Search for pseudoscalar bosons decaying into $e^+e^-$ pairs in the NA64 experiment at the CERN SPS

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We report the results of a search for a light pseudoscalar particle $a$ that couples to electrons and decays to $e^+e^-$ performed using the high-energy CERN SPS H4 electron beam. If such light pseudoscalar exists, it could explain the ATOMKI anomaly (an excess of $e^+e^-$ pairs in the nuclear transitions of $^8$Be and $^4$He nuclei at the invariant mass $\approx 17$ MeV observed by the experiment at the 5 MV Van de Graaff accelerator at ATOMKI, Hungary). We used the NA64 data collected in the “visible mode” configuration with a total statistics corresponding to $8.4 \times 10^{10}$ electrons on target (EOT) in 2017 and 2018. In order to increase sensitivity to small coupling parameter $\epsilon$ we also used the data collected in 2016–2018 in the “invisible mode” configuration of NA64 with a total statistics corresponding to $2.84 \times 10^{11}$ EOT. The background and efficiency estimates for these two configurations were retained from our previous analyses searching for light vector bosons and axionlike particles (ALP) (the latter were assumed to couple predominantly to $\gamma$). In this

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work we recalculate the signal yields, which are different due to different cross section and lifetime of a pseudoscalar particle \(a\), and perform a new statistical analysis. As a result, the region of the two dimensional parameter space \(m_a - \epsilon\) in the mass range from 1 to 17.1 MeV is excluded. At the mass of the central value of the ATOMKI anomaly (the first result obtained on the beryllium nucleus, 16.7 MeV) the values of \(\epsilon\) in the range \(2.1 \times 10^{-4} < \epsilon < 3.2 \times 10^{-4}\) are excluded.

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## I. INTRODUCTION

Gauge-singlet pseudoscalar particles have been attracting attention for many years in view of understanding the phenomenology of the strong CP problem (lack of CP violation in QCD) [1–3]. Such particles appear in models with a spontaneously broken global symmetry and are considered as candidates for either dark matter or for mediators to a dark sector (see e.g., Refs. [4–11]).

Previously, a neutral pseudoscalar particle \(a\) decaying to \(e^+e^-\) [12,13] was proposed to explain the ATOMKI anomaly [14–16]. Such particles could also cause a deviation from the expected value of the electron anomalous magnetic moment [17–19].

The NA64 experiment previously derived limits on light vector particles decaying to \(e^+e^-\) [20]. The production cross section and decay width of a pseudoscalar particle differ from the corresponding values predicted for a vector particle with the same mass. In this paper we use the available data of the NA64 experiment and some results of the previous analyses of these data to derive limits on the particle \(a\).

## II. THE SEARCH METHOD

The NA64 experiment in the “visible mode” configuration, i.e., configured for searches for dark matter particles, such as dark photons \(A'\) or \(a\) particles, decaying visibly, into \(e^+e^-\) pairs, is described in Refs. [20,21] and shown in Fig. 1.

The experiment uses the high purity H4 electron beam at the CERN SPS (beam energy 100 GeV in 2017 and 150 GeV in 2018). The backgrounds coming from the beam are further significantly suppressed by using the synchrotron radiation detector (SRD) to identify electrons [22]. This suppression factor for the hadron contamination of the beam is \(\sim 10^{-4}\). The most important subdetectors in this setup are the two electromagnetic (EM) calorimeters; the compact target-calorimeter WCAL assembled from the tungsten and plastic scintillator plates with wavelength shifting fiber read-out and ECAL, a matrix of 6×6 shashlik-type lead-plastic scintillator sandwich modules [22]. We also use a veto counter \(W_2\) placed immediately after the WCAL and a decay counter \(S_4\) installed downstream the vacuum decay tube. Measuring the energy deposition in \(W_2\) ensures that no charged particle exits from the WCAL, while a signal compatible with two minimum ionizing particles (MIPs) in \(S_4\) indicates that a decay to \(e^+e^-\) happened in the decay volume. The high efficiency thick (5 cm) counter VETO and the hadron calorimeter HCAL are installed downstream the ECAL. The HCAL consists of four modules—three of them are placed at the axis of the beam deflected by the MBPL magnets. The fourth module serves as a veto against electro-production of hadrons in the WCAL. The fourth module serves as a veto against upstream interactions of electrons before reaching the target. Some most important distances of the setup are shown in Table 1. The distances in the invisible mode configuration in 2016 and 2017 were slightly different; this was taken into account in the exact signal yield calculation, which can be made only using the detailed simulation.

