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Atoms of Dark Matter from Stable Charged Particles – a solution for puzzles of dark matter searches

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Based on the work by M.K., A.Mayorov and E.Soldatov

DARK MATTER FROM CHARGED PARTCILES?

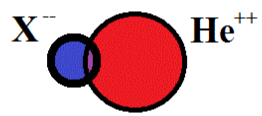
Nuclear-interacting composite dark matter: O-helium « atoms »

If we have a stable double charged particle X^{--} *in excess over its partner* X^{++}
it may create Helium like neutral atom (O-helium) at temperature $T > I_o$

Where: $$I_o = Z_{He}^2 Z_\Delta^2 \alpha^2 m_{He} = 1.6\,MeV$$

^4He is formed at T ~100 keV (t~100 s)
This means that it would rapidly create a neutral atom, in which all X^{--} are bound

$$X^{--} + {}^4He \Rightarrow (X\,He) + \gamma$$



The size of O-helium « atom » is

$$R_o = 1/\left(Z Z_{He} \alpha m_{He}\right) = 2 \cdot 10^{-13}\,cm$$

References
1. M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1;
2. D. Fargion, M.Khlopov, C.Stephan, *Class. Quantum Grav.* 23 (2006) 7305;
2. M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D 77 (2008) 065002]

Constituents of composite dark matter

Few possible candidates for -2 charges:

Stable doubly charged "leptons" with mass >100 GeV (~1 TeV range):

• *AC « leptons » from almost commutative geometry*

D. Fargion, M.Khlopov, C.Stephan, Class. Quantum Grav. 23 (206) 7305

• *Technibaryons and technileptons from Walking Technicolor (WTC)*

M. Y. Khlopov and C. Kouvaris, Phys. Rev. D 77 (2008) 065002; M. Y. Khlopov and C. Kouvaris, Phys. Rev. D 78 (2008) 065040

Hadron-like bound states of:

• *Stable U-quark of 4-th family in Heterotic string phenomenology*

M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1

• *Stable U-quarks of 5th family in the approach, unifying spins and charges*

N.S. Mankoc Borstnik, Mod. Phys. Lett. A 10 (1995) 587

M.Yu.Khlopov, A.G.Mayorov, E.Yu.Soldatov (2010), arXiv:1003.1144

O-helium dark matter

$$T < T_{od} = 1 keV$$

$$n_b \langle \sigma v \rangle \left(m_p / m_o \right) t < 1$$

$$T_{RM} = 1 eV$$

$$\boxed{M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl} \left(\frac{m_{Pl}}{T_{od}} \right)^2 = 10^9 M_{Sun}}$$

- Energy and momentum transfer from baryons to O-helium is not effective and O-helium gas decouples from plasma and radiation
- O-helium dark matter starts to dominate
- On scales, smaller than this scale composite nature of O-helium results in suppression of density fluctuations, making O-helium gas more close to warm dark matter

O-HELIUM DARK MATTER IN UNDERGROUND DETECTORS

O-helium in Earth

- Elastic scattering dominates in the (OHe)-nucleus interaction. After they fall down terrestrial surface the in-falling OHe particles are effectively slowed down due to elastic collisions with the matter. Then they drift, sinking down towards the center of the Earth with velocity

$$V = \frac{g}{n\sigma v} \approx 80 S_3 A_{med}^{1/2} \,\mathrm{cm/s}.$$

Here $A_{med} \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A_{med}$ is the number of terrestrial atomic nuclei, σv is the rate of nuclear collisions and $g = 980 \ \mathrm{cm/s^2}$.

O-helium concentration in Earth

The O-helium abundance the Earth is determined by the equilibrium between the in-falling and down-drifting fluxes.

The in-falling O-helium flux from dark matter halo is

$$F = \frac{n_0}{8\pi} \cdot |\overline{V_h} + \overline{V_E}|,$$

where $\boldsymbol{V_h}$ is velocity of Solar System relative to DM halo (220 km/s), $\boldsymbol{V_E}$ is velocity of orbital motion of Earth (29.5 km/s) and

$n_0 = 3 \cdot 10^{-4} S_3^{-1}\, \mathrm{cm}^{-3}$ is the local density of O-helium dark matter.

