Limits on Axion Couplings from the first 80-day data of PandaX-II Experiment

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We report new searches for the solar axions and galactic axion-like dark matter particles, using the first low-background data from PandaX-II experiment at China Jinping Underground Laboratory, corresponding to a total exposure of about $2.7 \times 10^4$ kg-day. No solar axion or galactic axion-like dark matter particle candidate has been identified. The upper limit on the axion-electron coupling $(g_{\alpha e})$ from the solar flux is found to be about $4.35 \times 10^{-12}$ in mass range from $10^{-5}$ to $1 \text{ keV}/c^2$ with 90% confidence level, similar to the recent LUX result. We also report a new best limit from the $^{57}$Fe de-excitation. On the other hand, the upper limit from the galactic axions is on the order of $10^{-13}$ in the mass range from 1 keV/c$^2$ to 10 keV/c$^2$ with 90% confidence level, slightly improved compared with the LUX.

Various theories beyond the Standard Model have predicted new weakly-coupled light $U_A(1)$ Goldstone bosons $\eta$, which may answer many fundamental questions related to CP violation, possible Lorentz violation, dark matter, etc. The axion, a pseudo-scalar Goldstone boson introduced by Wilczek [10] and Weinberg [11], arises when the so-called Peccei-Quinn symmetry $U_A(1)$ in quantum chromodynamics (QCD) is spontaneously broken, which provides a natural solution to the so-called “strong CP problem” in QCD.

Different experimental methods [12] have been employed to search for the QCD axion or axion-like particles (ALPs), including the helioscopes [13], Light Shining through a Wall [14], microwave cavities [15], nuclear magnetic resonance [16], and the so-called axioelectrical effect [17]. Similar to the photoelectric effect, an axioelectrical effect refers to that an axion or ALP is absorbed by a bound electron in an atom, producing a free electron emission, i.e:

\[ a + e + Z \rightarrow e' + Z. \]  

The cross section for this process is related to that of the photoelectric effect through [18] [19],

\[ \sigma_{\alpha e}(E_A) = \sigma_{pe}(E_A) \frac{g_{\alpha e}^2}{\beta} \frac{3E_A^2}{16\pi \alpha m_e^2} \left(1 - \frac{\beta^2/3}{3}\right), \]  

where $\sigma_{pe}$ is the photoelectric cross section, $g_{\alpha e}$ the coupling constant between the axion and electron, $E_A$ the incident axion energy, $\alpha$ the fine structure constant, $m_e$ the mass of electron, and $\beta = v/c$ the axion velocity. The recoiling electron kinetic energy is $E_A - E_B$, where $E_B$ is the binding energy of the electron. Therefore, the recoiling electron signals (ER) in direct dark matter search experiments can be used to search for axions or ALPs. Previous reports on the axion couplings from dark matter experiments can be found in the Ref. [19] [26].

PandaX, located at China Jinping Underground Laboratory (CJPL), is a series of experiments utilizing the xenon time-projection-chamber detectors. The total mass in the target is about 120 kg in PandaX-I [29] [30], and about 580 kg in PandaX-II [31] [32]. By combining the prompt scintillation photons (S1) and the delayed electroluminescence photons (S2), PandaX has excellent (~cm) vertex reconstruction capabilities, which allow powerful background suppression via self-shielding and fiducialization. To set the scale, the ER background rate in PandaX-II has reached a very low level of $2.0 \times 10^{-3}$ evt/keV/day ($=2.0 \text{ mDRU}$), which makes it a highly sensitive detector to search for axion-electron scattering. In this paper, we report the new constraints on axion/ALP electron coupling strength $g_{\alpha e}$ by using the first low-background data in PandaX-II experiment.
(Run 9) with a total exposure of about $2.7 \times 10^4$ kg-day, one of the largest reported xenon data sets in the world to date.

As in Ref. [31], the Run 9 data was divided into 14 time bins according to the temporal change of detector parameters and background rates. For each event, the electron-equivalent energy $E_{ee}$ was reconstructed from S1 and S2 as

$$E_{ee} = \frac{S1}{PDE} + \frac{S2}{EEE \times SEG},$$

where PDE, EEE, and SEG are photon detection efficiency, electron extraction efficiency, and single electron gain, respectively. Most of the data cuts were identical to those in Ref. [31, 32], except we enlarged the energy window of search by replacing the upper S1 and S2 cuts with a single cut of $E_{ee} < 25$ keV. Based on the tritiated methane (CH$_3$T) calibration, the detection threshold was determined to be 1.29 keV, and in high energy region the detection efficiency was 94%. In total, 942 candidate events survived. The distribution of these events in log$_{10}(S2/S1)$ vs. reconstructed energy is shown in the upper panel in Fig. 1 as the red dots. For comparison, the distribution bands corresponding to the ER calibration data from the tritium with a $\beta$-decay end point at 18.6 keV is overlaid in the figure (shadow dots).

