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Formation of dark atoms

Authors: Vitaly A. Beylin [*,1]; Maxim Yu. Khlopov [*,+,x,2]; Danila O. Sopin [+,x,3]

* Virtual Institute of Astroparticle Physics, 75018, Paris, France
+ National Research Nuclear University MEPhI 115409 Moscow, Russia
x Research Institute of Physics, Southern Federal University, 344090 Stachki 194, Rostov on Don, Russia

1. vitbeylin@gmail.com
2. khlopov@apc.in2p3.fr
3. sopindo@mail.ru

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Dark atom

$$X^{-2n} + n\,He^{+2} \rightarrow XHe$$

Outline

- **Problems**
- **Generation of multicharged heavy particles X^{-2n}**
  - Sphaleron solution
  - WTC model
- **Recombination of dark atoms XHe**
  - Recombination temperatures
  - Kinetic equations
  - Interaction of dark ions *XN*
- **Conclusion**

Problems

Generation of negatively charged heavy particles X^{-2n}

Properties of the sphaleron transitions:

- Value of the shaleron energy E_{Sph} should change [1, 2]
- Additional solutions may arise [2]

The sphaleron freezing out temperature should change

Predicted ratio $\frac{\Omega_{DM}}{\Omega_b}$ changes

Recombination of dark atoms XHe

New reactions on nucleosynthesis stage:

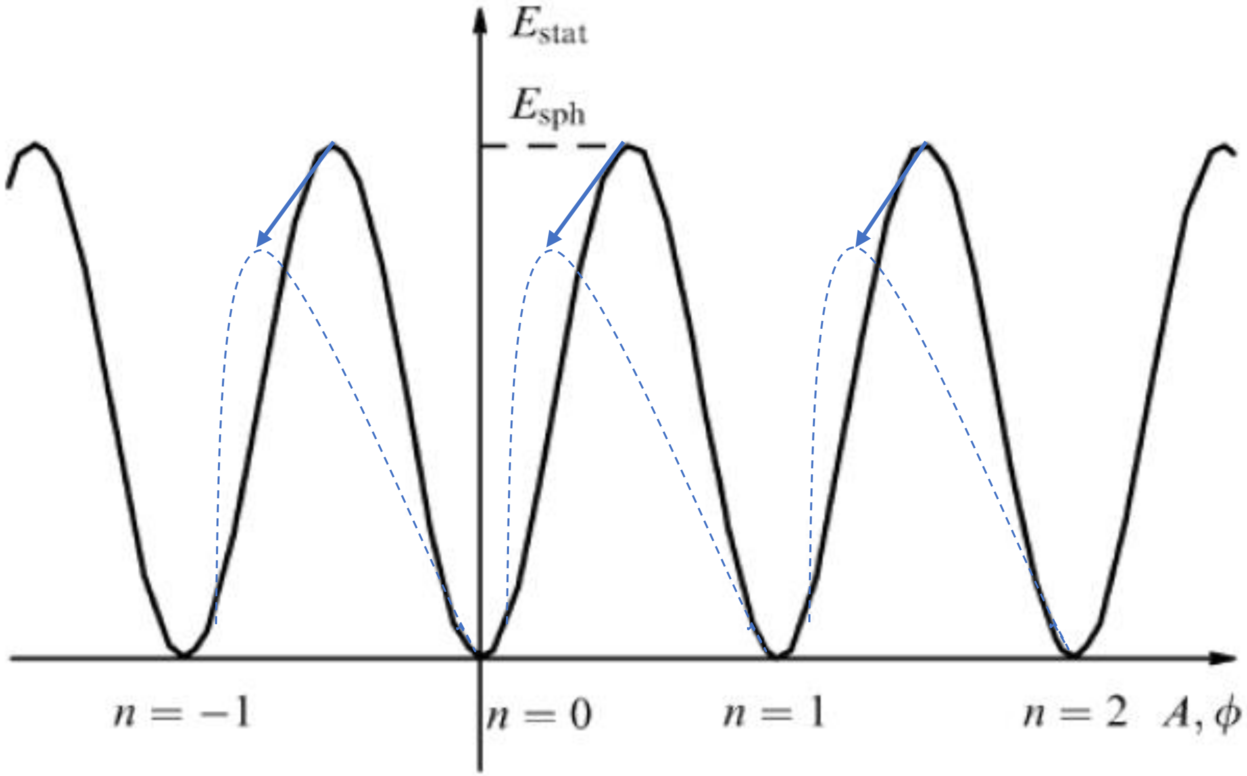
- Caption of additional light nuclei
- Interaction of two dark atoms

The danger of overproduction of anomalous isotopes and primordial metals [3]

[1] G. Nolte, J. Kunz: Sphaleron barrier in the presence of fermions, Phys.Rev. D. **48(12)** (1993) 5905–5916
[2] M. Spannowsky, C. Tamarit: Sphalerons in composite and nonstandard Higgs models, Phys. Rev. D **95** (2017)
[3] E. Akhmedov, M. Pospelov: BBN catalysis by doubly charged particles, arXiv: 2405.06019

Sphaleron solution

Sphaleron transitions are the nonperturbative electroweak processes violating the baryon and lepton numbers.