At a depth *L* below the Earth's surface, the drift timescale is ~*L/V.* It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth L ~ 10^5 cm to the corresponding change in the equilibrium underground concentration of OHe on the timescale

$$t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1}\, \mathrm{s}$$

Annual modulation of O-helium concentration in Earth

The equilibrium concentration, which is established in the matter of underground detectors, is given by

$$n_{oE} = \frac{2\pi \cdot F}{V} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot sin(\omega(t - t_0)),$$

where $\omega = 2\pi/T$, T=1*yr* and $\boldsymbol{t_o}$ is the phase. The averaged concentration is given by

$$n_{oE}^{(1)} = \frac{n_o}{320 S_3 A_{med}^{1/2}} V_h$$

and the annual modulation of OHe concentration is characterized by

$$n_{oE}^{(2)} = \frac{n_o}{640 S_3 A_{med}^{1/2}} V_E$$

The rate of nuclear reactions of OHe with nuclei is proportional to the local concentration and the energy release in these reactions leads to ionization signal containing both constant part and annual modulation.

OHe solution for puzzles of direct DM search

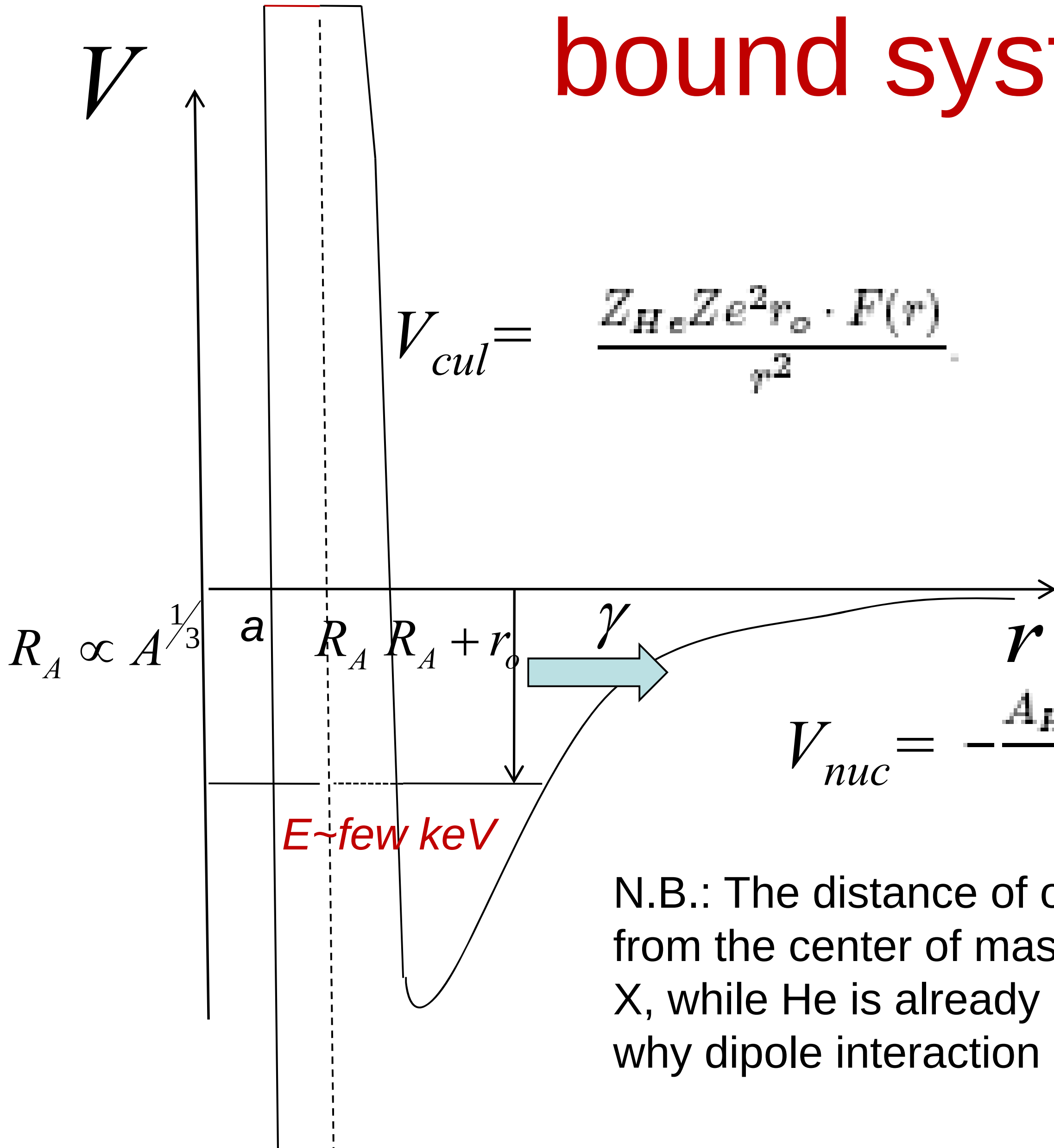
- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour
- The process

