Relativistic capture of dark matter by electrons in neutron stars

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Dark matter can capture in neutron stars and heat them to observable luminosities. We study relativistic scattering of dark matter on highly degenerate electrons. We develop a Lorentz invariant formalism to calculate the capture probability of dark matter that accounts for the relativistic motion of the target particles and Pauli exclusion principle. We find that the actual capture probability can be five orders of magnitude larger than the one estimated using a nonrelativistic approach. For dark matter masses 10 eV–10 PeV, neutron star heating complements and can be more sensitive than terrestrial direct detection searches. Our results show that old neutron stars could be the most promising target for discovering leptophilic dark matter.

In this Letter, we show that despite making up only \(\sim 3 \times 10^{-5}\) of the stellar mass, the electrons in a neutron star are excellent targets for capturing dark matter. Neutron star heating can search for DM masses and couplings to electrons that greatly exceed the limits set by Earth-based direct detection experiments. Electrons in the neutron star are highly degenerate and have Fermi momenta \(p_F = 146\) MeV much larger than their mass \(m_e = 0.51\) MeV. Thus the star’s electrons are ultrarelativistic targets moving in random directions. Further, DM is quasirelativistic as it approaches the neutron star; it is accelerated to the star escape velocity \(v_{\text{esc}} \sim 0.6\). Because each DM–electron center of momentum frame is distinct and highly boosted from the neutron star frame, the capture probability cannot be accurately calculated using the conventional formalism based on the geometric cross section. The invalidity of this nonrelativistic approach for relativistic targets is seen in the frame dependence of the capture probability, which must be Lorentz invariant.

To accurately calculate the capture probability for a quasirelativistic incident DM particle and an ultrarelativistic target electron, it is necessary to specify the key scattering ingredients in different reference frames. The DM–electron scattering cross section is most conveniently expressed in the center of momentum frame of each DM–electron pair; it is non-trivial to obtain an analytical expression by boosting all electron momenta to the neutron star frame. On the other hand, the Fermi–Dirac distributions of targets, essential for estimating the Pauli blocking factor, are best defined in the neutron star frame.

In this work, we develop a manifestly Lorentz invariant formalism to express the capture probability per DM particle in the neutron star in terms of the kinematic ingredients discussed above. It incorporates the Pauli blocking effect and other capture conditions and allows us to integrate over the phase space available for DM scattering and capture. We further apply this formalism to two benchmark DM scenarios and estimate sensitivities on model parameters from neutron star heating. The first one assumes a contact operator to model DM–electron interactions. The second contains a light mediator particle with fixed masses of 1 keV and 1 MeV, well below the Fermi momentum. For completeness, we also present results for DM capture due to nonrelativistic targets available in the neutron star, namely the muon, proton and neutron.

We find that the actual electron capture probability can be a factor of \((p_F/m_e)^2 \sim 10^5\) larger than the estimate using a nonrelativistic approach. For DM masses 10 eV–10 PeV, the neutron star constraints are stronger than current limits from DM direct detection experiments in most of the mass range including the light dark matter regime. In particular, neutron star heating could be the most promising method to discover leptophilic DM. Furthermore, despite the complications of ultrarelativistic scattering kinematics, the sensitivity regions exhibit distinct scaling features that can be understood analytically, demonstrating a rich interplay between kinematics and Pauli blocking that underlies the DM–electron system.

**Lorentz-invariant capture.** A DM particle is bound to a neutron star if it loses its halo kinetic energy \(E_{\text{halo}} = \)
and $m_e v_e^2/2$ by scattering within the star. For $N_{\text{hit}}$ scatters that deposit average energy $\Delta E$, capture occurs when $N_{\text{hit}} \Delta E > E_{\text{halo}}$. We take the DM velocity in the halo to be $v_h = 220 \text{ km/s}$. The rate of kinetic energy deposition is $K = (\gamma x - 1) \dot{M}_x f$, where $\gamma x = (1 - v_{\text{esc}}^2)^{-1/2}$, $\dot{M}_x \sim 10^{33} \text{ GeV/s}$ is the mass capture rate, and $f$ is the probability for a transiting DM particle to capture in the star. This process equilibrates on galactic timescales and the deposited energy is radiated as heat. The resulting blackbody temperature is $T_B \approx 1600 f^{1/4} K$ [25, 26]. For $f = 1$ this is $O(10)$ higher than that of a 10$^9$ year-old neutron star that is not heated by DM [35, 36]. The key step to accurately study DM signals from neutron star heating is to calculate the capture probability per DM particle, $f$.