If the particle \(a\) exists, it would be produced via scattering of high-energy electrons off nuclei of an active target-dump WCAL due to its coupling to electrons \(ee\),

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**FIG. 1.** The NA64 setup to search for \(A'(a) \rightarrow e^+e^-\) decays of the bremsstrahlung \(A'(a)\) produced in the reaction \(eZ \rightarrow eZA'(a)\) of the 150 GeV electrons incident on the active WCAL target. The figure is reproduced from Ref. [20].
where $e$ is the electron charge and $c$ is a coupling parameter [23]. The Lagrangian term corresponding to the coupling with electrons $\psi_e$ is $L \supset -ieca\bar{\psi}_e\gamma\gamma\psi_e$. The $a$ production is followed by its decay into $e^+e^-$ pairs,

$$e^- + Z \to e^- + Z + a; a \to e^+e^-.$$  \hspace{1cm} (1)

The $a$ can be detected if it decays in flight beyond the rest of the dump and the veto counter $W_2$ in the decay volume. The occurrence of the process (1) would manifest itself as an excess of events with two EM-like showers in the setup, with electrons following main criteria:

- $\text{minimized.}$

The cuts used for the event selection are explained in more detail in the previous paper [20].

In order to increase the sensitivity to $a$ at small values of $c$ (below $\sim 2 \times 10^{-5}$), we also used the NA64 data collected in 2016–2018 in the “invisible mode” configuration [24] with only one electromagnetic calorimeter ECAL serving as a target, with an analysis scheme exactly as in our ALP search [25] (the picture of the setup can be found in the same reference). In this method the HCAL is used not only as a veto, but also as a detector of possible $a \to e^+e^-$ decays.

The “invisible mode” configurations are characterized by much longer distance from the creation zone to the end of veto, as can be seen in Table I. However, for small values of $c$ this is not a problem as the particle $a$ is relatively long-lived. There is a significant probability that after its creation in the ECAL and passing the first HCAL1 module serving as a shield/veto it would be observed in the NA64 detector in one of the two signatures: (S1) as an event with $a \to e^+e^-$ decay inside the HCAL2 or HCAL3 modules (HCAL2,3 in the following), or (S2) as an event with a significant missing energy if it decays beyond HCAL2,3. In both cases the main requirements were that the shower profile in ECAL is compatible with electron, the VETO counter signal is smaller than 0.9 MIP and that the energy deposition in HCAL, $E_H \geq 15$ GeV, and that the energy deposition in HCAL1 is smaller than 1 GeV. The main requirements for the signature (S1) event were that the total energy deposition in HCAL $E_H \geq 15$ GeV, and that the energy deposited in HCAL2,3 is concentrated in the central cell [25]. For the signature (S2) the total energy deposition in ECAL was required to be smaller than 50 GeV and the energy in all HCAL modules should be smaller than 1 GeV. There was also a number of other criteria explained in more details for the signature (S1) in [25] and for the signature (S2) in [22,24].

