pair. We find that CCM probes a large area of the anomaly-allowable parameter space. We also show the prediction for a 100-ton LAr detector and five-ton EOS water detector.

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Introduction—Beyond the standard model new physics ideas are well-motivated. Various ongoing experiments are probing scales of new physics ideas that could explain the origin of dark matter, neutrino masses, mixings, and anomalies observed in different experiments. Rare decay processes, various electron and proton beam dump experiments, reactor-based experiments, and astrophysical observations are probing models possessing low energy scales for new physics while the LHC is searching for higher energy scales mostly around and above the weak scale. A wide range of new physics scales are also being searched at the direct and indirect detection experiments.

Among the existing anomalies, a very interesting excess has been reported by the ATOMKI pair spectrometer experiment [1–4] in recent times. A more than 5σ excess is observed in the internal pair conversion (IPC) decays of excited ^8Be nuclei with noticeable bumps in both the invariant mass and the angular spectra of e^+e^- . These bumps cannot be explained by electromagnetic IPC from virtual photons where a smooth and rapidly declining

distribution of opening angles is expected. More recently, similar anomalous measurements are reported in the IPC decays of excited ^4He [5,6] and ^{12}C nuclei [7].

The anomalies suggest there could be a new boson X with mass ~ 17 MeV [3–12] in the deexcitations of the nuclei such as ^8Be , ^4He , and ^{12}C . The decay of the slow-moving boson X into a pair of e^+e^- explains the anomaly where the boson X requires interactions with quarks and e^+e^- . Since X decays quickly into the e^+e^- pair, the coupling cannot be too small and it is found that coupling strengths $\sim 10^{-3}$ – 10^{-4} can explain the excess.

At present, several experimental groups are trying to probe this excess by performing similar measurements as ATOMKI. In this Letter, we propose a novel way to investigate this anomaly at the ongoing proton beam-dump based neutrino experiments. We utilize the ongoing 1 GeV proton beam-based experiments, e.g., CCM [13–16], where the detectors are situated around 20 meter from the Lujan target. We will also include a 100-ton upgrade (PIP2-BD) in our analysis for a future projection [17], and the five-ton EOS detector if it is situated at Lujan [18].

The X boson, in our proposal, needs to be produced and decay in the detector, since its lifetime is small compared to the time of flight from the target to the detector. We utilized excited states of oxygen around 18 MeV and above with appropriate isospins to produce the X boson.

In CCM, the photomultiplier tubes (PMT) glass is made out of SiO_2 and there are 200 of them in the inner walls of the detector. The PMT glass oxygen transitions to the excited state by inelastic scattering of neutrons from the target. The LAr used in the CCM detector does not possess

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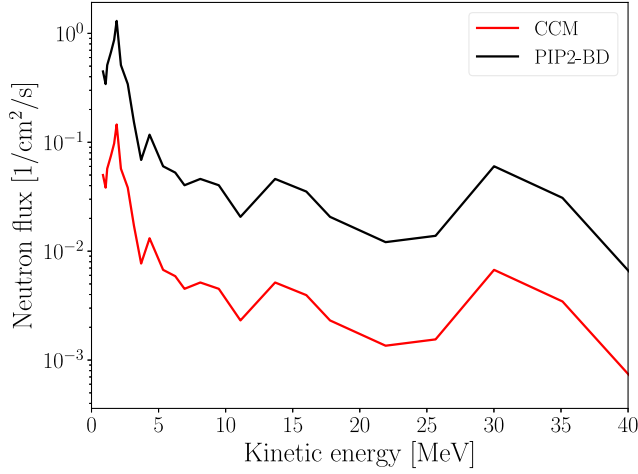


FIG. 1. Neutron flux at CCM LAr detector (after the shielding) and PIP2-BD LAr 100t LAr detector.

any excited state around 17 MeV and above with sufficient strength to produce the X boson. We will calculate the neutron-oxygen inelastic cross sections using the nuclear Gamow shell model to estimate the production of a 17 MeV X boson. The final state electrons emerging from the X decay are of $\mathcal{O}(10)$ MeV.