$$OHe + (A,Z) \Rightarrow [OHe(A,Z)] + \gamma$$

is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- Signal in DAMA detector is not accompanied by processes with large energy release. This signal corresponds to a formation of anomalous isotopes with binding energy of few keV

Formation of OHe-nucleus bound system



$$V_{cul} = \frac{Z_{He} Z e^2 r_o \cdot F(r)}{r^2}$$

$$V_{nuc} = -\frac{A_{He} A g^2 exp(-\mu r)}{r} \qquad g_A \propto A$$

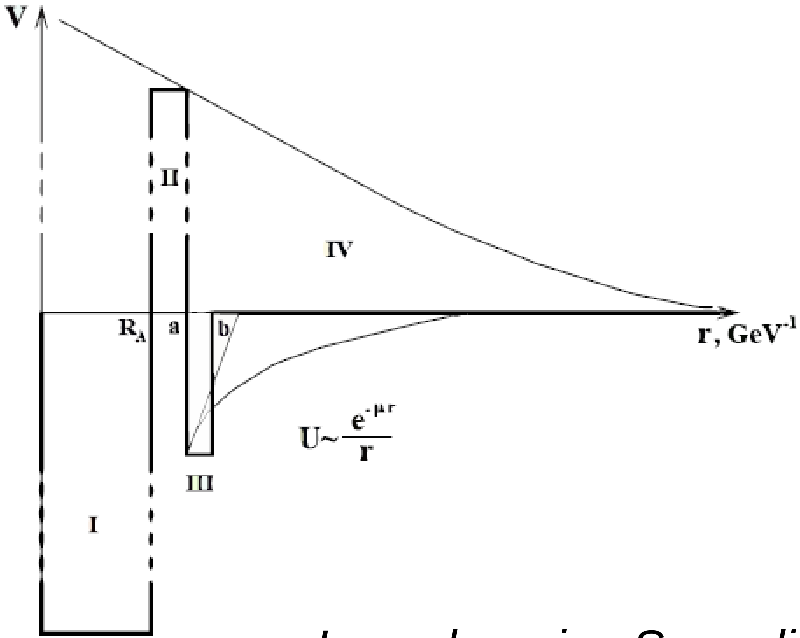
Due to exponential tail of nuclear Yukawa force OHe is attracted by nucleus. At the distance of order of the size of OHe dipole Coulomb barrier is switched on. If the system emits a photon, OHe forms a bound state with nucleus with binding energy of few keV.

N.B.: The distance of order of size of OHe is measured from the center of mass of OHe, which coincides with X, while He is already at the nuclear surface. That is why dipole interaction is repulsive and not attractive.

Few keV Level in OHe-nucleus system

- The problem is reduced to a quantum mechanical problem of finding energy level of OHe-nucleus bound state in the spherically symmetric potential well, formed by Yukawa attraction and Coulomb barrier for He nucleus component of OHe in vicinity of a nucleus.
- The numerical solution for this problem is simplified for rectangular wells and walls, giving a few keV level for NaI.

