Main properties of new heavy hadrons and the luminosity of hadronic dark matter

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New heavy hadrons and hadronic DM

WIMP Rigid restrictions on $\sigma(WN) \rightarrow$ SIMP

(Wandelt e a, 2000; McGuere e a, 2001; Huo e a, 2016; Luca e a, 2019; Bhattacharya e.a.,2019)

Hadronic DM - one of SI candidate on DM particles $M = (qQ)$

Q is new heavy quark (QCD strong interaction)

Origin of Q:
a) 4-th generation (Khlopov, Maltony, Novikov, Okun, Vysotsky, Belotsky, Fargion, ...)
b) Mirror or chiral-symmetric models
c) Extension of SM with singlet quark

Vector-like interactions of Q with gauge bosons γ and Z. (W).
Strong QCD-type interaction of Q with $q \longrightarrow$ coupled states:
(qQ), (qqQ), (qQQ), (QQQ), ...

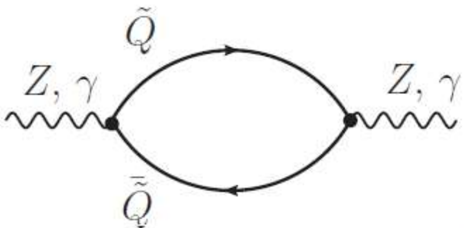
WIMP $\longrightarrow$ SIMP: processes $(2 \rightarrow 2) \longrightarrow (3 \rightarrow 2)$ (N-changing processes, Bhattacharya e.a.)

Crucial modifications in dynamics of DM evolution (annihilation, scattering, etc.)

EW restrictions on Q

Vector-like interactions of Q with gauge bosons γ and $Z \longrightarrow$ cause small contributions into polarizations.

$$L(Q_a, A, Z) = g_a(c_w A_\mu - s_w Z_\mu)\bar{Q}_a \gamma^\mu Q_a, \;\; Q_a = Q_s, U, D$$



$P_{\gamma\gamma},\ P_{ZZ},\ P_{\gamma Z};\ (P_{WW} = 0)$ PT parameters

$$S = -U = \frac{ks_w^4}{9\pi}[-\frac{1}{3} + 2(1 + 2\frac{M_{\tilde{Q}}^2}{M_Z^2})(1 - \sqrt{\beta}\arctan\frac{1}{\sqrt{\beta}})].$$

$$\beta = 4M_Q^2/M_Z^2 - 1$$

$M_Q > 500$ GeV $\quad S = |U| < 10^{-2}, T = 0$

PDG 2019: $\mathrm{S, T, U} \lesssim 10^{-1}$

No mixing $q \leftrightarrow Q$: FCNC are absent $\rightarrow$ there are no restrictions from rare processes (rare decays, oscillations)

Quantum numbers, isotopic and quark structure of new hadrons

$J^P = 0^-$	$T = \frac{1}{2}$	$M_U = (M_U^0\, M_U^-)$	$M_U^0 = \bar{U}u,\ M_U^- = \bar{U}d$
$J^P = 0^-$	$T = \frac{1}{2}$	$M_D = (M_D^+\, M_D^0)$	$M_D^+ = \bar{D}u,\ M_D^0 = \bar{D}d$
$J = \frac{1}{2}$	$T = 1$	$B_{1U} = (B_{1U}^{++}\, B_{1U}^+\, B_{1U}^0)$	$B_{1U}^{++} = Uuu, B_{1U}^+ = Uud, B_{1U}^0 = Udd$
$J = \frac{1}{2}$	$T = 1$	$B_{1D} = (B_{1D}^+\, B_{1D}^0\, B_{1D}^-)$	$B_{1D}^+ = Duu,\ B_{1D}^- = Ddd, B_{1D}^0 = Dud$
$J = \frac{1}{2}$	$T = \frac{1}{2}$	$B_{2U} = (B_{2U}^{++}\, B_{2U}^+)$	$B_{2U}^{++} = UUu, B_{2U}^+ = UUd$
$J = \frac{1}{2}$	$T = \frac{1}{2}$	$B_{2D} = (B_{2D}^0\, B_{2D}^-)$	$B_{2D}^0 = DDu, B_{2D}^- = DDd$
$J = \frac{3}{2}$	$T = 0$	(B_{3U}^{++})	$B_{3U}^{++} = UUU$
$J = \frac{3}{2}$	$T = 0$	(B_{3D}^-)	$B_{3D}^- = DDD$