Nevertheless, there exists literature [19,20] that contradicts the ATOMKI anomaly in which [19] finds no significant signal of X boson. Reference [20] claims that the X boson production is dominated by direct transitions such as $E1$, instead of nuclear deexcitation, and that protophobic vector boson X does not explain ATOMKI anomaly.

Model—Over the last several years, various models have been proposed to explain the anomaly and it appears that new interactions involving an axial vector boson appear to explain the anomaly after satisfying all the experimental constraints.

The Lagrangian of such interaction is given by

$$\mathcal{L} = \epsilon_p \bar{p} \gamma^\mu \gamma^5 p X_\mu + \epsilon_n \bar{n} \gamma^\mu \gamma^5 n X_\mu. \quad (1)$$

Production of X —We utilize the neutron flux produced at the target when the ~ 1 GeV proton beam hits the target. The neutron that arrives at the CCM detector and PIP2-BD detector is shown in Fig. 1. The CCM flux is computed using the MCNP simulation incorporating the target geometry which matches with the experimental data [21]. The neutron flux at PIP2-BD is assumed to be scalable from CCM by distance and POT (protons on target).

In CCM and PIP2-BD experiments, the neutron excites the oxygen in the PMT glass window [22]. The PMT glass window is made of borosilicate glass (SiO_2), in which ^{28}Si does not have any excitation levels above 17 MeV in current experiments, while ^{16}O has several levels above 17 MeV [23]. X can be produced during the deexcitation of the

nucleus. The excited nuclei decay to the ground state and emit a photon or X . Shortly after X is produced, it decays to $e^\pm$, which will be detected by the PMT dynode. The production and decay of X is as follows:

$$n + \mathcal{N} \rightarrow n + \mathcal{N}^* \quad (2)$$

$$\mathcal{N}^* \rightarrow \mathcal{N} + \gamma/X \quad (3)$$

$$X \rightarrow e^+ + e^-, \quad (4)$$

where $\mathcal{N} = ^{16}\text{O}$.

The minimum of opening angle of $e^\pm$ is given by

$$\theta_{\pm}^{\min} \approx \cos^{-1}(2v_X^2 - 1), \quad (5)$$

where v_X is velocity of X boson. The opening angle is generally close to π , which induces a unique signature of the X boson. This unique signature enhances background subtraction and thus improves the sensitivity of the search.

Benchmark experiments—CCM makes use of a 0.8 GeV proton beam (0.29 μs wide, 20 Hz frequency) impinging on a tungsten target, which produces 5.6×10^{14} POT per second. Currently, CCM is operating a ten-ton (seven-ton fiducial) LAr detector, located 20 meters away from the target. The proton beam impinging on the tungsten target produces a large amount of neutrons (about 20 neutrons per proton). To reduce the neutron and random backgrounds for the primary physics goals, CCM has concrete and steel shielding surrounding the LAr detector. This reduces the neutrons from the target, which will negatively impact the ATOMKI analysis. The neutron flux after shielding is shown in Fig. 1.

PIP2-BD at Fermilab [17,24,25] is a future experiment and will use a 2 GeV proton beam (2 μs wide, 120 Hz frequency) impinging on a light target such as carbon. A 100-ton LAr detector with a 20 keV threshold will be located at different distances, 15 m or 30 m, from the target. Similar experiments are also being proposed at LANL.

Analysis— X boson flux ϕ_X can be calculated from the transition lines of the nucleus $\mathcal{N} = ^{16}\text{O}$ as follows:

$$\phi_X = \phi_\gamma \frac{\Gamma_X}{\Gamma_\gamma}, \quad (6)$$

where Γ_γ and Γ_X are decay rates for $\mathcal{N}^* \rightarrow \mathcal{N} + \gamma$ and $\mathcal{N}^* \rightarrow \mathcal{N} + X$, respectively. Decay rates Γ_X for 1^+ states and 1^- states are given by [8]

$$\begin{aligned} \Gamma_X^{J=1^+} &= \frac{p_X}{18\pi} \left(2 + \frac{E_X^2}{m_X^2} \right) |\langle \epsilon_p \hat{\sigma}^p + \epsilon_n \hat{\sigma}^n \rangle|^2 \\ &= \frac{p_X}{18\pi} \left(2 + \frac{E_X^2}{m_X^2} \right) (\epsilon_p + \epsilon_n)^2 |\langle \hat{\sigma} \rangle|^2 \end{aligned} \quad (7)$$

TABLE I. Summary of variables in Eq. (9).

