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New evidence supporting the existence of the hypothetic X17 particle

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We observed electron-positron pairs from the electro-magnetically forbidden M0 transition depopulating the 21.01 MeV 0^- state in ^{4}He. A peak was observed in their e^+e^- angular correlations at 115° with 7.2σ significance, and could be described by assuming the creation and subsequent decay of a light particle with mass of $m_\mathrm{X}c^2$=16.84$\pm$0.16($stat$) $\pm$ 0.20($syst$) MeV and Γ_X= 3.9×10^{-5} eV. According to the mass, it is likely the same X17 particle, which we recently suggested [Phys. Rev. Lett. 116, 052501 (2016)] for describing the anomaly observed in ^{8}Be.

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Recently, we measured electron-positron angular correlations for the 17.6 MeV, and 18.15 MeV, $\mathrm{J}^\pi = 1^+ \rightarrow J^\pi = 0^+$, M1 transitions in ^{8}Be and anomalous angular correlation was observed [1]. Significant peak-like enhancement of the internal pair creation was observed at large angles in the angular correlation of the 18.15 MeV transition [1]. This was interpreted as the creation and decay of an intermediate particle X17 with mass $m_\mathrm{X}c^2$=16.70$\pm$0.35(stat) $\pm$0.5(sys) MeV. The possible relation of the X boson to the dark matter problem and the fact that it might explain the (g-2)$_\mu$ puzzle, triggered an enhanced theoretical and experimental interest in the particle and hadron physics community [2, 3].

Zhang and Miller [4] investigated the possibility to explain the anomaly within nuclear physics. They explored the nuclear transition form factor as a possible origin of the anomaly, and find the required form factor to be unrealistic for the ^{8}Be nucleus.

The data were explained by Feng and co-workers [5, 6] with a 16.7 MeV, $\mathrm{J}^\pi = 1^+$ vector gauge boson X17, which may mediate a fifth fundamental force with some coupling to Standard Model(SM) particles. The X17 boson is thus produced in the decay of an excited state to the ground state, $^8\mathrm{Be}^* \rightarrow {}^8\mathrm{Be}$ + X17, and then decays through the X17 $\rightarrow e^+e^-$ process.

Constraints on such a new particle, notably from searches for $\pi_0 \rightarrow Z' + \gamma$ by the NA48/2 experiment [7], require the couplings of the Z' to up and down quarks to be protophobic, i.e., the charges $e\epsilon_u$ and $e\epsilon_d$ of up and down quarks, written as multiples of the positron charge e, satisfy the relation $2\epsilon_u + \epsilon_d \leq 10^{-3}$ [5, 6]. Subsequently, many studies of such models have been performed including an extended two Higgs doublet model [8].

At the same time, Ellwanger and Moretti made another possible explanation of the experimental results through a light pseudoscalar particle [9]. Given the quantum-numbers of the ^{8}Be* and ^{8}Be states, the X17 boson could indeed be a $J^\pi = 0^-$ pseudoscalar particle, if it was emitted with L = 1 orbital momentum. They predicted about ten times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV one, which is in nice agreement with our results.

The QCD axion is one of the most compelling solutions to the strong CP problem. There are major current efforts in searching for an ultra-light, invisible axion, but visible axions with decay constants at or below the electroweak scale are believed to have been long excluded by laboratory searches. Considering the significance of the axion solution to the strong CP problem, Alves and Weiner [10] revisited experimental constraints on QCD axions in the O(10 MeV) mass window. In particular, they found a variant axion model that remains compatible with existing constraints. This model predicts new particles at the GeV scale coupled hadronically, and a variety of low-energy axion signatures, including nuclear de-excitations via axion emission. This reopens the possibility of solving the strong CP problem at the GeV scale. Such axions or axion like particles (ALPs) are expected to decay predominantly also by the emission of e^+e^- pairs.