To develop a formalism for $f$ that is manifestly Lorentz invariant, we first consider the frame-invariant number of scattering events $(d\nu)$ constructed in the DM rest frame in which the cross section and relative velocity can be properly defined [37]:

$$d\nu = (d\sigma \cdot v \cdot d\nu_T \cdot \Delta t \cdot dn_X \cdot \Delta V)_{\text{DM}}, \quad (1)$$

where $d\sigma$ is the cross section, $v$ is the relative velocity, $dn_X, d\nu_T$ are infinitesimal DM and target number densities respectively, $\Delta V$ denotes interaction volume and $\Delta t$ transit time; all evaluated in the DM frame. Since $d\nu$ and $dn_X \Delta V$ are Lorentz invariant, so is their ratio $df = d\nu/\Delta V dn_X = (d\sigma \cdot v \cdot d\nu_T \cdot \Delta t)_{\text{DM}}$, the infinitesimal scattering probability. So we can write $f$ in terms of the corresponding variables in the neutron star frame $df = (d\sigma \cdot v \cdot dn_T \cdot \Delta t)_{NS}$. For a given target momentum $p_\mu = (E_p, \vec{p})_{\text{NS}}$ and DM momentum $k_\mu = (E_k, \vec{k})_{\text{NS}}$ in the neutron star frame, there is a relation, $(d\sigma \cdot v)_{\text{NS}} = (d\sigma)_{\text{DM}} v_{\text{Møl}}$, where $v_{\text{Møl}} = \sqrt{(p \cdot k)^2 - m_e^2 m_f^2/(E_p E_k)_{\text{NS}}}$ is the Møller velocity. From this and using the fact that the cross section is invariant under boost along the collision axis, i.e., $(d\sigma)_{\text{DM}} = (d\sigma)_{\text{CM}}$, where “CM” denotes the center of momentum frame, we obtain an expression for $df$,

$$df = \frac{d\sigma}{d\Omega}_{\text{CM}} d\Omega_{\text{CM}} (v_{\text{Møl}} dn_T \Delta t)_{NS}, \quad (2)$$

where $d\Omega_{\text{CM}} = d\cos \psi da$, for CM polar and azimuthal angles $\psi$ and $\alpha$. Note that the last term in parentheses is Lorentz invariant. For what follows, we will suppress subscript “NS” when referencing a variable in the neutron star frame, except in a few instances to avoid confusion.

**Pauli blocking and phase space.** To evaluate $f$ in Eq. 2 we need to perform the phase-space integral over $d\Omega_{\text{CM}} dn_T$. However, not all parts of the phase space are allowed to interact due to the Pauli exclusion principle, which requires the target particle to be knocked out of its Fermi sea in order to interact. Making use of the Lorentz invariance of $f$, we analyze the Pauli blocking condition in the neutron star frame, where the Fermi surface is spherical. The condition can be expressed in the form of the Heaviside step function $\Theta(\Delta E + E_p - E_f)$, where $E_F$ is the Fermi energy and $\Delta E$ the energy transfer of the target per collision; both of them are in the neutron star frame. Note that $\Delta E$ is related to the momentum transfer in the CM frame $(\vec{q}_{\text{CM}})$ as $\Delta E = \beta_{\text{CM}} \cdot \vec{q}_{\text{CM}} / \sqrt{1 - \beta_{\text{CM}}^2}$, where $\beta_{\text{CM}} = (\vec{p} + \vec{k})/(E_p + E_k)$ is the boost from the neutron star to the CM frame. Finally, we must satisfy the capture condition, $N_{\text{hit}} \Delta E > E_{\text{halo}}$, and vary $N_{\text{hit}}$ to maximize $f$. This accounts for the case when many scatters with smaller $\Delta E$ are more efficient than a single scatter with large $\Delta E$. Putting these together, we have