Variable	Definition	CCM	PIP2-BD
ϕ_n	Neutron flux	$\mathcal{O}(10^{-4}) - \mathcal{O}(1) \text{ cm}^{-2} \text{ s}^{-1}$	
σ_n	Neutron cross section	$\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-2}) \text{ barn}$	
M_s	PMT glass molar mass	60.08 (SiO ₂)	
n	Number of nucleus per molecule	2 (SiO ₂)	
w	PMT glass window weight	130 kg	841.1 kg
Γ_{tot}	$\mathcal{N}^* \rightarrow \mathcal{N} + \text{any}$: Total decay width	$\mathcal{O}(10) - \mathcal{O}(10^2) \text{ keV}$	
Γ_γ	$\mathcal{N}^* \rightarrow \mathcal{N} + \gamma$: Photon decay width	$\mathcal{O}(10^{-2}) - \mathcal{O}(10^{-1}) \text{ keV}$	
N_A	Avogadro constant	6×10^{23}	

$$\Gamma_X^{J=1^-} = \frac{p_X^3}{144\pi} (\epsilon_p - \epsilon_n)^2 |\langle \widehat{D}_3^\sigma \rangle|^2, \quad (8)$$

where $\hat{\sigma}$ is spin operator and $\widehat{D}_3^\sigma$ is isovector axial spin dipole. We assume isosymmetry, i.e., $\hat{\sigma}^p = \hat{\sigma}^n$. Refer to the Appendix A and B for derivation.

The photon flux, ϕ_γ , is calculated from the inelastic neutron scattering is given as

$$\phi_\gamma = nw \frac{N_A}{M_s} \frac{\Gamma_\gamma}{\Gamma_{\text{tot}}} \int \sigma_n(E_n) \frac{d\phi_n}{dE_n} dE_n, \quad (9)$$

where Γ_γ is with a certain excited state of $\mathcal{N}$. The detailed definitions and values of the other variables are described in Table I. Note that Γ_γ cancel out by combining Eqs. (6) and (9) and that the X boson flux is independent of the photon decay branching ratio ($\Gamma_\gamma/\Gamma_{\text{tot}}$) but dependent on the total decay width Γ_{tot} .

Nuclear physics—Given that X boson is spin-1 and ^{16}O ground state is spin-0, the nuclear excited states must be spin-1. The energy of excited states must also be at least 17 MeV due to the mass of X . Both positive and negative parities are feasible. We consider up to ~ 23 MeV of state energy since the higher energy states would likely have lower neutron cross section. All the available states [23,26] are summarized in Table II.

We perform a large-scale shell model (LSSM) to compute the strength $|\langle J_i | \hat{O} | J_f \rangle|^2$ using the code BIGSTICK [27,28]. The YSOX interaction [29,30] is exactly diagonalized within full psd model space. Spin operator $\hat{\sigma}$ (1^+ states) is relatively easy to calculate. However, the computation of $\widehat{D}_3^\sigma$ (1^- states) is challenging for ^{16}O . The energy gaps between the states are small in both of shell model calculation and experimental measurement, so it's difficult to uniquely identify the mapping of a calculated state to a measured state. Hence, some 1^- ^{16}O states share the same calculated $\widehat{D}_3^\sigma$ strength.

Neutron cross section—We calculate the cross section of inelastic neutron scattering reactions $^{16}\text{O}(n, n')$ using the state-of-the-art coupled-channels Gamow shell model (GSM-CC) [31,32]. Employing the core + valence

configuration-interaction framework, the GSM-CC approach is the tool par excellence for studies of both nuclear structure and reaction observables at the same time. In this Letter, the ^{12}C core for target nucleus ^{16}O is mimicked by a Woods-Saxon potential, and the interaction among valence nucleons is modeled through the Furutani-Horiuchi-Tamagaki (FHT) nuclear interaction [32–34], in which the Coulomb interaction is added for protons.