As the event selection was exactly the same as in the previous analyses, we reused the results of the background estimation from them. The main background in the NA64 “invisible mode” configuration comes from the electroproduction of $K^0_S$ and their decays $K^0_S \to \pi^0\pi^0$ in flight, followed by conversion of one of the decay photons.

| Run                  | Beam energy (GeV) | Calorimeter size along the beam (cm) | Distance end of calorimeter–end of veto (cm) | Decay length (m) |
|----------------------|-------------------|--------------------------------------|---------------------------------------------|-----------------|
| 2017 visible mode    | 100               | 17.3                                 | 2.7                                         | 3.12            |
| 2018 visible mode    | 150               | 17.3                                 | 0.6                                         | 3.14            |
| 2018 invisible mode  | 100               | 45                                   | 198                                         | $\approx 3.4$   |

TABLE I. Some parameters and distances of the NA64 experimental setups.
After optimization of the setup in 2018 this background, determined from data, amounted to less than 0.005 events per \(10^{10}\) EOT [20]. The main background in the “invisible mode” configuration comes from neutral hadron production by electrons in the target. These neutral hadrons either pass without interaction the first HCAL module and deposit energy in the downstream modules HCAL2,3, or completely escape detection because of insufficient aperture of the HCAL. These backgrounds, of the order of 0.1 events, were also determined from data [24,25].

### III. SIGNAL YIELD AND RESULTS

In the calculations of the signal yield we used the fully GEANT4 [26] compatible package DMG4 [27]. This package can simulate the production of four types of DM mediator particles in the electron bremsstrahlung processes, including the vector and pseudoscalar cases. It contains a collection of corresponding cross sections, total and differential, including the ones for a pseudoscalar particle \(a\) from the model of Ref. [12]. The total cross sections are calculated at the exact tree level (ETL). We assumed that the \(a\) decay branching ratio to \(e^+e^-\) is 100%.

The package DMG4 was compiled together with the program based on Geant4 for the full simulation of the NA64 experimental setup. The produced signal samples were processed by the same reconstruction program as the real data and passed the same selection criteria. We remind that no candidate events were found in all previously made analyses that we reuse and combine here. For the statistical analysis, there were three main data bins, see Table II. The bins 1 and 3 were further subdivided into bins corresponding to different years and conditions. The total number of bins was up to 9. The backgrounds and various uncertainties in these bins were estimated in the previously published analyses [20,22,24,25] and reused. This concerns also most of the signal yield uncertainties. The uncertainties depending on the \(a\) energy and path to decay distributions were recalculated for the new signal samples, but turned out to be compatible with the values determined previously and remained unchanged. All uncertainties, summed up in quadrature, don’t exceed 20%.

The exclusion limits were calculated by employing the multi-bin limit setting technique in a program based on RooStats package [28] with the modified frequentist approach, using the profile likelihood as a test statistic [29–31]. The 90% C.L. excluded region in the two-dimensional plot \(m_a - \epsilon\) is shown in Fig. 2. The regions excluded by the \((g - 2)_e\) measurements are also shown, the most stringent is LKB [18]. The central value of this measurement has the sign opposite to possible contribution from a pseudoscalar particle \(a\) coupled to electrons. We used a frequentist approach to calculate the 90% C.L. limit from it. We note that the limits from the \((g - 2)_e\) measurements are model dependent and can be significantly less strict in some scenarios [11,32].

![FIG. 2. The 90% C.L. limits on the pseudoscalar particles decaying to \(e^+e^-\) pairs. On the right vertical axis we use the standard notation for the pseudoscalar coupling \(\xi_\epsilon = \epsilon(V/m_e)\sqrt{4\pi\alpha_{QED}}\), where \(V = 246\) GeV is a vacuum expectation value of the Higgs field [33]. This corresponds to the Lagrangian term \(L \supset -i\xi_\epsilon e\bar{\psi}_e \gamma\nu \psi_e\). The red vertical line corresponds to the ATOMKI anomaly at \(m_a = 16.7\) MeV (central value of the first result on beryllium). The \(\epsilon\) range excluded at this mass is \(2.1 \times 10^{-4} < \epsilon < 3.2 \times 10^{-4}\). The region excluded using only the data collected with the visible mode geometry is denoted as “NA64 vis.”, the extension of this region obtained using all data is denoted as “NA64 invis.”. The regions excluded by the \((g - 2)_e\), measurements (Berkley [17] and LKB [18]) are shown. The limits from the electron beam-dump experiments E774 [34] and Orsay [35] are taken from Ref. [33].]
IV. CONCLUSION