Few keV Level in OHe-nucleus system: Scroedinger equation



$$I : \frac{1}{r}\frac{d^2}{dr^2}(r\psi_1) + k_1(r)^2\psi_1 = 0, k_1(r) = k_1 = \sqrt{2m(U_1 - |E|)};$$

$$II : \frac{1}{r}\frac{d^2}{dr^2}(r\psi_2) + k_2(r)^2\psi_2 = 0, k_2(r) = k_2 = \sqrt{2m(U_2 - |E|)};$$

$$III : \frac{1}{r}\frac{d^2}{dr^2}(r\psi_3) + k_3(r)^2\psi_3 = 0, k_3(r) = k_3 = \sqrt{2m(U_3 - |E|)};$$

$$IV : \frac{1}{r}\frac{d^2}{dr^2}(r\psi_4) - k_4(r)^2\psi_4 = 0, k_4(r) = k_4 = \sqrt{2m|E|}.$$

In each region Scroedinger equation gives a well known solution

$$I : \psi_1 = A\frac{\sin(k_1 r)}{r}; \quad II : \psi_2 = \frac{B_1 \cdot exp(-k_2 r) + B_2 \cdot exp(k_2 r)}{r}; \quad III : \psi_3 = C\frac{\sin(k_3 r + \delta)}{r}$$

$$IV : \psi_4 = D\frac{\exp(-k_4 r)}{r}$$

So the problem is reduced to their sewing

Few keV Level in OHe-nucleus system: solution

Sewing conditions:

$$I - II : k_1 \cdot ctg(k_1 R_A) = k_2 \cdot \frac{exp(k_2 R_A) - F \cdot exp(-k_2 R_A)}{exp(k_2 R_A) + F \cdot exp(-k_2 R_A)},$$

$$II - III : k_3 \cdot ctg(k_3 a + \delta) = k_2 \cdot \frac{exp(k_2 a) - F \cdot exp(-k_2 a)}{exp(k_2 a) + F \cdot exp(-k_2 a)},$$

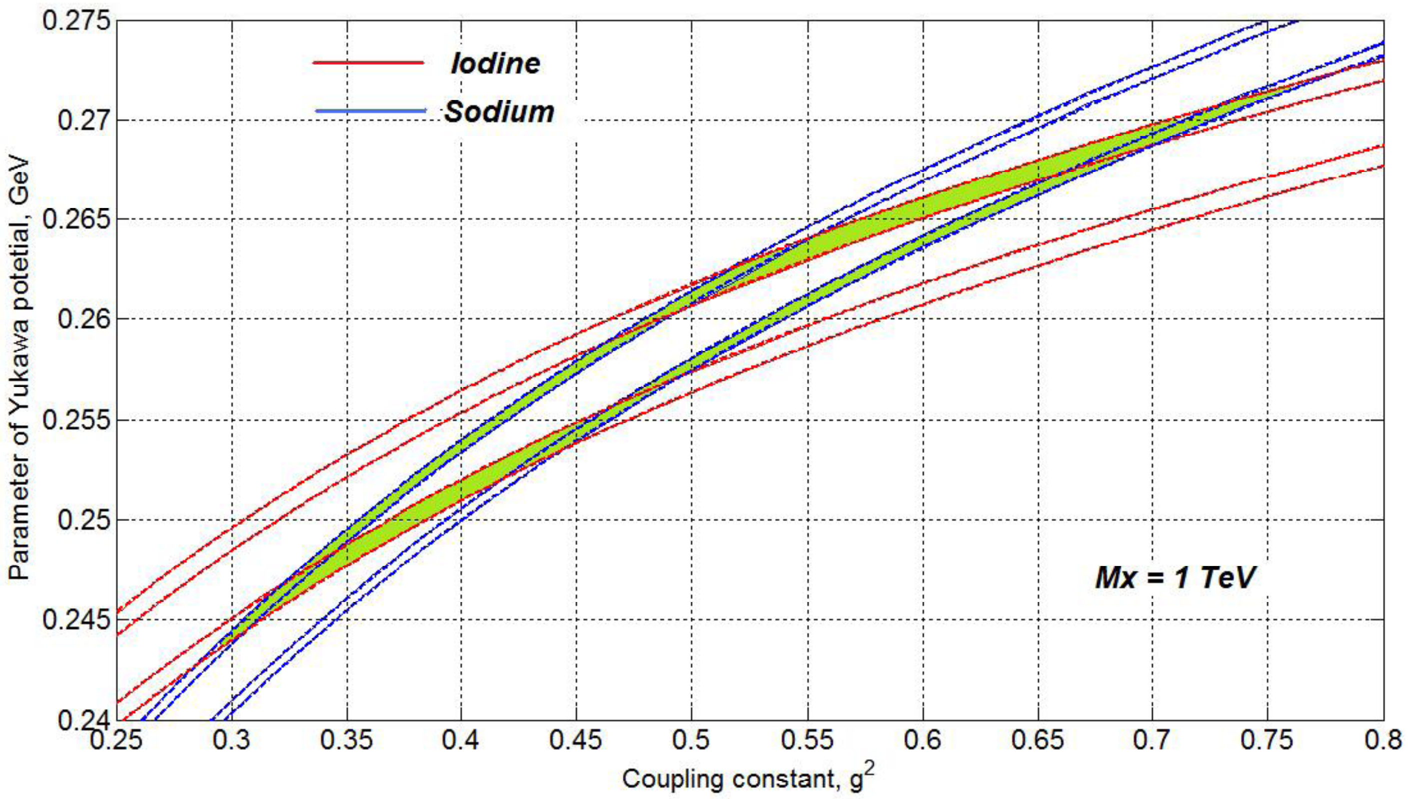
$$III - IV : k_3 \cdot ctg(k_3 b + \delta) = -k_4,$$