New heavy meson doublets M_U and M_D

$M_U^0 = (\bar{U}u)$ is stable - candidate on DM particles

Mass of new meson

Mass $M = m(M^0) \approx m(Q)$; $M^0 = (\bar{Q}q)$ (pseudoscalar meson)

$$(\sigma(M)v_r)^{exp} = (\sigma(M)v_r)^{theor}$$

$(\sigma(M)v_r)^{DM} = 2 \cdot 10^{-9}\ \mathrm{Gev}^{-2}$ The data on DM relic density

$$(\sigma(M)v_r)^{theor} \approx \sigma(Q\bar{Q} \to q\bar{q}, gg) = \frac{44\pi}{9}\frac{\alpha_s^2}{M^2}$$

$$M_0 \approx M_Q \approx 10\ \mathrm{TeV}$$

ZE effect

$$(\sigma(M)v_r) = (\sigma(M)v_r)_0 \cdot \frac{2\pi\alpha/v_r}{1-\exp(-2\pi\alpha/v_r)}$$

At M-scale $\alpha_w \sim 0.03$ and $v \sim 0.1 \to M \approx 15$ TeV.

Fine and hyperfine structure of excited states of heavy hadrons

FINE SPLITTING.

Mass-splitting of $M^0 = (\bar{U}u)$ and $M^- = (\bar{U}d)$

$$\Delta m = m(M^-) - m(M^0)$$

M-mesons $\Delta m > 0$, $(\sim 1\ \mathrm{MeV})$; (unstable $M^- \rightarrow \Delta m > m_e$)

Decay: $M^- \rightarrow M^0 e \bar{\nu}_e \quad \Gamma \approx G_F^2 (\Delta m)^5 / 60\pi^3$

$$\Delta m = (1 - 10)\ \mathrm{MeV} \longrightarrow \tau \sim (10^5 - 10^0)\ \mathrm{s}$$

M^- is long-lived $\rightarrow$ co-annihilation

M^- signals in cosmic rays (Bazhutov e.a.)

Hyperfine splitting

Heavy quark symmetry provides relations between masses of the first excited states $\frac{1}{2}(1^-)$ and ground states $\frac{1}{2}(0^-)$ of B and D mesons

$$\delta m_K = 400 \text{ MeV}$$
$$\delta m_D = 140 \text{ MeV}$$
$$\delta m_B = 45 \text{ MeV}$$

$$\frac{m(B^*) - m(B)}{m(D^*) - m(D)} = \frac{m_c}{m_b} \longrightarrow 0.32 \approx 0.31.$$

Then, for the case of heavy meson, $M = 10$ TeV, we get:

$$\frac{\delta m(M)}{\delta m(B)} = \frac{m(M^*) - m(M)}{m(B^*) - m(B)} = \frac{m_b}{M} \longrightarrow \delta m(M) \approx 2\text{KeV}.$$

The effect of hyperfine splitting has two principal phenomenological consequences in a study of hidden matter:

1. It provides additional channels of interaction of DM with photons and other SM particles.
2. This effect can manifest itself as kev-signals in underground detectors (XENON1 etc).

Luminosity of hidden matter

KeV range $\rightarrow \gamma$ -ray with $\lambda \sim 10^{-9}$ cm.

If $M^0 = (u\bar{U})$ has characteristic size an order of nucleon radius, $R_M \sim 10^{-13}$ cm, then $\lambda >> R_M$, cross-section is small.

At $\lambda_{trans} \lesssim R_M$, that is $E_\gamma \gtrsim 10$ MeV, the interaction γM^0 can be notesible. and hidden matter is not dark (luminous hidden matter).

Effect of luminosity can be observed for the case of narrow spectral line, $\Gamma = 1/\tau$ (long-lived excited states).