Delle Rose and co-workers [11] showed that the anomaly can be described with a very light Z_0 bosonic state, stemming from the U(1)0 symmetry breaking, with significant axial couplings so as to evade a variety of low scale experimental constraints. They also showed [12] how both spin-0 and 1 solutions are possible and describe the Beyond the Standard Model (BSM) scenarios that can accommodate these. They include BSM frameworks with either an enlarged Higgs, or gauge sector, or both.

In parallel to these recent theoretical studies, we reinvestigated the ^{8}Be anomaly with an improved setup. We have confirmed the signal of the assumed X17 particle and constrained its mass ($m_{\rm X}c^2 = 17.01(16)$ MeV) and branching ratio compared to the γ-decay ($B_x = 6(1) \times 10^{-6}$) [13, 14]. We also re-investigated the e^+e^- pair correlation in the 17.6 MeV transition of ^{8}Be, in which a much smaller deviation was observed [15].

In order to confirm the existence of the X17 particle we have conducted a search for its creation and decay in the 21.01 MeV $0^- \to 0^+$ transition of ^{4}He. Emission of a $m_{\rm X}c^2 = 17$ MeV vector boson ($J\pi$=1^+) or pseudoscalar particle (J^π=0^-) is allowed in this transition with orbital angular momentum 1 or 0, respectively. In this Letter we report on anomalous creation and angular correlation of electron-positron pairs in this transition, which is in good agreement with the scenario of its decay by the assumed X17 particle.

The ^{3}H(p,γ)^{4}He reaction at E_p=900 keV bombarding energy was used to populate the wide ($\Gamma = 0.84$ MeV) 0^- second excited state in ^{4}He [16], located at E_x= 21.01 MeV. This bombarding energy is below the threshold of the (p,n) reaction (E_{thr}=1.018 MeV) and excites the ^{4}He nucleus to E_x=20.49 MeV, which is below the centroid of the wide 0^- state. A proton beam with a typical current of 1.0 μA was impinged on a ^{3}H target. The ^{3}H was absorbed in a 3 mg/cm^2 thick Ti layer evaporated onto a 0.4 mm thick Mo disc. The density of the ^{3}H atoms was 2.66×10^{20} atoms/cm^2. The disk was cooled down to liquid N_2 temperature to prevent ^{3}H evaporation.

The investigated 0^- state overlaps with the first excited state in ^{4}He (J^π=0^+, E_x=20.21 MeV, Γ=0.50 MeV), which was also excited but but give only a managable background to the e^+e^- spectra.

The experiment was performed at the 5 MV Van de Graaff accelerator in Debrecen. Compared to our previous experiment [1, 17], we increased the number of telescopes (from 5 to 6) and we replaced the gas-filled MWPC detectors to a double-sided silicon strip detector (DSSD) array.

The e^+e^- pairs were detected by six plastic scintillator + DSSD detector telescopes placed perpendicularly to the beam direction at azimuthal angles of 0°, 60°, 120°, 180°, 240° and 300°. The sizes of the scintillators are $82\times86\times$ 80 mm^3 each. The positions of the hits were registered by the DSSDs having strip widths of 3 mm and a thickness of 500 μm. The telescope detectors were placed around a vacuum chamber made of a carbon fiber tube with a wall thickness of 1 mm.

γ rays were also detected for monitoring. A ϵ_{rel}=50% HPGe detector was used at 25 cm from the target.

In the investigation of such rare processes, the cosmic ray background needs to be taken into account. The background was measured for two weeks before and after the experiment, and was subtracted out by using the same gates and conditions as for the in-beam data. In order to determine the normalization factor for the subtraction, a gate of 25 MeV $\leq$E(sum)$\leq$ 50 MeV was used to determine the angular correlations of the cosmic rays for both cases (in-beam and off-beam). In this energy range, no in-beam counts were expected. The elimination of cosmic-ray background was then performed until all events disappeared with this high-energy gate.

In order to reduce the cosmic-ray background, an active shield was also installed above the e^+e^- spectrometer. It consisted of 12 pieces of 1.0 cm thick, 4.5 cm wide and 100 cm long plastic scintillators. Half of the cosmic-ray yield could be suppressed in this way.