We performed a model-independent search for light pseudoscalar particles that couple to electrons and decay predominantly to $e^+e^-$ pairs in the NA64 experiment at the CERN SPS North Area. The active target calorimeter of this experiment was exposed to the electron beams with the energy of 100 and 150 GeV. No signal of such particles was found, allowing us to exclude the region of the $(m_\sigma, \epsilon)$ parameter space in the mass range from 1 to 17.1 MeV. Additional exposure will increase sensitivity, in particular at the mass of the ATOMKI anomaly of 16.7 MeV [36].

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[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
[2] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
[3] F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
[4] R. Essig et al., arXiv:1311.0029.
[5] J. Alexander et al., arXiv:1608.08632.
[6] M. Battaglieri et al., arXiv:1707.04591.
[7] J. Beacham et al., J. Phys. G 47, 010501 (2020).
[8] R. K. Ellis et al., arXiv:1910.11775.
[9] A. Berlin, N. Blinov, G. Krmija, P. Schuster, and N. Toro, Phys. Rev. D 99, 075001 (2019).
[10] E. Aprile et al., Phys. Rev. D 102, 072004 (2020).
[11] D. Buttazzo, P. Panci, D. Teresi, and R. Ziegler, Phys. Lett. B 817, 136310 (2021).
[12] D. S. Alves, Phys. Rev. D 103, 055018 (2021).
[13] U. Ellwanger and S. Moretti, J. High Energy Phys. 11 (2016) 039.
[14] A. J. Krasznahorkay et al., Phys. Rev. Lett. 116, 042501 (2016).
[15] A. Krasznahorkay et al., arXiv:1910.10459.
[16] A. J. Krasznahorkay, M. Csatlós, L. Csige, J. Gulyás, A. Krasznahorkay, B. M. Nyakó, I. Rajta, J. Timár, I. Vajda, and N. J. Sas, Phys. Rev. C 104, 044003 (2021).
[17] R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Müller, Science 360, 191 (2018).
[18] L. Morel, Z. Yao, P. Cladé, and S. Guellati-Khélifa, Nature (London) 588, 61 (2020).
[19] Y. M. Andreev et al., Phys. Rev. Lett. 126, 211802 (2021).
[20] D. Banerjee et al., Phys. Rev. D 101, 071101 (2020).
[21] D. Banerjee et al., Phys. Rev. Lett. 120, 231802 (2018).
[22] D. Banerjee et al., Phys. Rev. D 97, 072002 (2018).
[23] Y.-S. Liu and G. A. Miller, Phys. Rev. D 96, 016004 (2017).
[24] D. Banerjee et al., Phys. Rev. Lett. 123, 121801 (2019).
[25] D. Banerjee et al., Phys. Rev. Lett. 125, 081801 (2020).
[26] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).
[27] M. Bondi, A. Celentano, R. R. Dusaev, D. V. Kirkichnikov, M. M. Kirsanov, N. V. Krasnikov, L. Marsican, and D. Shchukin, Comput. Phys. Commun. 182, 1384 (2011).
[28] T. Junk, Nucl. Instrum. Methods Phys. Res., Sect. A 434, 435 (1999).
[29] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Eur. Phys. J. C 71, 1554 (2011).
[30] A. L. Read, J. Phys. G 28, 2693 (2002).
[31] D. S. Alves and N. Weiner, J. High Energy Phys. 07 (2018) 092.
[32] S. Andreas, O. Lebedev, S. Ramos-Sánchez, and A. Ringwald, J. High Energy Phys. 08 (2010) 003.
[33] A. Bross, M. Crisler, S. Pordes, J. Volk, S. Errede, and J. Wrbanek, Phys. Rev. Lett. 67, 2942 (1991).
[34] M. Davier and H. N. Ngoc, Phys. Lett. B 229, 150 (1989).
[35] E. Depero et al., Eur. Phys. J. C 80, 1159 (2020).