[1] G. Nolte, J. Kunz: Sphaleron barrier in the presence of fermions, Phys.Rev. D. **48(12)** (1993) 5905–5916
[2] M. Spannowsky, C. Tamarit: Sphalerons in composite and nonstandard Higgs models, Phys. Rev. D **95** (2017)

WTC model

- Techniquarks $\begin{pmatrix} U \\ D \end{pmatrix}$
- Technileptons $\begin{pmatrix} N \\ E \end{pmatrix}$

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} &= \frac{1}{2}\text{Tr}\left[D_\mu M D^\mu M^\dagger\right] + \frac{m^2}{2}\text{Tr}[MM^\dagger] \\ &- \frac{\lambda}{4}\text{Tr}\left[MM^\dagger\right]^2 - \lambda'\text{Tr}\left[MM^\dagger MM^\dagger\right] + 2\lambda''\left[\text{Det}(M) + \text{Det}(M^\dagger)\right] \\ &+ \frac{m_{\text{ETC}}^2}{4}\text{Tr}\left[MBM^\dagger B + MM^\dagger\right] , \end{aligned}$$

$$M = \begin{pmatrix} i\Pi_{UU} + \widetilde{\Pi}_{UU} & \frac{i\Pi_{UD} + \widetilde{\Pi}_{UD}}{\sqrt{2}} & \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^+ + A^+}{\sqrt{2}} \\ \frac{i\Pi_{UD} + \widetilde{\Pi}_{UD}}{\sqrt{2}} & i\Pi_{DD} + \widetilde{\Pi}_{DD} & \frac{i\Pi^- + A^-}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{\sqrt{2}} \\ \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^- + A^-}{\sqrt{2}} & i\Pi_{\overline{UU}} + \widetilde{\Pi}_{\overline{UU}} & \frac{i\Pi_{\overline{UD}} + \widetilde{\Pi}_{\overline{UD}}}{\sqrt{2}} \\ \frac{i\Pi^+ + A^+}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{2} & \frac{i\Pi_{\overline{UD}} + \widetilde{\Pi}_{\overline{UD}}}{\sqrt{2}} & i\Pi_{\overline{DD}} + \widetilde{\Pi}_{\overline{DD}} \end{pmatrix}$$

[4] R. Foadi, M. T. Frandsen, T. A. Ryttov, F. Sannino: Minimal walking technicolor: Setup for collider physics, Phys. Rev. D **76** (2007)

[5] F. Sannino: Conformal Dynamics for TeV Physics and Cosmology, arXiv: 0911.0931.

Formation of dark atoms

(1) $N^1 + N^2 \to N^3 + N^4,$

(2) $X + N \to XN + \gamma,$

(3) $XN^1 + N^2 \to XN^3 + \gamma \backslash N^4,$

(4) $XN^1 + XN^2 \to X_2N^3 + \gamma \backslash N^4.$

Recombination temperatures

(2) $X^{-2n} + N^{+q} \to (XN)^{-2n+q} + \gamma$

$$n_i^{\text{now}} \left(\frac{T}{T_{\text{now}}} \right)^3 = g_i \left(\frac{m_i T^{\frac{3}{2}}}{2\pi} \right) e^{-\frac{m_i}{T}}$$

⇓

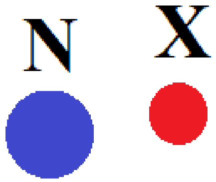
$$T_{\text{rec}} = E_{X-N} \left(\ln \left(\frac{g_X g_N}{g_{XN}} \left(\frac{m_N T_{\text{now}}^2}{2\pi\, E_{X-N}} \right)^{\frac{3}{2}} \frac{1}{n_N^{\text{now}}} \right) \right)^{-1}$$

[6] Gorbunov, D. S.;Rubakov V. A. INTRODUCTION TO THE THEORY OF THE EARLY UNIVERSE Hot Big Bang, Theory World Scientific Publishing Co. Pte. Ltd.: Singapore, 2011;

Structure of the dark atoms

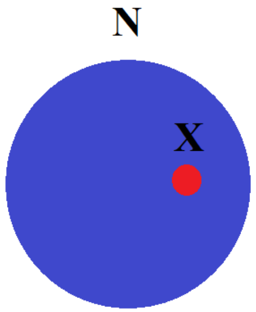
$$a = \frac{r_N}{r_B} \approx Z_X Z_N \, \alpha \, m_N \, r_0 \, A_N^{1/3}$$