In the original total energy spectrum of the e^+e^- pairs determined using all combinations of the telescopes we have got a very large background from external pairs created by γ-rays coming from the direct proton capture, which has a cross section of about 2 μb/sr at E_p= 900 keV [18]. In order to reduce the background from the external pair creation, we have created two total-energy spectra. One was constructed from e^+e^- pairs, which were detected by telescope pairs with relative angles of 120°, while the other from e^+e^- pairs which were detected by telescope pairs with relative angles of 60°. Since the e^+e^- pairs from the X17 boson are expected at around 115°, the first spectrum is expected to contain the majority of such events, while the second is expected to be mainly background. To enhance the X17 boson events, we subtracted the second spectrum after appropriate normalization from the first spectrum.

Fig. 1 shows the resulting spectrum of the e^+e^- pairs.

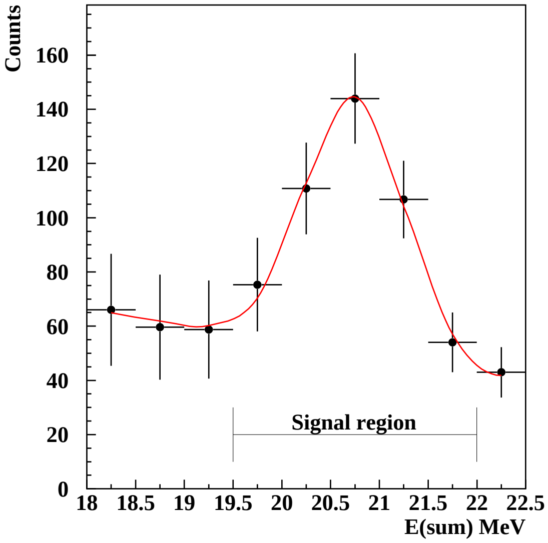

FIG. 1. *Background subtracted total energy spectrum of the e^+e^- pairs.*

The spectrum (black dots with error bars) is originated from the 20.21 MeV E0 transition and from the low-energy part (E_x=20.49 MeV) of the broad 21.01 MeV electro-magnetically forbidden $0^- \to 0^+$ M0 transition in ^{4}He.

The efficiency calibration of the telescopes was performed by using the same dataset but with uncorrelated pairs from consecutive events. Accordingly, an energy-independent efficiency curve could be extracted. The energy dependence of the efficiency calibration was simulated by the GEANT3 code (for the same e^+e^- sum-energy gate as we used in the experimental data reduction) and taken into account as a minor correction on the experimentally determined efficiency curve.

Fig. 2 shows our experimental results (red asterisks with error bars) for the angular correlation of e^+e^- pairs gated by the total energy of the signal region (19.5 MeV$\leq E_{tot} \leq$22.0 MeV), using the asymmetry parameter ($-0.5 \leq y \leq 0.5$) as defined in Ref.[1] and corrected for the relative efficiency of the spectrometer. Black stars with error bars show the angular correlation of e^+e^- pairs for the background region (5 MeV$\leq E_{tot} \leq$19 MeV and $-0.5 \leq y \leq 0.5$).

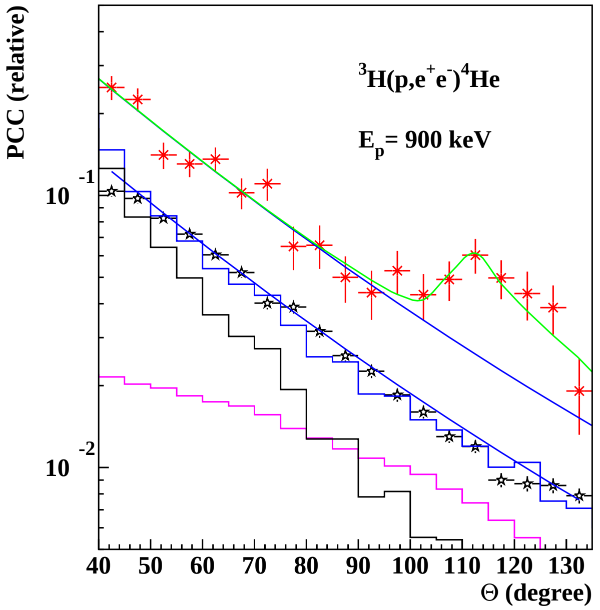

FIG. 2. *Angular correlations for the* e^+e^- *pairs measured in the* $^3H(p,\gamma)^4He$ *reaction at the* E_p*=900 keV.*