$$f = \max_{N_{\text{hit}}} \left\{ \frac{N_{\text{hit}}}{N_{\text{hit}}} \int d\Omega_{\text{NS}} \int \frac{d\vec{p}}{V_p} \int \frac{|\vec{p}|^2}{V_{\text{NS}} V_p} [\int d\Omega_{\text{CM}} (d\sigma/d\Omega)_{\text{CM}} \Theta(\Delta E + E_p - E_f) \Theta(\Delta E - E_{\text{halo}}/N_{\text{hit}})] \right\}, \quad (3)$$

where $\langle n_T \rangle$ is the average number density of the target species in the neutron star core, $V_F = 4\pi p_F^3/3$ is the Fermi volume, and $dn_T = |\vec{p}|^2 d|\vec{p}| d\Omega_{\text{NS}}/V_F$. We take $\langle n_T \rangle = 3 M_\star Y_T/4\pi m_n R_\star^3$, where $Y_T$ is the target’s volume-averaged number per nucleon, $M_\star$ is the mass of the neutron star and $R_\star$ its radius. For the constituents $\{e^-, \mu^-, p^+, n\}$, we take their corresponding $Y_T = \{0.06, 0.02, 0.07, 0.93\}$ and Fermi momenta $p_F = \{146, 50, 160, 373\}$ in MeV as predicted in the the Brussels-Montreal model [38]. We take $M_\star = 1.5 M_\odot$ and $R_\star = 12.6 \text{ km}$ to be consistent with [38].

We recover the usual form of $f$ from Eq. 3 for non-relativistic targets. As $p_F \to 0$, the differential cross section becomes independent of $p_\mu$ and $v_{\text{Møl}} \to \beta_X$, also the Pauli blocking step function $\to 1$. These imply $\int |\vec{p}|^2 d|\vec{p}| d\Omega_{\text{NS}}/V_F \to 1 \text{.}$ Assuming that a single scatter deposits at least $E_{\text{halo}}$, Eq. 3 gives $f = \int d\Omega_{\text{CM}} (d\sigma/d\Omega)_{\text{CM}} / (\langle n_T \rangle \beta_{\text{CM}} \Delta t)^{-1}$, a well-known result, where the denominator is the geometric cross section.

**DM model with a heavy mediator.** We apply our framework to estimate sensitivities from neutron star heating for representative DM models and compare them with limits from DM direct detection experiments. We assume the DM candidate is a Dirac fermion ($\chi$) that
FIG. 1. Projected sensitivities from neutron star heating for vectorial interactions of Dirac DM with Standard Model fermions (solid), together with Earth-based direct detection constraints (dashed) [39–46]. Left: A heavy mediator scenario characterized by a cutoff scale \( \Lambda \) for capture by various neutron star constituents. The dotted line shows a non-relativistic calculation that underestimates (overestimates) the sensitivity above (below) the electron mass. Right: A light mediator scenario for the capture by electrons and protons, with sensitivities displayed for the product of the mediator’s couplings to DM and Standard Model fermions. The direct detection constraints here assume that the mediator is massless. In both panels, the colored regions correspond to \( f = 1, \) i.e., \( T_\star = 1600 \) K. Projected sensitivities are stronger if we take lower \( T_\star \).

couples to Standard Model fermions (\( \xi \)) via vectorial interactions. We first assume that the mediator mass is much higher than the relevant scales and use an effective operator, \( \bar{\chi} \gamma^{\mu} \chi (\xi \gamma_{\mu} \xi) / \Lambda^2 \), to parametrize the interaction and determine a lower limit on \( \Lambda \).

Fig. 1 (left) shows our projected sensitivities to the cutoff scale \( \Lambda \) vs the DM mass \( m_\chi \), obtained numerically, for the target fermions \( \xi = e^-, \mu^-, p^+, n \). The upper boundaries correspond to \( f = 1 \), or signal temperature \( T_\star = 1600 \) K. Stronger sensitivities could be obtained for \( f < 1 \), corresponding to smaller \( T_\star \). The dotted blue curve denotes \( f = 1 \) for capture through electrons obtained by (incorrectly) treating them as nonrelativistic. For all targets, there are three distinct regimes. For \( m_\chi \gtrsim 1 \) PeV, the sensitivities decrease as the DM mass increases further. In this region, DM becomes so massive that multiple scatterings (\( N_{\text{hit}} > 1 \)) are required for successful capture, suppressing the capture probability, as indicated in Eq. 3. For \( p_F \lesssim m_\chi \lesssim 1 \) PeV, there are plateaus insensitive to the DM mass. In this mass range, the momentum transfer is typically larger than the Fermi momentum and Pauli blocking is unimportant. In addition, the cross section is almost independent of the DM mass, as we will show later.

