Formation of Anomalous Isotopes in Celestial Bodies within the Dark-Atom Model

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Motivation

The nature of hidden mass in the Universe remains an open question. One possible answer is the dark-atom model, which may be related to the composite nature of the Higgs boson and can explain paradoxical results of direct dark-matter searches, including the positive result of the DAMA/LIBRA experiment.

In this model, hypothetical stable or nearly stable particles X^{-2n} with charge -2ne are considered. These particles can form bound states with baryonic nuclei, (NX^{-2n}), referred to as dark atoms.

Such candidates for hidden-mass particles interact through nuclear forces. When they enter sufficiently dense and extended baryonic matter, they should slow down, become gravitationally captured, and accumulate inside astrophysical objects: stars, planets, and small Solar-System bodies.

The interaction of dark atoms with matter nuclei can transfer the X^{-2n} particle to other nuclei and form bound states that chemically appear as anomalously heavy isotopes of the corresponding elements, for example iron.

Aim of the Work

Aim of the work - to build an approximate methodological model for the capture and deceleration of free particles in stars, as well as a model of thermalization and subsequent accumulation of dark atoms in astrophysical objects; to analyze the conditions under which interactions of dark atoms with baryonic nuclei may lead to the formation of anomalously heavy isotopes.

Tasks:

1. Consider the limiting methodological case of a free charged particle X^{-2n} in stellar plasma.
2. Estimate transport cross sections, mean free paths, collision numbers, and the gravitational-capture condition.
3. Perform calculations for the Sun and compare capture efficiency for stars of different classes: the Sun, Proxima Centauri, Arcturus, and Sirius B.
4. Move to the bound-state case and estimate the mean free path, number of collisions, thermalization length, and thermalization time in the solar medium.
5. Construct a kinetic model for further evolution of captured dark atoms, including transfer of X^{-2n} to other nuclei.
6. After capture in a planetary body, determine where dark atoms accumulate.
7. Estimate the distribution of captured dark atoms inside the Earth after thermalization.

Constraints and Selected Values

1. Experimental mass constraint

Searches for multiply charged particles at the Large Hadron Collider set a lower bound on the mass of such particles. In this work the following estimate is adopted:

$$m_X \gtrsim 1\text{–}2\ \mathrm{TeV}$$

Therefore, the TeV scale is considered as the minimal characteristic mass scale of a dark atom.

2. Cosmological concentration constraint

If X^{-2n} particles or dark atoms, (NX^{-2n}), are stable and do not bind into neutral dark atoms, their concentration must be small:

$$\frac{n_X}{n_b} \lesssim 10^{-9}\text{–}10^{-10}.$$

3. Selected masses for calculations

Three characteristic values are used in the calculations:

$$m_X = 1\ \mathrm{TeV}, \qquad m_X = 10\ \mathrm{TeV}, \qquad m_X = 10^{10}\ \mathrm{GeV}$$

Calculation for a Free Charged Particle X^{-2n} in Stellar Plasma

MEPhI

1. The velocity near the star

$$v = \sqrt{u^2 + v_{\text{esc}}^2} \qquad v_{\text{esc}} = \sqrt{\frac{2GM_*}{R_*}}$$

2. The particle concentrations in plasma

$$n_p = \frac{X_H \rho}{m_p} \qquad n_\alpha = \frac{Y_{He}\rho}{4m_p} \qquad n_e = n_p + 2n_\alpha$$

3. The Debye length

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n_e e^2}}$$

4. The transport cross section

$$\sigma_{\text{tr},i} = \int (1 - \cos\theta)\frac{d\sigma_i}{d\Omega}\, d\Omega \qquad \sigma_{\text{tr},i} \simeq 4\pi b_{0,i}^2 \ln \Lambda_i$$

$$b_{0,i} = \frac{|Z_X Z_i| e^2}{4\pi\varepsilon_0 \mu_i v^2} \qquad \ln\Lambda_i = \ln\left(\frac{\lambda_D}{b_{0,i}}\right)$$