According to our simulations such background is originated from external pair creation on the target backing and on the surrounding materials (black histogram) and from the IPC e^+e^- pairs crated in the J$^\pi$=$0^+ \rightarrow 0^+_{gs.}$ E0 transition (magenta histogram). The sum of that two components fitted to the experimental data is shown as a blue histogram. The data measured for the background were fitted by a 4-th order exponential polynomial, and the result is shown in a blue full curve. This blue curve was rescaled to fit the background of the angular correlation shown in red in the range of $40^\circ \leq \theta \leq 90^\circ$. The obtained experimental angular correlation exhibits a rather sharp bump at around 115°. This feature is similar to the anomaly observed in ^{8}Be, and seems to be in agreement with the X17 boson decay scenario. The green full curve shows the simulated angular correlation including the decay of the expected X17 particle, which was fitted to the data. In order to derive the exact value for the mass of the decaying particle from the present data, we carried out a fitting procedure for both the mass value and the height of the observed peak.

The fit was performed with RooFit [19] by describing the e^+e^- angular correlation distribution with the following probability density function (PDF):

$$PDF(e^+e^-) = N_{Bg} * PDF(exp) + N_{Sig} * PDF(sig)\ , \qquad (1)$$

where $PDF(exp)$ was determined experimentally for the background region, $PDF(sig)$ was simulated by GEANT4 for the two-body decay of the X particle as a function of its mass, and N_{Bg} and N_{Sig} are the fitted number of background and signal events, respectively.

The signal PDF was constructed as a 2-dimensional model function of the e^+e^- opening angle and the mass of the simulated particle. To construct the mass dependence, the PDF linearly interpolates the e^+e^- opening angle distributions simulated for discrete particle masses.

Using the composite PDF described in Equation 1 we first performed a list of fits by fixing the simulated particle mass in the signal PDF to a certain value, and letting RooFit estimate the best values for N_{Sig} andN_{Bg}. Letting the particle mass lose in the fit, the best fitted mass is calculated for the best fit and shown also in Fig. 2. in green. The significance of the peak observed in the e^+e^- angular correlations was found to be 7.2σ. The mass of the particle derived from the fit is: $m_X c^2$=16.84$\pm$0.16 MeV.

The partial width of the boson-decay Γ_X from the 0^--state to the ground state is estimated as follows:

$$\Gamma_X/\Gamma_{E0} = \left(\frac{\sigma(X17)}{\sigma(E0)}\right)_{exp.} \left(\frac{\sigma(0^+)}{\sigma(0^-)}\right)_{th} . \qquad (2)$$

The σ(X17)/σ(E0)= 0.20 was obtained from the fit of the simulated e^+e^- angular correlations to our data. The exciataion energy of the nucleus in the case of E$_p$=900 keV is 20.49 MeV. At that energy the contribution of the 0^+ and 0^- resonances are equal, so the ratio of the cross sections in the resonant proton capture reaction could be calculated as follows:

$$\left(\frac{\sigma(0^+)}{\sigma(0^-)}\right)_{th} = \frac{\Gamma_{tot}(0^+)}{\Gamma_{tot}(0^-)} = 0.59. \qquad (3)$$

Since Γ_{E0}=(3.3 $\pm$ 1) $\times$ 10^{-4} is known [20], than Γ_X=0.2 $\times$ 0.59 $\times$ 3.3 $\times$ 10^{-4} = 3.9 $\times$ 10^{-5} eV.