To investigate uncertainties due to nuclear Hamiltonians, we perform three different GSM-CC models for $^{16}\text{O}(n, n')$ calculations. For the $^{16}\text{O}(n, n')$ reaction, the first was established from Ref. [32], which has been successfully used for the description of the reaction $^{15}\text{O}(p, p)$ and $^{14}\text{O}(p, p)$. In this calculation, neutron psd partial waves are represented using the Berggren basis, which treats bound states, unbound resonant states, and nonresonant continuum states on an equal footing. While the harmonic oscillator (HO) states are used for the proton psd partial waves. Details of the calculation are similar to those elaborated in Ref. [32]. The second is based on the psd -shell GSM interaction [35]. It gives comprehensive studies of structure and reactions aspects of nuclei from the psd region of the nuclear landscape. The third one fits low-lying

 TABLE II. Available nuclear states, where $\hat{O}$ is the nonvanishing operator in the X decay rate. $|\langle J_i | \hat{O} | J_f \rangle|^2$ is computed by shell model, the other columns are experimental measurements. $|\langle J_i | \hat{\sigma} | J_f \rangle|^2$ is dimensionless, and $|\langle J_i | \widehat{D}_3^\sigma | J_f \rangle|^2$ is in MeV^{-2} .

Nucleus	Energy [MeV $\pm$ keV]	J^π	Γ_{tot} [keV]	$\hat{O}$	$ \langle J_i \hat{O} J_f \rangle ^2$
^{16}O	17.09 ± 40	1^-	380 ± 40	$\widehat{D}_3^\sigma$	7.29310×10^{-6}
^{16}O	17.14 ± 10	1^+	34 ± 3	$\hat{\sigma}$	0.042008
^{16}O	17.282 ± 11	1^-	78 ± 5	$\widehat{D}_3^\sigma$	7.29310×10^{-6}
^{16}O	18.79 ± 10	1^+	120 ± 20	$\hat{\sigma}$	0.011664
^{16}O	19.47 ± 30	1^-	200 ± 70	$\widehat{D}_3^\sigma$	2.38115×10^{-5}
^{16}O	20.945 ± 20	1^-	300 ± 10	$\widehat{D}_3^\sigma$	3.02156×10^{-6}
^{16}O	22.15 ± 10	1^-	680 ± 10	$\widehat{D}_3^\sigma$	1.87670×10^{-6}
^{16}O	22.89 ± 10	1^-	300 ± 10	$\widehat{D}_3^\sigma$	1.87670×10^{-6}

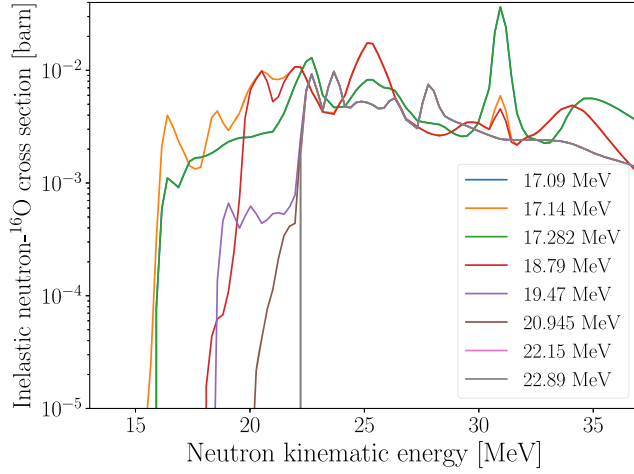


FIG. 2. Inelastic neutron-nucleus cross section for ^{16}O . The labels indicate the energy of the state.

spectra of $^{13-15}\text{C}$, $^{13-16}\text{N}$, $^{14,15}\text{O}$ and $^{15,16}\text{F}$, and includes the *sdpf* partial waves [36].

The results of neutron cross section among different shell models we calculate are consistent and within one order of magnitude of each other. However, these different GSM-CC calculations still have discrepancies with experimental measurements for the high excitation energies relevant to this Letter. To incorporate this uncertainty into the neutron cross section, we set an energy tolerance (e.g., ± 3 MeV) for each experiment state. The calculated states which have the matching parity and stay within the tolerance are selected. Finally, the neutron cross section of the experiment state is the maximum of the calculated cross sections of the selected states, as shown in Fig. 2.

