Probing (Light) Dark Matter by Electromagnetic Interactions

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Energy Density of the Universe

The stuff our world is made of...

- Total energy density is critical: $\Omega_{\text{tot}} \lesssim 1$
- Data from CMB, SN1A, baryon genesis and structure formation
- Baryonic matter contributes only $< 5\%$
- 23% contributed by Dark Matter (DM)

$$\Omega_\Lambda \lesssim 72\%, \quad \Omega_{\text{DM}} \lesssim 23\%, \quad \Omega_B \lesssim 4.6\%, \quad \Omega_\gamma \lesssim 0.005\%, \quad 0.1\% \lesssim \Omega_\nu \lesssim 1.5\%$$

Dark Matter from two points of view

- DM is needed in the cosmological Standard Model ($\Lambda$CDM) to explain $\Omega_{\text{tot}}$
- DM appears in particle physics automatically e.g. by attempts to understand the weak scale

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Properties of DM Particles

Basic properties and constraints

- Data for e.g. Big Bang Nucleosynthesis, structure formation and of CMB constrain the wide candidate zoo
- Although baryonic DM is possible (Cold gas, MACHOs), it cannot explain $\Omega_{DM}$ due to contradictions to primordial nucleosynthesis $\Rightarrow$ Need for non-baryonic DM
- DM particles are nonbaryonic, massive, stable, neutral, only interacting by weak interaction and not included in the Standard Model $\Rightarrow$ called WIMPs (Weakly Interacting Massive Particles)
- One has to distinguish between thermal and non-thermal non-baryonic DM relics
  - non-thermal relics created non thermally in e.g. phase transitions (Axions)
  - thermal relics created thermally in the early universe (like WIMPS)
- One must distinguish between hot, warm and cold DM in case of thermal DM
## Dark Matter Candidates

<table>
<thead>
<tr>
<th>Selected DM candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axions</strong></td>
</tr>
<tr>
<td>Introduced in an attempt to solve the strong CP problem (<a href="#">Peccei-Quinn-Weinberg-Wilczek theory</a>); are produced non-thermally; calculation of relic density difficult due to the lack of knowledge of their production mechanism</td>
</tr>
<tr>
<td><strong>Neutrinos</strong></td>
</tr>
<tr>
<td>Although included in the Standard Model of particle physics $\nu$’s were treated as DM candidates (<a href="#">hot DM</a>). Contradictions with structure formation in the early universe and their small mass $\Rightarrow$ cannot explain $\Omega_{DM}$</td>
</tr>
<tr>
<td><strong>WIMPs</strong></td>
</tr>
<tr>
<td>= Supersymmetric candidates (<a href="#">cold DM</a>). Arise from explanations of unsolved weak scale questions. Possible candidates:</td>
</tr>
<tr>
<td>- Lightest Supersymmetric Particle (<a href="#">LSP</a>) = <strong>Neutralino</strong></td>
</tr>
<tr>
<td>- <strong>Gravitino</strong></td>
</tr>
<tr>
<td>- <strong>Axino</strong></td>
</tr>
<tr>
<td>- Dark sector hidden gauge bosons, e.g. <strong>extra $U(1)$</strong> gauge symmetry (Fayet 1980)</td>
</tr>
<tr>
<td>and many other (proposed) particles like <strong>sterile neutrinos</strong> or <strong>light, scalar DM</strong>.</td>
</tr>
</tbody>
</table>
The 511 keV Anomaly

Excess of 511 keV photons

- Excess of 511 keV photons from galactic center caused by $e^+$ annihilations is known for 30 years
- Due to unprecise data a determination of positron sources was not possible
- INTEGRAL data are more precise
- Majority of radiation is emitted from galactic bulge
- Arising question: Can the source of these positrons now be determined?

"Usual" explanations of 511 keV anomaly

- Possible sources of the positrons e.g. are radioactive nuclei from supernovae, gamma-ray bursts, pulsars, black holes or cosmic ray
- Problem: predictions for possible astrophysical source candidates do not reconcile the data
- Other approaches are needed

The LDM Model

Light Dark Matter as possible explanation

- "Exotic" approaches to explain the 511 keV line are motivated by the INTEGRAL data like low-mass X-ray binaries, decaying axinos, dark energy stars or even Light Dark Matter (LDM) (Boehm, Fayet 2004)
- Decay $\text{LDM} \rightarrow e^+e^-$ can explain INTEGRAL observations, as long as DM particles are light, i.e. with mass smaller than 100 MeV
- INTEGRAL data give constraints to LDM ($M_\chi \leq 3 - 20$ MeV) and allow a precise determination of the annihilation cross section
- Model is "easiest exotic" explanation of 511 keV line