In the case of ^{8}Be it was Γ_X= $\Gamma_\gamma \times B_X$ = 1.9$\times$6$\times$$10^{-6}$ eV = 1.2$\times$$10^{-5}$ eV. This value is indeed expected to be smaller due to the phase space correction factor.

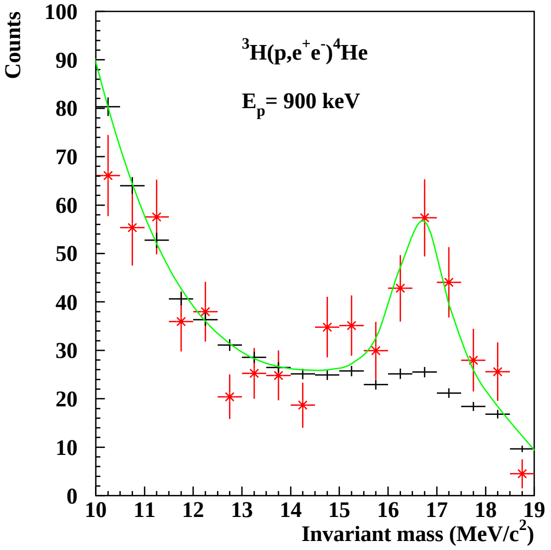

FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in* ^{4}*He.*

The invariant mass distribution was also calculated from the measured energies and angles of the same dataset:

$$m_X c^2 = \sqrt{1-y^2}E\sin(\theta/2) + 2m_e^2\left(1+\frac{(1+y^2)}{(1-y^2)}\cos(\theta)\right),$$

where $E = E_{e^+} + E_{e^-}$ and $y = (E_{e^+} - E_{e^-})/(E_{e^+} + E_{e^-})$. The result is shown in Fig. 3 for the signal (19.5 MeV$\leq E_{tot} \leq$22.0 MeV, in red) and background (5 MeV$\leq E_{tot} \leq$19 MeV, in black) regions.

The observed local p$_0$ probability as a function of m_X, associated to the invariant mass distribution is shown in Fig. 4. It is the probability that the observed excess is due to a statistical oscillation of the background, as defined and used in high energy physics [21].

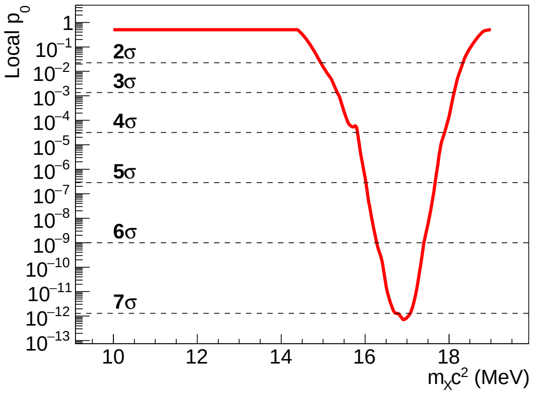

FIG. 4. *The observed local* p_0 *as a function of the hypothesized X17 boson mass for the X17* $\rightarrow e^+e^-$ *channel.*

The significance of the peak observed in the e^+e^- invariant mass distribution was found to be 7.1σ. The mass of the particle derived from the fit is: $m_X c^2$=17.00±0.13 MeV. This value agrees within the erroor bar with the one we derived from the fit of the angular correlation.

The systematic uncertainties was estimated by taking into account the uncertainty of the target position along the beam line, which was estimated to be ± 2 mm, which may cause $m_X c^2$± 0.06 MeV uncertainty. The uncertainty of the place of the beam spot perpendicular to the beam axis was estimated to be in worst case also ± 2 mm, which may cause a shift in the invariant mass of $m_X c^2$± 0.15 MeV/c^2. The whole systematic error was conservatively estimated as: $m_X c^2$±0.20 MeV.