Parameter space search—Summing over the states in Table II, the expected number of X boson events,

$$N_X = \Delta T \sum_i \phi_X^i, \quad (10)$$

where ΔT is the observation time, ϕ_X^i is X flux produced by nuclear state i .

We investigate the X boson in CCM and PIP2-BD. CCM has 200 PMTs (total of 69.33 kg of oxygen in the 130 kg of glass), 7.5×10^{21} POT per year, and has begun a three year run ending in 2025. PIP2-BD has 1,294 PMTs, 9.9×10^{22} POT per year, and plans to run for at least five years. The PMT e^+e^- signal deposits most of its energy as scintillation light in the glass, producing events with very unique reconstruction signatures. CCM data analysis has shown that the scintillation backgrounds above ten MeV similar to e^+e^- signal process is small [15]. However, it is prudent to further reduce the backgrounds from the many neutron inelastic scattering channels producing protons, deuterons, alpha particles on oxygen, and other *in situ* materials and contaminants. To achieve this reconstruction of the opening angle and energy of the e^+e^- pair from the X decay would

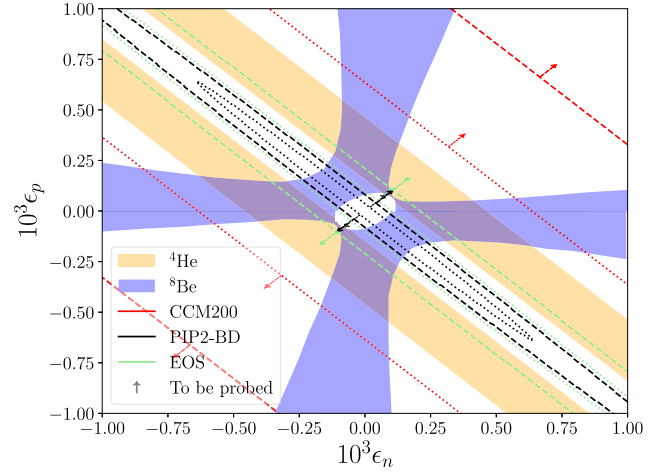


FIG. 3. The disallowed space (indicated by arrows) of ATOMKI for 2.3 events (dotted line) and ten events (dashed line) for CCM (red), PIP2-BD (black), and EOS (green). The color shaded region is the allowed space of ^4He (yellow) and ^8Be (blue). ϵ_p and ϵ_n are coupling of X boson to proton and neutron, respectively.

enable determination of the invariant mass, further restricting the backgrounds. Reconstruction of the invariant mass in the PMT glass will be difficult since the geometry of the e^+e^- interaction is not ideal, with a high probability of one of the leptons escaping the glass without depositing much energy. To improve invariant mass reconstruction, we plan to deploy a low contaminate solid spherical piece of pure glass with a weight on the order of 130 kg (similar to all the PMT glass) at the center of the CCM detector. This will provide a much more favorable e^+e^- geometry to reconstruct the lepton pair opening angle and individual energies (see Appendix C). Recent work on CCM has shown the ability to reconstruct Cherenkov light down to a $\sim\text{MeV}$ for γ rays from a Na-22 source [37], which will further improve invariant mass reconstruction. The reconstruction of Cherenkov light is critical to reconstruct the individual e^+e^- energies and angle in order to reconstruct the invariant mass. A benefit of using Cherenkov light reconstruction is that it rejects final state backgrounds from neutron inelastic scattering which only produces scintillation light. Figure 3 shows the limits of our model on the ATOMKI anomaly at CCM and PIP2-BD with 2.3 and 10 signal events. The shaded region (blue and orange) emerges from the ATOMKI signal associated with ^8Be and ^4He , respectively [8]. It's worth mentioning that it's challenging to simultaneously fit all examined nuclei (^{16}O , ^8Be , and ^4He) due to the uncertainties of nuclear physics such as energy, transition strength, and operator matrix element. We find that CCM investigates the parameter space associated with the signal in a complementary way and a large portion of the parameter space will be probed. The proposed PIP2-BD detector would cover the remaining available parameter space. Finally, sensitivities are also shown for the five-ton

water (H_2O) based EOS detector [18], assuming it is situated at Lujan at the same distance and collects that same POT as CCM. EOS will have excellent Cerenkov light reconstruction and better X particle invariant mass reconstruction than CCM. With the increase in target mass, the sensitivities for EOS will be orders of magnitude better and will cover almost the entire parameter space.