To further understand the scaling features in Fig. 1 (left), we explore the scattering kinematics in more detail. The scattering cross section scales as \( (d\sigma / d\Omega)_{\text{CM}} \propto m_\chi^2 E_p^2 / (s \Lambda^4) \), where \( E_p \) is the target energy in the neutron star frame and \( s \) is the Mandelstam variable. In the nonrelativistic limit, \( E_p \approx m_\tau \) and \( s \approx (m_\chi + m_\tau)^2 \), and \( (d\sigma / d\Omega)_{\text{CM}} \) reduces to the well-known form \( (m_\chi m_\tau)^2 / (m_\chi + m_\tau)^2 \Lambda^4 \). The DM energy and momentum in the neutron star frame are \( E_k = \gamma_k m_\chi \) and...
|k| = β_k E_k = β_k γ_k m_χ respectively, where γ_k = 1.24 and β_k = 0.6. For the electrons these are E_ρ ≈ p_F and |p| = p_F respectively, as the electron Fermi momentum 146 MeV is much larger than its mass 0.51 MeV, i.e., electrons in the neutron star are ultrarelativistic.

Consider the heavy DM mass region, where m_χ ≫ p_F and Pauli blocking is unimportant. For the DM–electron system, s = (E_k + E_ρ)^2 − (k + p)^2 ≈ E_ρ^2 − k^2 = m_χ^2. Thus, the scattering cross section scales as \((dσ/dΩ)_\text{CM} \propto p_F^2/m_χ^4\). Compared to the cross section from the nonrelativistic approach in the neutron star frame, \(m_χ^2/4\), the actual cross section is a factor of \((p_F/m_χ)^2 \approx 10^5\) larger. Thus, the actual neutron star sensitivity on Λ is more than one order of magnitude stronger than estimated previously with nonrelativistic approach [32], as indicated in Fig. 1 (left). For the other targets, which are nonrelativistic, \((p_F/m_T)^2 < 1\), therefore the nonrelativistic approximation is valid.

For light DM \(m_χ < p_F\), the reach shown in Fig. 1 scales as \(Λ ≈ m_χ^{1/4}\) for all targets, which can be understood as follows. For the nonrelativistic targets n, p^+, and µ^−, DM energy loss has a weak dependence on the scattering angle, and the Pauli blocking factor scales as \(m_χ\). Moreover, the cross section \(∝ m_χ^2/4\). Thus, the capture probability \(∝ m_χ^3/4\). For the relativistic leptons, \(s = (E_k + E_ρ)^2 − (k + p)^2 ≈ −2k · p \propto m_χ p_F\), resulting in \((dσ/dΩ)_\text{CM} \propto m_χ p_F/m_χ^4\). Since the energy loss only occurs for CM frame forward scatterings in this case, there is an additional suppression in the phase space \(∝ m_χ\), which is not present for the nonrelativistic targets. Thus the Pauli blocking factor scales as \(m_χ^2\), and we again have \(∝ m_χ^3/4\) for the electron target. Note the nonrelativistic approach for electrons overestimates the sensitivity for \(m_χ < m_e\), because it does not take into account the fact that it is much harder to transfer energy to an ultrarelativistic electron than one at rest.

**DM model with a light mediator.** Next, we consider a DM model with a light vector mediator with its corresponding scattering cross section

\[
\left(\frac{dσ}{dΩ}\right)_\text{CM} \propto \frac{g_X^2 g_T^2 m_χ^2 E_ρ^2}{sm_\text{med}} \left(\frac{m_\text{med}}{|k|^2 \text{CM}}\right) \frac{|k|^2 \text{CM} + |q|^2 \text{CM}}{2} \approx \frac{g_X^2 g_T^2 m_χ^2 E_ρ^2}{sm_\text{med}},
\]

where \(g_X, g_T\) are the mediator’s couplings to DM and the target, respectively, and \(m_\text{med}\) is the mediator mass. We take \(m_\text{med} = 1\) keV and 1 MeV, well below the Fermi momentum.