The existence of bound state and its energy strongly depend on parameters of nuclear potential

$$U = -\frac{4 \cdot A \cdot (g^2) \cdot exp(-\mu r)}{r}.$$

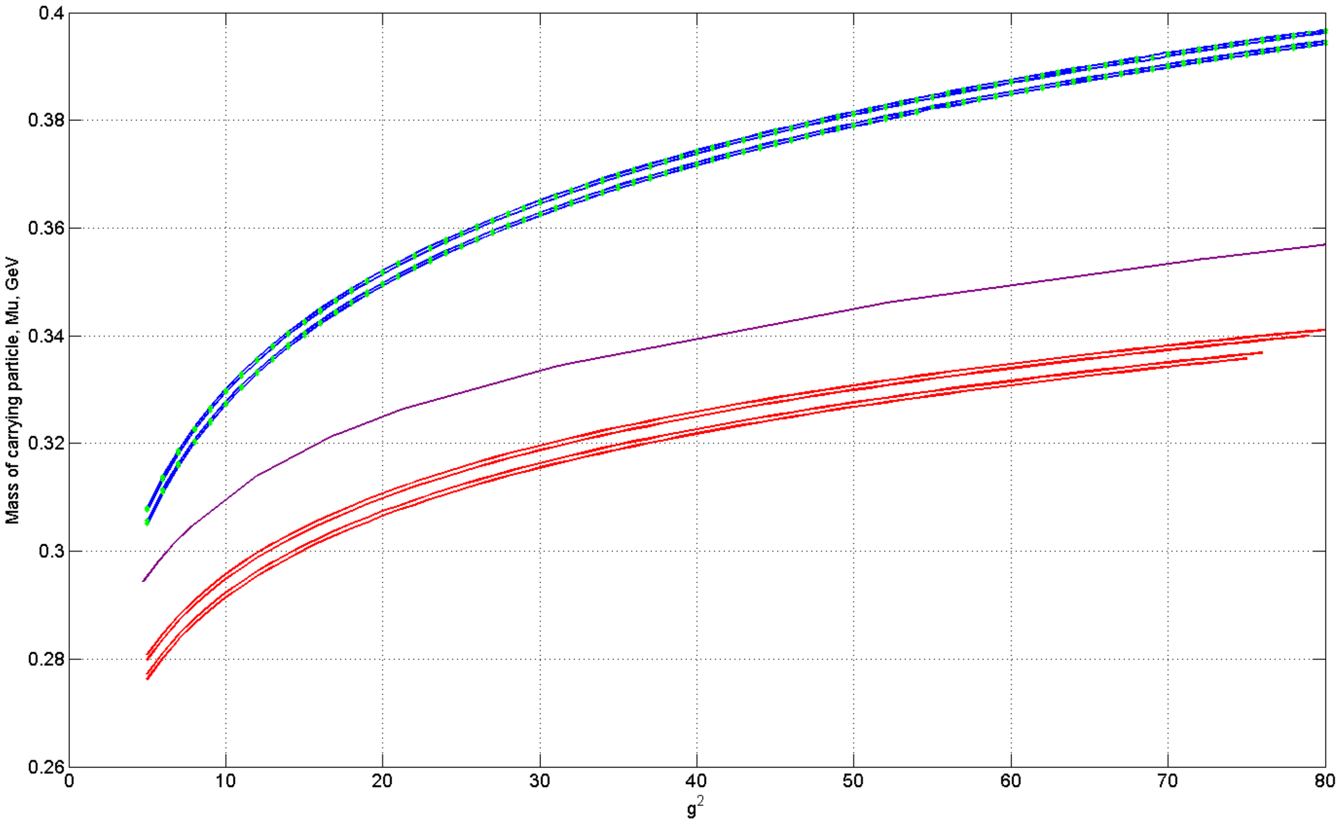
It is very sensitive to the precise value of nuclear radius.