Conclusions—We investigated the ATOMKI anomaly in a novel way in stopped pion facilities, e.g., ongoing CCM, planned PIP2-BD, and EOS. We take advantage of the neutrons produced when the proton beam with ~ 1 GeV hits the target. Neutrons are usually treated as background. However, to address the ATOMKI anomaly, we utilize these neutrons, which arrive at the detector. The neutrons inelastically scatter, excite the nucleus in the PMT glass, and produce the X boson which quickly decays into a pair of e^+e^- . We calculate the neutron-oxygen inelastic cross sections using the neutron energy spectra at CCM. The nuclear shell model produces a reliable estimation of neutron cross section. Using the calculations of the shell model along with the experimental measurements of the strengths, we can estimate the flux of the X boson from nuclear deexcitation processes. We perform the searches in ongoing and future experiments. The ongoing experiment, CCM, excludes a large area of signal parameter space, while future PIP2-BD and EOS experiments can exclude the remainder of the available parameter space. Beyond the investigation of the ATOMKI anomaly, the production of a X boson with mass $\lesssim 20$ MeV from the inelastic scattering of neutrons can be used to investigate various low-scale models.

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End Matter

Appendix A: Multipole expansion—Nuclear X decay rate (Eq. (3)) can be characterized by nuclear matrix element

$$\Gamma_X = |\langle J_f, X | \hat{H} | J_i \rangle|^2 = \int d^3\vec{r} \epsilon_a^\mu(\vec{q})^* \mathcal{J}_\mu(\vec{r}) e^{-i\vec{q}\cdot\vec{r}}, \quad (\text{A1})$$

where q/α are momentum/polarization, J_i/J_f are initial/final nuclear state. We can expand Eq. (A1) by Wigner-Eckart theorem and multipole operators, which are defined by

$$\hat{\mathcal{M}}_{JM} = \int d^3x [j_J(qx) Y_{JM}(\Omega_x)] \hat{\mathcal{J}}_0(x) \quad (\text{A2})$$

$$\hat{\mathcal{L}}_{JM} = \frac{i}{q} \int d^3x [\nabla [j_J(qx) Y_{JM}(\Omega_x)]] \cdot \hat{\mathcal{J}}(x) \quad (\text{A3})$$

$$\hat{\mathcal{T}}_{JM}^{\text{el}} = \frac{1}{q} \int d^3x [\nabla \times j_J(qx) \mathbf{Y}_{J1}^M(\Omega_x)] \cdot \hat{\mathcal{J}}(x) \quad (\text{A4})$$

$$\hat{\mathcal{T}}_{JM}^{\text{mag}} = \int d^3x [j_J(qx) \mathbf{Y}_{J1}^M(\Omega_x)] \cdot \hat{\mathcal{J}}(x), \quad (\text{A5})$$

where $j_J(qx)$ are Bessel functions, $Y_{JM}(\Omega_x)$ are spherical harmonics, and $\mathbf{Y}_{J1}^M(\Omega_x)$ are vector spherical harmonics. Thus Eq. (A1) reads

$$\Gamma_X = \frac{2q}{2J_i + 1} \left\{ \sum_{J \geq 0} \left| \langle J_f | \left[\frac{q}{m} \mathcal{M}_J - \frac{\omega}{m} \mathcal{L}_J \right] | J_i \rangle \right|^2 + \sum_{J \geq 1} \left[|\langle J_f | \mathcal{T}_J^{\text{el}} | J_i \rangle|^2 + |\langle J_f | \mathcal{T}_J^{\text{mag}} | J_i \rangle|^2 \right] \right\}. \quad (\text{A6})$$