LDM particles

- LDM consists of light ($m_\chi \leq 1 - 10$ MeV), neutral, scalar particles $\chi$
- Interaction between LDM and Standard Model matter like electrons is mediated by a light ($2$ MeV $\lesssim m_U \lesssim 100$ MeV), neutral vector boson $U$, which major decay channel is $\chi\chi^*$ or a heavy fermion $F^\pm$ with mass $M_F >$ several 100 GeV also necessary

The LDM Model

LDM processes

\[ \chi^* \rightarrow e^+ \]
\[ \chi \rightarrow e^- \]

**Exchange** of heavy fermion \( F^\pm \)
But: **Negligible** since an s-wave suppressed annihilation cross-section is needed (Boehm et al. 2004)

\[ \chi^* \rightarrow C \chi \rightarrow f_e \]
\[ \chi \rightarrow U \rightarrow e^+ \rightarrow e^- \]

**Exchange** of light vector boson \( U \)

⇒ In our computations only \( U \) boson exchange will be taken into account

Probing Light Dark Matter in the lab?

Experimental ideas for LDM search

- Heinemeyer 2007: propose experiment to search for Light Dark Matter with "ordinary" accelerators for electron-proton scattering:
  - Collide electron beam with proton target, i.e. electron-proton scattering at very low energies \( \sim 40 \text{ MeV} \ll m_\pi \)
  - Observables: electron energy, electron scattering angle, proton scattering angle
  - LDM effects shall appear in a particular kinematical region in which elastic scattering signal and QED radiation signals are not too strong
  - Particular experimental properties will allow identification of LDM particles

- Estimates are done by Heinemeyer et al. for phase space distribution and particular cross section

The process $ep \rightarrow epU$

### Basic Properties

- **Background process** of elastic electron proton scattering
- Indeed the process $e\,p \rightarrow e\,p \,U^* \rightarrow e\,p\,\chi\,\chi^*$ occurs, but **LDM particles will not be detected**.
- Feasibility studies for possible measurement at facilities like **MAMI@Mainz** shall investigate this.
- Can be treated analogously to well known **Bethe-Heitler process** ⇒ good comparability.
- But: Elastic $ep$ scattering and Bethe-Heitler provide a huge background from which the signal must be separated ⇒ Background and LDM signal must be understood precisely (→ existing studies of Vanderhaeghen et al. concerning background).
- In this work: Coupling $U \leftrightarrow e^+\,e^-$ purely vectorial, i.e. vertex factor is $f_e\,\gamma^\mu$.

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The process $e^- p \rightarrow e^- pU$

Feynman Diagrams and Amplitudes

\[ M_i = \frac{-i e^2 f e \varepsilon^*_\alpha (p_3)}{k^2 \cdot (q_i^2 - m^2)} \bar{u}_p(p_2) \Gamma^\mu u_p(p_b) \bar{u}_e(p_1) \gamma_\mu i(q_i + m) \gamma^\alpha u_e(p_a) \]

\[ M_f = \frac{-i e^2 f e \varepsilon^*_\alpha (p_3)}{k^2 \cdot (q_f^2 - m^2)} \bar{u}_p(p_2) \Gamma^\mu u_p(p_b) \bar{u}_e(p_1) \gamma_\alpha i(q_f + m) \gamma^\mu u_e(p_a) \]

with \[ k = p_2 - p_b, \quad q_i = p_a - p_3, \quad q_f = p_1 + p_3, \quad \sum_{\alpha} \varepsilon^*_\alpha (p_3) \varepsilon_\beta (p_3) = -g_{\alpha \beta} + \frac{p_3^\alpha p_3^\beta}{m_U^2} \]
Cross Section Computation

Kinematical relations and cross section (in lab frame)

- $\vec{p}_3$ can be eliminated by $\delta^{(3)}$ function
- Outgoing proton 3-momentum norm $|\vec{p}_2|^2$ will not be detected $\Rightarrow$ eliminated by remaining $\delta$ function component
- Infinitesimal momentum volume $d^3\vec{p}$ written in spherical polar coordinates
  $$d^3\vec{p} = |\vec{p}|^2 d|\vec{p}| d\phi d\cos \theta$$

