Nuclear Science and Techniques (2023) 34:81
https://doi.org/10.1007/s41365-023-01249-5

RESEARCH HIGHLIGHT

Dark matter is darker

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Published online: 13 June 2023

New results for directly searching for dark matter electromagnetic interactions have been reported by the PandaX Collaboration. The study reveals the most stringent upper limits on dark matter charge radius, millicharge, magnetic dipole moment, electric dipole moment, and anapole moment to date. These findings demonstrate that dark matter is significantly darker than previously anticipated.

Dark matter's existence in the universe has been established through various observations, including galaxy rotation curves, galaxy distributions, and cosmic microwave background radiation [1]. Although astrophysicist Fritz Zwicky first pointed out its existence nearly a century ago [2], the true nature of dark matter particles remains unidentified. As a candidate for dark matter, it is generally assumed that the particles have no interaction with photons. Indeed, if dark matter particles had a similar electric charge to electrons, many observed properties of dark matter in the early and current universe would contradict observations. [1]

On the other hand, dark matter could possess a suppressed interaction with photons, similar to neutrons, which are electrically neutral but still exhibit electromagnetic interactions such as charge radius, magnetic dipole, and anapole moments. This scenario arises in a wide range of models, particularly when dark matter is considered a composite state comprised of charged constituents with a totally neutral charge [3]. Discovering these interactions of dark matter would not only establish the microscopic particle identity of dark matter but also enable measurement of the dark matter composite scale.

In a recent publication in *Nature* [4], the PandaX Collaboration conducted a search for electromagnetic interactions of dark matter using the 0.63-tonne-year exposure during the PandaX-4T commissioning run. The PandaX-4T experiment features a large detector with 3.7 tonnes of liquid xenon and is situated within the China Jinping Underground Laboratory, the world's most well-shielded underground facility, located approximately 2400 ms underground. Due to the weak interactions between dark matter and ordinary matter, dark matter particles can traverse the detector and scatter off charged particles such as nuclei and electrons through potential photon-mediated interactions.

During this scattering process, some nuclei acquire recoil energy, typically on the order of 10 keV for a 100 GeV dark matter mass, derived from the kinetic energy of the dark matter particles. This recoil energy is then converted into prompt scintillation photons (S1). Simultaneously, the surrounding electrons are ionized, drift towards the detector's surface, and generate delayed electroluminescence photons (S2). An illustration of this photon-mediated scattering process and the corresponding dual-phase signature is shown in Fig. 1.

Thanks to the distinctive dual-phase signature, the PandaX Collaboration is able to utilize the two-dimensional distribution of S1 and S2 photon counts to discern between signal and background events. Owing to the reduced capability of nuclear recoils to induce ionizations, the signal events generated by dark matter exhibit smaller S2 signals compared to background events. The two dominant backgrounds, namely flat ER (including β decay of radon, ^{85}Kr, etc.) and tritium, exhibit higher S2 signals. To effectively mitigate background events, the collaboration employs the S2/S1 ratio as a selection variable, leading to a reduction in background events by two orders of magnitude. In the region of interest, there are 1058 events, which aligns with the expected background event count of 1037 ± 45.

While the PandaX-4T experiment has not yet discovered dark matter particles, its results contribute significantly to our understanding of dark matter properties and shed light on the question of "how dark is dark matter?" This article investigates five different photon-mediated interactions

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[1] There is one exceptional situation for superheavy dark matter, where the charge per mass ratio is significantly smaller than that of an electron. In this report and the accompanying paper, the mass of dark matter is assumed to be below a few TeV.

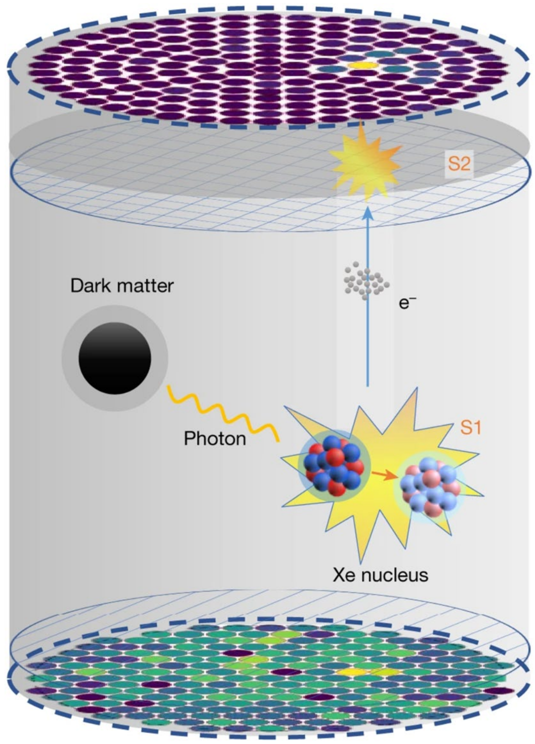

Fig. 1 (Color online) An illustrative plot for the PandaX-4T experiment to search for dark matter (taken from Ref. [4]). A dark matter particle interacts with a xenon (Xe) nucleus through photon-mediated interactions, resulting in a distinctive dual-phase signature within the liquid xenon medium. This signature is characterized by the production of prompt scintillation photons (S1) and delayed electroluminescence photons (S2)