Appendix B: Long wavelength limit—Expanding the multipole operators in terms of transfer momentum q ,

$$\mathcal{M}_{JM} \simeq \frac{q^J}{(2J+1)!!} \int d^3x x^J Y_{JM} \mathcal{J}^0(\vec{x}) \quad (\text{B1})$$

$$\mathcal{L}_{JM} \simeq \frac{-iq^{J-1}}{(2J+1)!!} \int d^3x x^J Y_{JM} \nabla \cdot \vec{\mathcal{J}}(\vec{x}) \quad (\text{B2})$$

$$\mathcal{T}_{JM}^{\text{el}} \simeq \frac{-iq^{J-1}}{(2J+1)!!} \sqrt{\frac{J+1}{J}} \int d^3x x^J Y_{JM} \nabla \cdot \vec{\mathcal{J}}(\vec{x}) \quad (\text{B3})$$

$$\mathcal{T}_{JM}^{\text{mag}} \simeq \frac{iq^J}{(2J+1)!!} \sqrt{\frac{J+1}{J}} \int d^3x \times \left[\frac{1}{J+1} \vec{x} \times \vec{\mathcal{J}}(\vec{x}) \right] \cdot \nabla x^J Y_{JM}. \quad (\text{B4})$$

In long wavelength limit ($q \rightarrow 0$), the multipole operators are approximated by

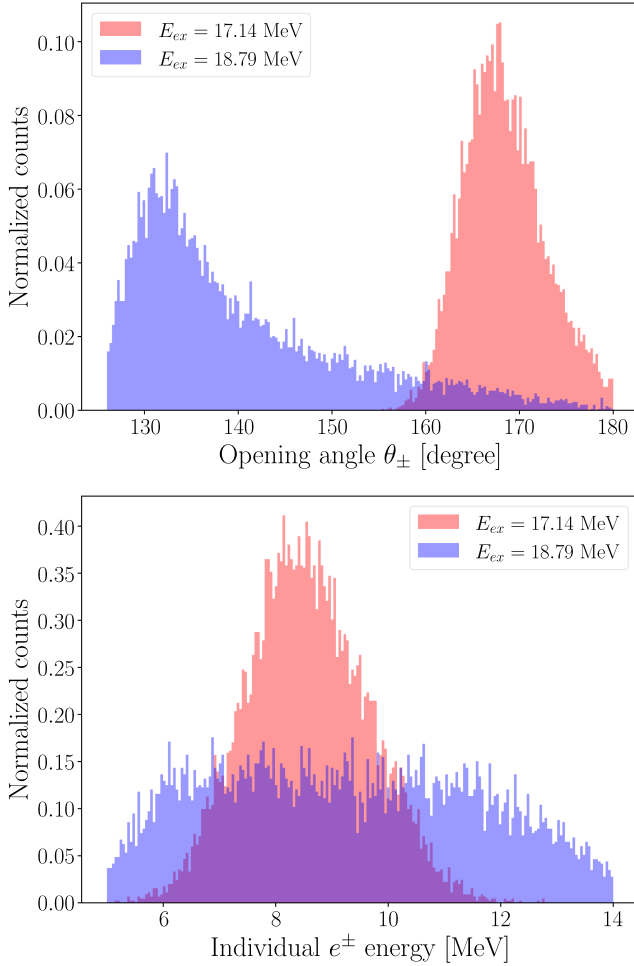


FIG. 4. Angle (top) and energy (bottom) spectrum of individual $e^\pm$ from a decaying X boson produced by nuclear state $E_{ex} = 17.14$ MeV (red) and $E_{ex} = 18.79$ MeV (blue). The angle and energy are smeared by gaussian with 3 degree and 10% energy width, respectively.