The solar axions may be produced through the following processes [19]: Compton-like scattering (C), axion-Bremsstrahlung (B), atomic-recombination (R), and atomic-deexcitation(D). Given $g_{Ac}$, they can all be calculated.

We took the calculations from Ref. [33] as our input axion spectrum for the axion energy range of $E_A < 10$ keV, which is valid for an axion mass less than 1 keV/$c^2$. As shown in Fig. 2 towards the lower energy (1–2 keV), the flux is dominated by axion-Bremsstrahlung process, and at the high energy region (9–10 keV), by Compton-like scattering.

Additionally, deexcitation of $^{57}$Fe$^+$ may also generated monoenergetic axions, i.e. $^{57}$Fe$^+ \rightarrow ^{57}$Fe + $a + 14.4$ keV [34]. This monoenergetic axion flux at the Earth’s orbit was estimated to be [19, 35]:

$$\Phi_{14.4} = 4.56 \times 10^{21} \cdot (g_{AN}^{eff})^2 \left(\frac{k_A}{k_\gamma}\right)^3 \text{cm}^{-2}\text{s}^{-1} \quad (4)$$

where $k_A/k_\gamma$ is the momentum ratio between the axion and the gamma, and the $g_{AN}^{eff}$ is a model and axion mass-dependent coupling constant between the axion and nucleus. In this work, we took the benchmark function of $g_{AN}^{eff}$ in the so-called Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model as in Ref. [19].

The axion (or ALP) flux from the Milky Way dark matter (MWDM) halo can be estimated as follows. The MWDM density at the Earth location is $\rho_{DM}^{(E)} \approx 0.3$ GeV/cm$^3$ [36]. If all the MWDM is composed of ALPs, the corresponding ALP flux $\Phi_A$ can then be written as

$$\Phi_A = \rho_{DM}^{(E)} \cdot \frac{v_A}{m_A} = 9 \times 10^{15} \frac{\beta}{m_A}, \quad (5)$$

where $v_A$ is the axion velocity relative to the Earth, $m_A$ is the axion mass in unit keV/$c^2$, and $\beta = v_A/c$. Considering the same axion electron scattering mechanism, the
FIG. 2: The expected solar-axion flux at the earth’s orbit deduced from theoretical models [11]. Five mechanisms are considered here: Compton-like scattering (C), axion-bremsstrahlung (B), atomic-recombination (R), and atomic-deexcitation (D). See the text for details. The 14.4 keV line is generated by $^{57}$Fe$^{*}$ deexcitation. In this plot, the corresponding axion parameters are set to be $g_{\text{Ac}} = 10^{-13}$ and $g_{\text{AN}}^{\text{eff}} = 10^{-8}$.

The expected ALP detection rate $R$ can be expressed as [37]:

$$ R \simeq g_{\text{Ac}}^2 \left( \frac{1.2 \times 10^{19}}{A} \right) \left( \frac{m_A}{\text{keV}/c^2} \right) \left( \frac{\sigma_{\text{pe}}}{\text{barn}} \right) \text{kg}^{-1}\text{day}^{-1}, $$

where $A = 131.9$ is the average mass number of the xenon.

PandaX-II data can be fitted by combining the axion signal and background models. The axion or ALP signals are computed by combining incident fluxes above with the axion-electron scattering cross section in Eq. (2). The background estimates are identical to those in Ref. [31], including $^{127}$Xe, $^{85}$Kr and other ER background, accidental, and nuclear recoil (NR) backgrounds. As in Ref. [31], Geant4-based [38] simulation using NEST [39] ER and NR models, together with the efficiencies in S1 and S2, produce the signal and background probability distribution functions in S1 and S2. For illustration, an example axion or ALP signal is overlaid in the lower panel of Fig. 1. For each pair of values of axion mass and $g_{\text{Ac}}$, profile likelihood ratio statistic [40] is constructed. The likelihood function [31] used here is

$$ L_{\text{pandax}} = \prod_{n=1}^{\text{bins}} L_n \times \left[ \text{Gauss}(\delta_{A}, \sigma_{A}) \prod_{b} \text{Gauss}(\delta_{b}, \sigma_{b}) \right], $$

where

$$ L_n = \text{Poisson}(N_{\text{opt}}^{n} | N_{\text{meas}}^{n}) \times \left[ \prod_{i=1}^{N_{\text{opt}}^{n}} \left( \frac{N_{\text{opt}}^{n}}{N_{\text{opt}}^{n}} \right) \left( \frac{(1 + \delta_{A}) P_{A}^{n}(S_{1}^{i}, S_{2}^{i})}{N_{\text{meas}}^{n}} \right) \right] \times \left[ \sum_{b} \frac{N_{b}^{n} (1 + \delta_{b}) P_{b}^{n}(S_{1}^{i}, S_{2}^{i})}{N_{\text{meas}}^{n}} \right]. $$