The obtained mass value agrees very well with that of derived for the X17 boson from the ^{8}Be experiments. This is remarkable taking into account the fact that in the present ^{4}He transition the anomalous bump in the angular correlation spectrum appears at a quite different angle than it appears in the ^{8}Be experiments due to the different energies of the two excited states. The good agreement between the two masses leads to the scenario of decaying both studied excited states by the same X17 particle. This strengthens the validity of the X17 boson hypothesis. It is also worth mentioning that strictly speaking it cannot be proved that in the ^{4}He case the anomalous decay belongs to the 21.01 MeV $0^- \rightarrow 0^+$ transition. The wide 20.21 MeV 0^+ first excited state overlaps with the 21.01 MeV 0^- state, and they both were populated in the experiment. However, the anomalous decay of the 0^+ state would result a different new particle than the decay of the 0^- state or the decay of the 1^+ state in the ^{8}Be. Assuming two new particles with the same mass is a less probable scenario than assuming only one X17 particle, which explains both anomalies.

We are expecting independent (particle physics) experimental results to come in the coming years. In the following we cite a few of them.

Recently, the NA64 experiment [22] at CERN presented the first direct search with a 100 GeV/c e$^-$ beam for this hypothetical $m_X c^2$=16.7 MeV boson and excluded part of its allowed parameter space, but left the still unexplored region $4.2 \times 10^{-4} \leq \epsilon_e \leq 1.4 \times 10^{-3}$ as quite an exciting prospect for further research. Experiment will be continued [23, 24].

The goal of ForwArd Search ExpeRiment (FASER) [25] at the LHC is to discover light, weakly interacting particles with a small (1 m^3) detector placed in the far-forward region of ATLAS. In particular, Ariga and his coauthors [26–30] considered the discovery prospects for ALPs. The project has already been approved, and the experiment will start in 2023.

Jiang, Yang and Qiao [31] presented a comprehensive investigation on the possibility of search for the X boson directly in $e^+ - e^-$ collisions, and through the decay of the created J/ψ particles at the BESIII experiment for both spin-0 and spin-1 hypotheses. They suggest that Z_0-like boson signal might be found or excluded in the present run of BESIII. The BESIII experiment has accumulated the largest J/ψ dataset (10^{10} J/ψ events) worldwide. They found that this is an ideal channel to test the spin of the particle. They are expecting $\approx 10^3$ scalar/Z_0-like X bosons when setting the reduced Yukawa coupling parameters to 10^{-3}, which is within the analysis sensitivity of BESIII.

Nardi and coauthors [32] suggested the resonant production of X17 in positron beam dump experiments. They explored the foreseeable sensitivity of the Frascati PADME experiment in searching with this technique for the X17 boson invoked to explain the ^{8}Be anomaly in nuclear transitions. PADME already took some test data and is running until the end of 2019 [33–37]. After that, the experimental setup will be moved to Cornell and/or JLAB to get higher intensity positron beams.

DarkLight will search for 10 - 100 MeV/c^2 dark photons [38]. The sensitivity is projected to reach the ^{8}Be anomaly region. The first beam was already used in summer 2016. Currently, they are doing proof-of-principle measurements [39].

In summary, we have observed e^+e^- pairs from an electro-magnetically forbidden M0 transition depopulating the 21.01 MeV 0^- state in ^{4}He. The energy sum of the pairs corresponds to the energy of the transition. The measured e^+e^- angular correlation for the pairs shows a peak at 115°, supporting the creation and decay of the X17 particle with mass of $m_X c^2$=16.84±0.16($stat$) ± 0.20($syst$) MeV. This mass agrees nicely with the value of $m_X c^2$=17.01 ±0.16 MeV we previously derived in the ^{8}Be experiment [1, 13, 14]. The partial width of the X17 particle decay is esimated to be: $\Gamma_X = 3.9 \times 10^{-5}$ eV. We are expecting more, independent experimental results to come for the X17 particle in the coming years.

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[1] A.J. Krasznahorkay et al., Phys. Rev. Lett. **116**, 042501 (2016).