$$\mathcal{M}_{00} \simeq \mathcal{M}_{1M} \simeq 0 \quad (\text{B5})$$

$$\begin{aligned} \mathcal{L}_{00} &\simeq -\frac{iq}{3\sqrt{4\pi}} \sum_s \epsilon_s (\vec{r}_s \cdot \vec{\sigma}_s) \\ &= -\frac{iq}{6\sqrt{4\pi}} [(\epsilon_p + \epsilon_n) \hat{d}_0^\sigma + (\epsilon_p - \epsilon_n) \hat{d}_3^\sigma] \end{aligned} \quad (\text{B6})$$

$$\mathcal{L}_{1M} \simeq \frac{i}{\sqrt{12\pi}} \sum_s \epsilon_s \vec{\sigma}_s \cdot \hat{e}_M = \frac{i}{\sqrt{12\pi}} [\epsilon_p \hat{\sigma}_M^p + \epsilon_n \hat{\sigma}_M^n] \quad (\text{B7})$$

$$\mathcal{T}_{1M}^{\text{el}} \simeq \frac{i}{\sqrt{6\pi}} \sum_s \epsilon_s \vec{\sigma}_s \cdot \hat{e}_M = \frac{i}{\sqrt{6\pi}} [\epsilon_p \hat{\sigma}_M^p + \epsilon_n \hat{\sigma}_M^n] \quad (\text{B8})$$

$$\begin{aligned} \mathcal{T}_{1M}^{\text{mag}} &\simeq \frac{iq}{2\sqrt{6\pi}} \sum_s \epsilon_s (\vec{r}_s \times \vec{\sigma}_s) \cdot \hat{e}_M \\ &= \frac{iq}{4\sqrt{6\pi}} [(\epsilon_p + \epsilon_n) \hat{D}_{0M}^\sigma + (\epsilon_p - \epsilon_n) \hat{D}_{3M}^\sigma]. \end{aligned} \quad (\text{B9})$$

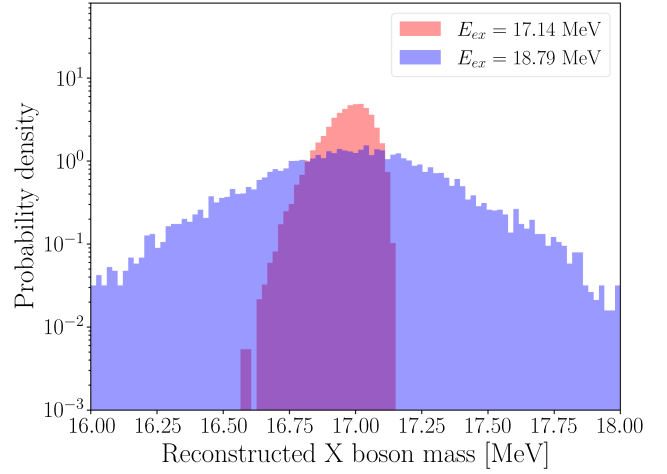


FIG. 5. Reconstructed X boson mass from GEANT simulation in Fig. 4. (10% energy resolution).

One can reproduce Eq. (7) by combining the approximated multipole operators with Eq. (A6) and ignoring high order terms.

Appendix C: Experiment simulation—We perform a simulation of X boson (17 MeV mass) decay inside a 130 kg glass sphere 24 cm in radius at the center of the LAr detector. X boson is produced by nuclear deexcitation from two different energy states: 17.14 MeV and 18.79 MeV. These two states are the most probable transitions as described in Table II. Figure 4 shows the angle and energy spectrum smeared with detector resolution of three degree and 10% energy, respectively, that results from Cherenkov light reconstruction of the individual e^+e^- leptons. X boson generated from the 17.14 MeV nuclear state has lower kinetic energy 0.14 MeV; thus its angle spectrum is closer to back-to-back decay. X boson with 18.79 MeV has 1.79 MeV kinetic energy, so its angle spectrum is farther from back-to-back decay. The unsmeared (i.e., perfect resolution) energy spectrum is flat distribution bounded by the kinematic energy limits (i.e., forward/backward decay). The smearing will make the measured energy outside the limits. Figure 5 uses energy and angle spectrum in Fig. 4 to reconstruct X boson mass m_X . Since $m_X = 17$ MeV is assumed in the simulation, the reconstruct mass spectrum peaks at 17 MeV. Since Cherenkov light is used for reconstruction, backgrounds arising from protons, alphas, deuteriums, etc., generated from neutron scattering are small since they only produce scintillation light. The dominant background will be from mis-ID single electrons or photons from random backgrounds, which, above 10 MeV are shown to be small [15].