of dark matter, including charge radius, millicharge, magnetic dipole moment, electric dipole moment, and anapole moment. Each interaction exhibits distinct Lorentz-invariant forms and differential event rates as a function of nuclear recoil energy E_{R}. For example, the millicharge interaction follows a $1/E_{\mathrm{R}}^2$ spectrum, while both the magnetic and electric dipole moments follow a $1/E_{\mathrm{R}}$ spectrum. The authors individually examine each dark matter–photon interaction, employing a two-sided profile likelihood ratio to test the signal hypothesis. However, no significant signals above the background are observed. Consequently, upper limits are established on the interaction strengths between dark matter and photons for all five interactions, as presented in Table 1. Additionally, Table 1 includes constraints on the electromagnetic interactions of neutrinos for comparison. Notably, the limits on dark matter's charge radius and electric dipole moment surpass those for neutrinos. This result is particularly remarkable, considering that we have less knowledge about dark matter compared to neutrinos.

Knowledge of the constraints on dark matter's electromagnetic interactions can provide insights into the

Table 1 Constraints on the interactions between dark matter and photons for dark matter masses ranging from 20 to 40 GeV, derived from the PandaX-4T experiment, are presented (taken from Ref. [4])

	Dark matter	Neutrino
Charge radius (fm^2)	$< 1.9 \times 10^{-10}$	$(-2.1, 3.3) \times 10^{-6}$
Millicharge (e)	$< 2.6 \times 10^{-11}$	$< 4 \times 10^{-35}$
Magnetic dipole (μ_{B})	$< 4.8 \times 10^{-10}$	$< 2.8 \times 10^{-11}$
Electric dipole (e cm)	$< 1.2 \times 10^{-23}$	$< 2 \times 10^{-21}$
Anapole (cm^2)	$< 1.6 \times 10^{-33}$	roughly 10^{-34}

For comparison, the corresponding constraints for neutrino are also included

composite scale of dark matter or the mass scale of other charged states within the dark sector. Taking the example of the magnetic dipole moment for a Dirac fermion χ (the dark matter particle), its relativistic interaction with a photon can be expressed as $\frac{e}{2\Lambda}\,\overline{\chi}\,\sigma^{\mu\nu}\chi\,F_{\mu\nu}$, where Λ represents the dark matter composite scale. The constraint on the dark matter's magnetic moment, which is less than 4.8×10^{-10} times the Bohr magneton μ_{B}, can be translated into a lower bound on Λ of $\Lambda > 1.1 \times 10^6$ GeV. Consequently, if dark matter is a composite particle composed of electrically charged constituents, the dynamical scale required for the formation of the dark matter state is approximately 10^6 GeV. This scale is relatively high and lies beyond the reach of other experiments such as the Large Hadron Collider.

In addition to composite dark matter models, electromagnetic interactions of dark matter can also emerge in weakly interacting models like supersymmetry or other dark matter portal models. For instance, in the lepton portal dark matter model [5], the magnetic dipole moment operator takes the form $\frac{e\,\lambda^2\,m_\chi}{16\pi^2\,M^2}\,\overline{\chi}\,\sigma^{\mu\nu}\chi\,F_{\mu\nu}$, where M represents the mass of the charged state in the dark sector and λ denotes a Yukawa coupling among the dark matter, the charged lepton, and the charged dark state. Choosing the dark matter mass $m_\chi = 40$ GeV and $\lambda \sim 1$, the constraint on the dark matter magnetic dipole moment from the PandaX-4T experiment can be translated into a lower bound on M of $M \gtrsim 6 \times 10^4$ GeV. This requirement also surpasses the capabilities of colliders in probing dark matter with masses above one GeV.

In addition to the five dark matter electromagnetic interactions explored in this article, the PandaX Collaboration has the potential to search for other interactions such as dipole transition or Rayleigh interactions [6]. In summary, the publication in *Nature* by the PandaX Collaboration [4] showcases the impressive capabilities of the PandaX-4T experiment in the search for dark matter particles. Even with just the data collected during the commissioning run, the experiment has achieved the most stringent constraints on dark matter electromagnetic interactions to date.

Undoubtedly, when the collaboration completes their full-scheduled science run in the near future, we can anticipate even more significant advancements in our understanding of dark matter.

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