[2] A. Datta, J. Feng, S. Kamali, J. Kumar, arXiv:1908.08625

[3] http://inspirehep.net/search?ln=en&p=refersto%3-Arecid%3A1358248

[4] Xilin Zhang, Gerald A Miller Phys. Lett. **B773** 159 (2017).

[5] J. Feng et al., Phys. Rev. Lett. 2016 **117**, 071803 (2016).

[6] J. Feng et al. Phys. Rev. **D 95**, 035017 (2017).

[7] J. Batley et al. (NA48/2 Collaboration), Phys. Lett. B 746, 178 (2015).

[8] Luigi Delle Rose et al., Phys. Rev. **D 96**, 115024 (2017) and references therein.

[9] U. Ellwanger and S. Moretti, JHEP 11 39 (2016).

[10] D.S.M. Alves, and N. J. Weiner, High Energy Phys. 92, (2018).

[11] Lugi Delle Rose et al., Phys. Rev. **D 99** 055022 (2019).

[12] Lugi Delle Rose et al., Frontiers in Physics **7** 73 (2019).

[13] A.J. Krasznahorkay et al., J. Phys.: Conf. Series 1056, 012028 (2017).

[14] A.J. Krasznahorkay et al., Acta Phys. Pol. **B 50**, 675 (2019).

[15] A.J. Krasznahorkay et al., Proceedings of Science, (Bormio2017) 036 (2017).

[16] D.R. Tilley, H.R. Weller, G.M. Hale, Nucl. Phys. **A541** 1 (1992).

[17] J. Gulyás et al., Nucl. Instr. and Meth. in Phys. Res. A **808**, 21 (2016).

[18] K.I. Hahn, C.R. Brune, R.W. Kavanagh, Phys. Rev **C 51**, 1624 (1995).

[19] W. Verkerke and D. P. Kirkby, "The RooFit toolkit for data modeling," eConf C **0303241** (2003) MOLT007 [physics/0306116].

[20] Th. Walcher, Phys. Lett. **31B** 442 (1970).

[21] E. Gross, CERN Yellow Reports: School Proceedings, Vol. 4/2017, CERN-2017-008-SP (CERN, Geneva, 2017).

[22] D. Banerjee, et al., on behalf of the NA64 collaboration Phys. Rev. Lett., 120, 231802 (2018).

[23] M. Kisarov., EPJ Web of Conferences 212, 06005 (2019).

[24] D Banerjee, on behalf of the NA64 collaboration, arXiv:1909.04363, 2019.

[25] J. L. Feng, et al., Phys. Rev. D 98, 055021 (2018).

[26] A. Ariga et al., for the PHASER collaboration, arXiv: 1811.10243 (2018).

[27] A. Ariga et al., for the PHASER collaboration, arXiv: 1901.04468 (2019).

[28] A. Ariga et al., for the PHASER collaboration, arXiv:1811.12522 (2019).

[29] A. Ariga et al., for the PHASER collaboration, arXiv:1812.09139 (2019).

[30] A. Ariga et al., for the PHASER collaboration, Phys. Rev. D99, 095011 (2019).

[31] Jun Jiang, Hao Yang, Cong-Feng Qiao, Eur. Phys. J. C79, 404 (2019).

[32] E. Nardi etal., Phys. Rev. D97,095004 (2018).

[33] C. Taruggi, for the PADME collaboration, Frascati Physics Series Vol.67, 17, (2018).

[34] C.D.R. Carvajal, Frascati Physics Series Vol. 67 (2018).

[35] G. Piperno for the PADME collaboration, Journal of Physics: Conf. Series1162 (2019) 012031.

[36] V. Kozhuharov, EPJ Web of Conferences 212, 06001 (2019).

[37] S. Spagnolo on behalf of the PADME Collaboration, Journal of Physics: Conf. Series1137 (2018) 012043.

[38] R.Corliss, DarkLight Collaboration, Nucl. Inst. Meth. 865, 125 (2017).

[39] Y. Wang et al., (DarkLight collaboration) Nuclear Inst. and Methods in Physics Research, A935, 1 (2019).