$0 < a < 1$



$$E_{X-N}^{\mathrm{Bohr}} = 2n^2 Z^2 \alpha^2 m_N = \frac{1}{2 m_N r_B^2}$$

$2 < a < \infty$



$$E_{X-N}^{\mathrm{Thompson}} = \frac{3}{2} \frac{Z_X Z_N \alpha}{r_N} \left(1 - \sqrt{\frac{r_B}{r_N}}\right)$$

$$E_{X-N}^{\mathrm{Bohr}} > E_{X-N}^{\mathrm{Thompson}}$$

[7] R. N. Cahn, S. L Glashow, Chemical Signatures for Superheavy Elementary Particles, Science 213 (1981) 607–611

Structure of the dark ions XN

$$a = \frac{r_N}{r_B} \approx Z_X Z_N \, \alpha \, m_N \, r_0 \, A_N^{1/3}$$

n	A			
	H	He	Li	Be
1	B	4	3	T
2	4	3	T	T
3	3	T	T	T
4	3	T	T	T
5	2	T	T	T

Recombination temperatures

$$T_{\rm rec} = E_{X-N}\left(\ln\left(\frac{g_X g_N}{g_{XN}}\left(\frac{m_N T_{\rm now}^2}{2\pi\, E_{X-N}}\right)^{\frac{3}{2}}\frac{1}{n_N^{\rm now}}\right)\right)^{-1}$$

n	$T_{\rm rec}$, keV			
	p	D	^3He	^4He
1	3 (B)	4 (B)	28 (B)	37 (B) / 6 (T)
2	13 (B)	19 (B)	$\sim$ 42 (T)	85 (T)
3	29 (B)	44 (B)	$\sim$ 116 (T)	180 (T)
4	54 (B)	79 (B)	$\sim$ 198 (T)	285 (T)
5	86 (B)	$\sim$ 126 (B) / 17 (T)	$\sim$ 286 (T)	395 (T)

- $n < 4$ the dominant branch is

$$X + He \rightarrow XHe + \gamma$$

- $n \geq 4$ it is

$$X + H \rightarrow XH + \gamma$$

Kinetic equations

(1) $N^1 + N^2 \to N^3 + N^4,$

(2) $X + N \to XN + \gamma,$

(3) $XN^1 + N^2 \to XN^3 + \gamma \backslash N^4,$

(4) $XN^1 + XN^2 \to X_2N^3 + \gamma \backslash N^4.$

$$\begin{cases} \dfrac{dn_i}{dt} + 3Hn_i = \sum\limits_{j,k} n_j n_k \langle \sigma v \rangle_i^{jk} - n_i \sum\limits_j n_j \langle \sigma v \rangle^{ij} \\ \dfrac{\partial \phi_{N_i}}{\partial t} = \sum\limits_{j,k} n_j n_k \dfrac{d(\sigma v)^{jk}_{N_i}}{dp_{N_i}} - \phi_{N_i} \sum\limits_j n_j (\sigma v)^{N_i j}(p_{N_i}) - \phi_{N_i} \sum\limits_j \int \phi_{N_j} (\sigma v)^{N_i N_j} dp_{N_j} \end{cases}$$

$$\frac{dn_N}{dp_N} = \phi_N(p_N, t)$$

[8] Khlopov, M. Fundamentals of Cosmic Particle Physics, Cambridge International Science Publishing Ltd, 2012

Interaction of dark ions

(3) $XN^1 + N^2 \to XN^3 + \gamma \backslash N^4,$

(4) $XN^1 + XN^2 \to X_2N^3 + \gamma \backslash N^4.$

$$n_{XN}\,\langle \sigma v\rangle\, t \approx \frac{3}{2\pi^2}\frac{\rho_c\,\Omega_{DM}^{now}\, m_{Pl}\,\sigma}{m_{XHe}T_{now}^3}\sqrt{\frac{10\,T^3}{g_*\,m_i}} \approx$$

$$\approx 3\cdot 10^9\,\frac{\sigma}{m_{XN}\sqrt{m_i}}T^{\frac{3}{2}} > 1.$$

$$n_{XN} \approx \frac{\rho_c}{m_{XHe}}\Omega_{DM}^{now}\left(\frac{T}{T_{now}}\right)^3 \qquad t = \frac{3}{4}\frac{m_{Pl}}{T^2}\sqrt{\frac{5}{\pi^3 g_*}}. \qquad <v>=\sqrt{\frac{8T}{\pi m_N}}$$

$$\sigma \approx 2\cdot 10^{-25}\,\mathrm{cm}^2 = 500\,\mathrm{GeV}^{-2} \Rightarrow m_X \le 10\,\mathrm{TeV}$$

Conclusion

To describe the dark atom formation completely in extensions of SM it is necessary to

- find the energy of sphaleron transitions in a particular model and then to estimate the freezing out temperature of sphaleron transitions;
- find the solution of the system of kinetic equations which describes the modified nucleosynthesis.

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1. vitbeylin@gmail.com
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3. sopindo@mail.ru

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Density of dark atoms