5. The mean free path

$$\lambda_i = \frac{1}{n_i \sigma_{\text{tr},i}}$$

6. The number of collisions

$$N_i \simeq n_i \sigma_{\text{tr},i} L$$

7. Condition for gravitational capture

$$\Delta E_{\text{req}} = \frac{1}{2} m_X u^2$$

8. Energy loss in one collision

$$N_{\text{req}} \sim \frac{\Delta E_{\text{req}}}{\Delta E_i}$$

9. Effective capture cross section of the star

$$\sigma_{\text{eff}} = \pi R_*^2 \left(1 + \frac{v_{\text{esc}}^2}{u^2}\right)$$

Conclusion for the Sun and Comparison of Stars of Different Classes

Effective capture cross section of the Sun

u, km/s	$1 + v_{esc}^2/u^2$	σ_{eff}, m^2
300	5.24	$7.97 \cdot 10^{18}$

Solar plasma is an opaque medium. During passage through the Sun, the particle undergoes an extremely large number of decelerating collisions with protons and helium nuclei. The energy loss required for capture is much smaller than the loss that can be provided by interactions with solar matter. Therefore, over the entire mass range considered, a free X^{-2n} particle should decelerate efficiently and become gravitationally captured by the Sun.

Object	Main nuclei	Characteristic λ, m	N_{tr}	σ_{eff}, m^2
Sun	p, α	10^{-7}–10^{-6}	$1.43 \cdot 10^{16}$	$7.97 \cdot 10^{18}$
Proxima Centauri	p, α	10^{-9}–10^{-8}	$1.15 \cdot 10^{17}$	$1.38 \cdot 10^{17}$
Arcturus	p, α	10^{-5}–10^{-3}	$1.32 \cdot 10^{15}$	$1.16 \cdot 10^{21}$
Sirius B	C, O	10^{-8}	$6.97 \cdot 10^{14}$	$5.43 \cdot 10^{16}$

In all considered cases, $\lambda \ll R_*$ and $N_{tr} \gg 1$. This means that, in the free-particle model, stars of different classes are opaque media and should efficiently decelerate such particles. Differences between objects appear in the scale of the effective capture cross section and in the physical conditions governing the further evolution of the captured states.

Bound State in the Solar Medium

1. The bound state thermalizes inside the Sun

(for all selected masses)

m_X	L_th, m	t_th, s
1 TeV	$4.6 \cdot 10^{1}$	$6.9 \cdot 10^{-5}$
10 TeV	$4.6 \cdot 10^{2}$	$6.9 \cdot 10^{-4}$
10^{10} GeV	$4.6 \cdot 10^{8}$	$6.9 \cdot 10^{2}$

$$L_{\mathrm{th}} < R_{\odot}$$

2. Population evolution of dark atoms and anomalous isotopes

Interactions of dark atoms with matter nuclei may transfer the particle to other nuclei and form bound states that chemically manifest as anomalously heavy isotopes.

Kinetic model

$$\frac{dN_{\mathrm{in}}}{dt} = C_{\mathrm{in}} - \frac{N_{\mathrm{in}}}{t_{\mathrm{th}}} - \Gamma_{\mathrm{in,loss}} N_{\mathrm{in}}$$

$$\frac{dN_A}{dt} = \frac{N_{\mathrm{in}}}{t_{\mathrm{th}}} - \sum_k \Gamma_{A\to k} N_A - \Gamma_{A,\mathrm{loss}} N_A$$

$$\frac{dN_k}{dt} = \Gamma_{A\to k} N_A - \Gamma_{k,\mathrm{loss}} N_k$$

EARTH: Capture, Settling, and Accumulation of Anomalous Isotopes

1. Effective capture cross section of the Earth
2. Flux of dark atoms onto the Earth
3. Capture rate
4. Number of accumulated dark atoms, including losses or reprocessing

$$\sigma_{\oplus} \simeq \pi(6.371 \cdot 10^6)^2 \simeq 1.28 \cdot 10^{14}\ \mathrm{m}^2$$

$$\Phi_A = n_{A,\infty} u.$$

$$N_A(t) \simeq C_{\oplus} t.$$

$$\frac{dN_A}{dt} = C_{\oplus} - \sum_k \Gamma_{A\to k} N_A.$$

Using a Gaussian spatial distribution for thermalized dark atoms inside the Earth, one can estimate the characteristic accumulation region.