Few keV Levels in OHe-Na and OHe-I systems



If both Na and I have levels in the range 2-6 keV, unrealistic parameters of sigma meson are needed. At more realstic values only Na has

Few keV Levels in OHe-Na system



Rate of OHe-nucleus radiative capture

As soon as the energy of level is found one can use the analogy with radiative capture of neutron by proton with the account for:

- Absence of M1 transition for OHe-nucleus system (which is dominant for n+p reaction)
- Suppression of E1 transition by factor $f \sim 10^{-3}$, corresponding to isospin symmetry breaking

(in the case of OHe only isoscalar transition is possible, while E1 goes due to isovector transition only)

Reproduction of DAMA/NaI and DAMA/LIBRA events

The rate of OHe radiative capture by nucleus with charge Z and atomic number A to the energy level E in the medium with temperature T is given by

$$\sigma v = \frac{f\pi\alpha}{m_p^2}\frac{3}{\sqrt{2}}\left(\frac{Z}{A}\right)^2\frac{T}{\sqrt{Am_pE}}.$$

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at energies above 6 keV means that binding energy of Na-Ohe in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV.

Annual modulation of signals in DAMA/NaI and DAMA/LIBRA events

The amplitude of annual modulation of ionization signal (measured in counts per day per kg, cpd/kg) is given by

$$\zeta = \frac{3\pi\alpha \cdot n_o N_A V_E t Q}{640\sqrt{2} A_{med}^{1/2}(A_I + A_{Na})} \frac{f}{S_3 m_p^2} (\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}} = 4.3 \cdot 10^{10} \frac{f}{S_3^2} (\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}}.$$

The result of DAMA/NaI and DAMA/LIBRA experiments can be reproduced for E(Na-OHe) =3 keV

Absence of signal in DAMA detector above 6 keV

The the results of DAMA experiment exhibit also absence of annual modulations at the energy above 6 keV. In our approach they can come from:

- Radiative capture to E>6keV levels in OHe-Tl system .
- Radiative capture of OHe by Na and I to deep internuclear ~tens MeV energy levels.
- Rapid decay of low energy levels of OHe-Na and OHe-I systems to deep inter-nuclear ~tens MeV levels in these systems.

For the two latter processes dipole Coulomb barrier provides suppression of their rates beyond the experimental upper limits.

Conclusions

• New stable quarks and leptons can appear in extensions of Standard Model and exist around us, bound within neutral « atomic » states. In particular, stable -2 charged clusters can appear in the framework of Norma's approach

•Composite dark matter can be in the form of nuclear interacting O-helium « atoms ». Their binding with nuclei in underground detectors possess annual modulation and can explain positive results of DAMA/NaI and DAMA/LIBRA experiments. Calculations for other experimental devices are in progress.

• The test for composite dark matter and its constituents is possible in cosmoparticle physics analysis of its signatures and experimental search for stable charged particles in cosmic rays and at accelerators.