$N_{\text{opt}}$ is the event number measured experimentally, and $N_{\text{meas}}$ is the expected event number. Axion (or ALPs) and background numbers are represented as $N_A$ and $N_b$. Their probability distribution functions (PDFs), $P_A$ and $P_b$, are generated using NEST-based models. Here background was divided in five independent components, $^{127}$Xe, $^{85}$Kr, other ER, accidental coincidence and neutron. $\sigma$ and $\delta$ are systematic uncertainties and nuisance parameters for individual components with values listed in Ref. [31].

For all channels we considered, data are consistent with no axion signals. For the solar axion from the CBRD mechanisms shown above, the results are presented in Fig. 3 in which the 90% confidence level (CL) is shown as the red solid curve. The upper limit of $g_{\text{Ac}}$ is set to about $g_{\text{Ac}} \leq 4 \times 10^{-13}$ with 90% CL in the axion mass range of $10^{-5} < m_A < 1 \text{ keV}/c^2$, similar to the recent limit from the LUX experiment [26]. Due to the high temperature in the solar core, the axion flux is generally independent of its mass, and the axioelectrical cross section picks up a gentle $\beta$-dependence (Eq. (2)) only when $m_A$ gets closer 1 keV/$c^2$. Therefore, this limit is largely independent of the axion mass. The constraint from the $^{57}$Fe 14.4 keV axion is drawn as red dotted line. The most sensitive upper limit on $g_{\text{Ac}}$ is set at $6 \times 10^{-14}$ at $m_A = 10 \text{ keV}/c^2$, which represents the best such limit to date. The fast decline of sensitivity for lower and higher mass is primarily due to the linear mass dependence of $g_{\text{AN}}^{\text{eff}}$ in the benchmark DSFZ model [11], and the axion momentum dependence in Eq. (4), respectively.

The limits on the galactic ALPs are shown in Fig. 4. The 90% limit to $g_{\text{Ac}}$ is set to be about $\leq 4 \times 10^{-13}$ in the mass range $1 < m_A < 25 \text{ keV}/c^2$. This limit is about 3–10 times improved from the results from XENON100, CDEX-II, and Majorana Demonstrator [22, 25, 27], and slightly improved from the LUX’s recent result [26]. The slightly weakened limit between 4–6 keV/$c^2$ is due to the $^{127}$Xe background in our detector, as shown in the lower panel of Fig. 4.

In summary, using the first low-background dark matter search data from PandaX-II experiment and via the axioelectrical effects, we have set new limits on the axion-electron coupling constant $g_{\text{Ac}}$ for solar axions and galactic ALPs. For the solar axions, the limit $g_{\text{Ac}}$ is $4.35 \times 10^{-11}$ for axion mass between $10^{-5}$ to 1 keV/$c^2$, similar to the recent limits from LUX [26]. Best limit on $g_{\text{Ac}}$ from $^{57}$Fe is also reported, with the lowest exclusion
limit of $6 \times 10^{-14}$ at a mass of 10 keV/c^2. For the galactic ALPs, $g_{Ae}$ is constrained to be $< 4.3 \times 10^{-14}$ (90% C.L.) for an axion mass between 1 to 25 keV/c^2, which represents the strongest constraints to date. PandaX-II will continue taking data, and more sensitive search of axion is expected in the future.

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### FIG. 3:

The 90% upper limits on solar CBRD axion (solid red line) and 14.4 keV/^{13}Fe solar axion in $g_{Ae}$ vs. $m_A$. The constraints from other representative experiments are also shown, including those using solar neutrinos [22], and data from Si(Li) target [43], CDEX-II [22], XMASS [25], EDELWEISS-II [19], KIMS [28], XENON100 [24], LUX [26], MAJORANA Demonstrator [27] (converted to $g_{Ae}$ using the same benchmark DSFZ model values for $g_{AN}^\text{eff}$ as in this paper), and observations of Red Giant [44]. The benchmarks of the QCD axion models, DFSZ [19, 41] and KSVZ (Kim-Shifman-Vainstein-Zakharov) [19, 45], are also displayed.

### FIG. 4:

Constraints on $g_{Ae}$ as a function of MWDM ALP mass. PandaX’s 90% limit is shown as the red curve, with $\pm 1\sigma$ and $\pm 2\sigma$ sensitivity bands in green and yellow respectively. The constraints from other representative experiments are also shown, including those from the solar neutrinos [42], data from CDEX-II [22], CoGeNT [21], CDMS [20], EDELWEISS-II [19], XENON100 [25], LUX [26] and MAJORANA Demonstrator [27].
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