$$n_A(r) = n_A(0) \exp\left(-\frac{r^2}{r_A^2}\right)$$

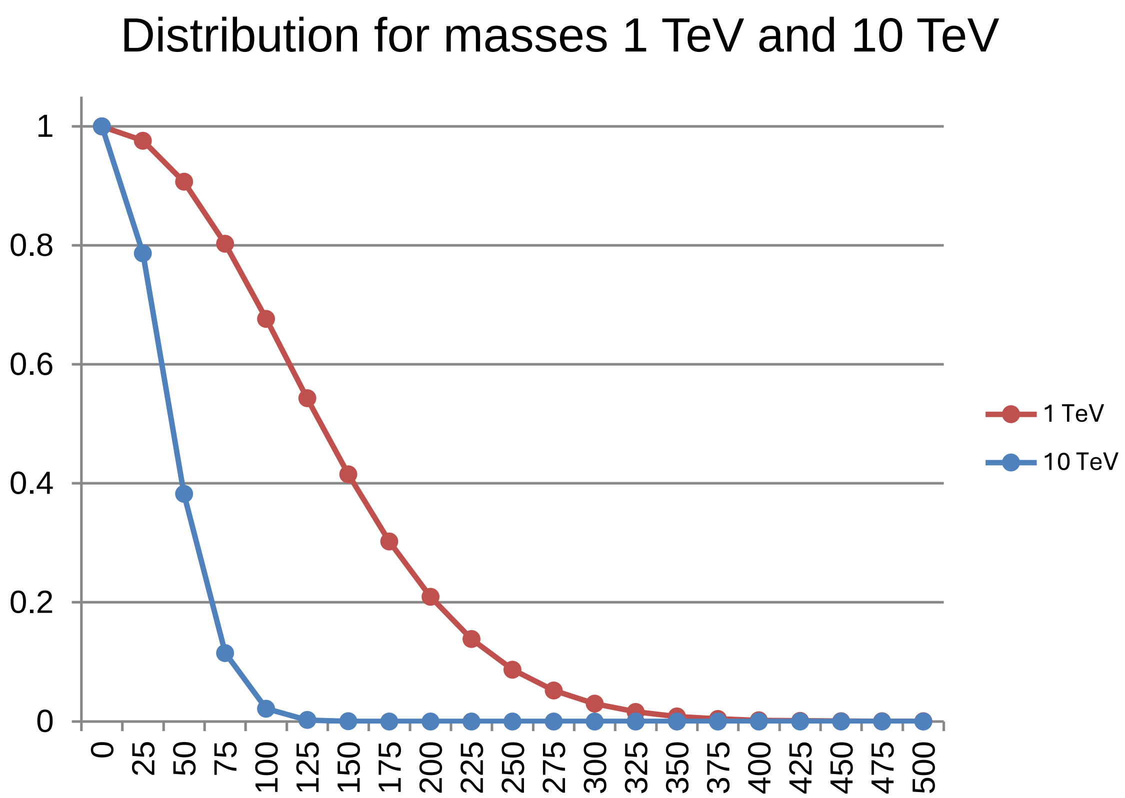
The obtained values show that, for all considered masses, dark atoms concentrate much closer to the Earth's center than the size of the inner core:

r_A << R_inner core ≈ 1220 km

Characteristic distribution radius of dark atoms inside the Earth

m_X	r_A, km
1 TeV	160 km
10 TeV	51 km
10^{10} GeV	51 m

EARTH: Capture, Settling, and Accumulation of Anomalous Isotopes



As the mass increases from 1 to 10 TeV, the dark-atom distribution becomes narrower. Heavier dark atoms settle more strongly toward the Earth’s center. For 1 TeV, the characteristic distribution radius is about 160 km, while for 10 TeV it is about 51 km. Therefore, accumulation of dark atoms and possible anomalous isotopes is expected in the central region of the Earth.

Conclusions

1. A methodological calculation was performed for a free particle; it showed that stellar plasma efficiently decelerates such particles. The table gives results for stars of different classes.
2. It was found that the bound state has time to thermalize in the Sun.
3. It was shown that, after capture, anomalously heavy isotopes may form in celestial bodies.
4. The Earth calculation showed that dark atoms concentrate in the central region of the planet.
5. A plot of the dark-atom mass distribution as a function of radius was constructed.

Plans

Study the formation of the concentration distribution in the Earth and the possible formation of a central anomalous Earth core.

Thank you for your attention