Mandelstam variables: $s = (q + p_b)^2$, $t = (q - p_2)^2$, $u = (p_b - p_2)^2$, $q = p_a - p_1$

$$\frac{d\sigma}{d|\vec{p}_1|^2 d\Omega_1 d|\vec{p}_2|^2 d\Omega_2} = \frac{1}{(2\pi)^5 32M} \frac{|\vec{p}_1|^2}{|\vec{p}_a|^2} \frac{|\vec{p}_2|^2}{\sqrt{|\vec{p}_2|^2 + M^2}} |\mathcal{M}|^2 \cdot$$

$$\delta \left( \nu^L + M - \sqrt{|\vec{p}_2|^2 + M^2} - \sqrt{|\vec{q} - \vec{p}_2|^2 + m_U^2} \right)$$

$$\sqrt{|\vec{q} - \vec{p}_2|^2 + m_U^2}$$

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Coupling Constants

Derivation of the numerical coupling constant value

The coupling strength is connected to the thermal averaged dark matter freeze-out cross section \( \Omega_{DM} \approx 0.23 \cdot 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \) and can be constrained by e.g. contributions to \((g - 2)\) for electrons and muons:

\[
\Rightarrow |C_{\chi f_e}| \approx 10^{-6} \frac{m_U^2 - 4m_\chi^2}{m_\chi (1.8 \text{ MeV})} \sqrt{B_{\text{ann}}^{ee}}
\]

Coupling constant \( f_e \) plotted as function of \( m_U \) and \( m_\chi \) for \( B_{\text{ann}}^{ee} = 1 \) and \( c_\chi = 1 \) (left) and \( c_\chi = 10^{-2} \) (right)

Cross section

4 times Differential Cross Section

\[
\frac{d^4 \sigma}{d |\vec{p}_1|_L \, d \cos \theta_1 \, d \phi \, d \cos \theta_2} = \frac{1}{(2\pi)^4} \frac{|\vec{p}_1|_L}{32M} \frac{|\vec{p}_2|_L^2}{|\vec{p}_2|_L^2 + M^2} \cdot \frac{d \cos \theta_2}{d \cos \theta_2} \cdot \frac{1}{f'(|\vec{p}_2|_L)} \frac{|\mathcal{M}|^2}{\sqrt{q - |\vec{p}_2|_L^2 + m_U^2}}
\]

First Results

- Cross checks by $m_U \to 0$: Confirmed Bethe-Heitler computations by Vanderhaeghen et al. and these computations agree!
- Numerical integration over proton angle of $d \sigma^5 / d |\vec{p}_1|_L \, d \Omega_1^L \, d \Omega_2^cm$ leads to 3-times differential cross section
- Shown plot: beam energy $E_a^L = 40$ MeV, electron scattering angle $\theta_1^L = 90^\circ$

$\Rightarrow$ Confirms cross section estimates by Heinemeyer et al.
Cross section

- Beam energy $E_{a}^{L} = 40$ MeV, outgoing electron energy $E_{1}^{L} = 1$ MeV and $E_{1}^{L} = 10$ MeV, respectively, electron scattering angle $\theta_{1}^{L} = 90^\circ$, out-of-plane angle $\phi = 0^\circ$

- LDM signal about $10^{-9}$ times weaker than Bethe-Heitler signal in

\[ \frac{d^5\sigma}{dE_1^L d\Omega_1^L d\Omega_2^{cm}} \]

plots for chosen kinematics and coupling ($C_\chi = 1$, $B_{\text{ann}}^{ee} = 1$)
Cross section

- Ratio of LDM signal and Bethe-Heitler process on level of $\frac{d^5\sigma}{dE_1^L d\Omega_1^L d\Omega_2^{cm}}$
- Beam energy $E_a^L = 40$ MeV electron scattering angle $\theta_1^L = 90^\circ$, out-of-plane angle $\phi = 0^\circ$, proton scattering angle $\theta_2^{cm} = 90^\circ$, $B_{ann}^{ee} = 1$, $m_U = 10$ MeV, $m_\chi = 2$ MeV
Conclusions and Outlook

Conclusions

- 511 keV anomaly can not satisfactorily be explained by ordinary approaches
- LDM can explain observed phenomena
- Computations support idea to detect LDM effect as background of elastic electron proton scattering

Outlook

- Simulations for a wide parameter space will be done
- Present LDM model is not the only promising idea to probe Dark Matter by electromagnetic interactions, other models can be taken into account
- Precise background study must be performed
- Experiment at MESA
Backup Slides
MESA Project

- Possible Experiment at "Mainz Energy recovering Superconducting Accelerator" (MESA)
- In mode for LDM experiments: 10 mA current at 104 MeV beam energy
- Target: pseudo internal windowless H gas target
- Windowless gas target to minimize unphysical background
- First estimates: Statistics of LDM events is high enough if the physical background can be clearly separated