Fig. 1 (right) shows our sensitivities to \(g_X g_T\) for electron and proton targets. For comparison, we include direct detection limits from [39] [10] [42] [15], where the mediator particle is assumed to be massless. Thus, they are conservative estimates for the light-mediator model we consider. Much like the case of the heavy-mediator model, neutron star heating may provide a much stronger probe for a vast range of the DM mass. In particular, neutron stars may provide promising tests for sub-GeV DM, because of the plateau behaviour as we will explain later. For leptophilic DM heavier than 1 TeV, neutron stars can probe up to 100 times smaller \(g_X g_T\) compared to current direct detection bounds.

For both targets, the projected reaches have distinct features in the \(m_χ\) dependence. In particular, the sensitivity curves change their slopes when \(m_χ ≈ m_\text{med}\). On the low mass end, where \(m_χ < m_\text{med}\), the mediator mass dominates over the momentum transfer in the cross section shown in Eq. [4]. Since the mediator mass is also much smaller than the Fermi momentum, this is similar to the heavy-mediator model in the region of \(m_χ ≪ p_F\). Thus, \(f \propto g^2_X g^2_T m_χ^2/s m_\text{med}\) and the reach on \(g_X g_T \propto m_χ^{3/2}\).

For higher DM masses \(m_χ > m_\text{med}\), there are plateaus that are not sensitive to the DM mass. Interestingly, the plateaus DM mass range in this model is much more extended towards the low mass end, compared to the heavy-mediator model. As we discussed before, as \(m_χ\) drops below \(p_F\), Pauli blocking plays a significant role in suppressing the phase space and reducing the capture probability. However, for the light-mediator model, the scattering cross section is enhanced by a small momentum transfer. These two competing effects reach a balance, resulting in the plateaus shown in Fig. 1 (right).

More specifically, we consider the momentum transfer \(|q|^2 \text{CM} = 2|k|^2 \text{CM}(1 − \cos \psi)\), where \(ψ\) is the scattering angle in the CM frame, and expect the balance to be achieved for \(1 − \cos \psi ≈ m_\text{med}/|k|^2 \text{CM}\), as indicated in Eq. [4]. Hence the phase-space integral is \(∫ d\cos ψ′ m_\text{med}/|k|^2 \text{CM}\). The allowed phase space is also suppressed in the magnitude of \(|p|\) as \(|q|^2 \text{CM}/p_F ≈ m_\text{med}/p_F\). Putting these factors together with Eq. [4] we have

\[
f \propto \frac{g^2_X g^2_T m_χ^2 E_ρ^2}{s m_\text{med}} \left(\frac{m_\text{med}}{|k|^2 \text{CM}}\right) \frac{|k|^2 \text{CM} + |q|^2 \text{CM}}{2} \approx \frac{g^2_X g^2_T m_χ^2 E_ρ^2}{s m_\text{med}},
\]

where we use \(s = k^2 \text{CM} ≈ m_\text{med}^2 E_ρ^2\). Thus, \(f\) is not sensitive to \(m_χ\) in this region. As we increase \(m_χ\), the cross section is suppressed by a high momentum transfer, and multiple scatterings become relevant; both effects lead to a small capture probability, resulting in weak reaches.

**Conclusions.** We have studied relativistic capture of DM by electrons in a neutron star and developed a formalism to calculate the capture probability. It is manifestly Lorentz invariant and incorporates relativistic scattering kinematics, Pauli blocking, and the effect of multiple DM–electron scatterings during stellar transit. We further applied the formalism to explore the sensitivities to parameter space of two benchmark DM scenarios and compared them with direct detection limits. The Lorentz-invariant capture probability can be five orders of magnitude larger than the traditional nonrelativistic approach. This makes neutron star heating one of the most promising testing grounds for probing leptophilic DM models. The DM–electron system also
exhibits characteristic features in scattering kinematics that are reflected in our sensitivity curves from our numerical studies. We have provided analytical explanations to the features to further validate our formalism and results. In the future, it would be interesting to apply our formalism to other DM models, especially those with momentum-suppressed interactions and inelastic DM self-interactions, where relativistic scattering kinematics developed in this work is very relevant. Moreover, we may consider exotic matter phases in neutron stars and DM capture in a specific stellar region like the crust. Finally, to implement the proposed searches, the next step will be to investigate the discovery potential of old neutron stars using upcoming radio telescopes and infrared surveys, see, e.g., [50–53].

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