HFS provides effects with $O(keV)$ electron recoil in direct detection experiments (XENON1T signals, luminous dark matter)

$U(NM) > 0$ and $\sigma(NM \rightarrow NM) \sim 1$ barn, $\lambda = 1/(n\sigma) \sim$ cm.

Repulsive potential of NM interaction and large elastic cross-section lead to absorbtion and thermalization of heavy DM-particles in the planets and stars.

Low-energy interaction of nucleon and dark matter particles

$U(1)\cdot SU(3)$ -gauge scheme of interaction of nucleons and vector mesons

$$L_{NV} = g_\omega \omega_\mu(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n) + \frac{1}{2} g\rho^0_\mu(\bar{p}\gamma^\mu p - \bar{n}\gamma^\mu n)$$
$$+ \frac{1}{\sqrt{2}} g\rho^+_\mu \bar{p}\gamma^\mu n + \frac{1}{\sqrt{2}} g\rho^-_\mu \bar{n}\gamma^\mu p,$$

To apply gauge scheme for M -mesons we extend doublet (M^0, M^-) to triplet $M = (M^0, M^-, M^-_s)$, where $M^-_s = (s\bar{U})$.

Lagrangian of low-energy interactions of M -particles with vector singlet V^0_μ and octet V_μ is defined by the standard gauge form:

$$L_{MV} = (D^\mu M)^\dagger D_\mu M, \;\; D_\mu M = (\partial_\mu - itV^0_\mu - \frac{ig}{\sqrt{2}} V_\mu) M,$$

Physical Lagrangian of interaction of M -particles with vector mesons:

$$L_{MV} = ig_{\omega M}\omega^\mu(\bar{M}^0 M^0_{,\mu} - \bar{M}^0_{,\mu} M^0 + M^+_{,\mu} M^- - M^+ M^-_{,\mu})$$
$$+ (ig_{\omega M_s}\omega_\mu + ig_{\phi M_s}\phi_\mu)(M^+_s M^{-,\mu}_s - M^{+,\mu}_s M^-_s)$$
$$+ (\frac{ig}{2}\rho^0_\mu + ig_{\phi M}\phi_\mu)(\bar{M}^0 M^0_{,\mu} - \bar{M}^0_{,\mu} M^0 + M^+_{,\mu} M^- - M^+ M^-_{,\mu})$$
$$+ \frac{ig}{\sqrt{2}}\rho^{+\mu}(\bar{M}^0 M^-_{,\mu} - \bar{M}^0_{,\mu} M^-) + \frac{ig}{\sqrt{2}}\rho^{-\mu}(M^+ M^0_{,\mu} - M^+_{,\mu} M^0).$$

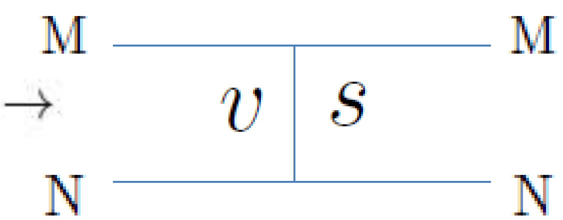
One-meson exchange approach to NM-interaction

Cold DM: Low-energy MNI model $MN \to (v, s) \to MN$, (ω, ρ)

Potential of MN-interaction in Born approximation

$$V(\vec{r}) = -\frac{1}{4\pi^2\mu}\int f(q)\exp(i\,\vec{q}\,\vec{r})\,d^3q,$$

$f(q) \to$



Asymptote of MN-potential: $V_v(r) = (K_v/r)\ \exp(-r/r_v)$

$V > 0$ MN-repulsion (at long distance)

Coupled states (MN) at low energy (cold DM) are absent

C.-C. restrictions. The problems of anomalous H and He

Cross-section of low-energy NM interactions

The expression for elastic MN scattering cross-section:

$$\sigma(N_a M_b \to N_a M_b) = \frac{g^4 m_p^2}{16\pi m_v^4}(1 + \frac{k_{ab}}{\sin^2\theta})^2,$$

where $N_a = (p, n)$, $M_b = (M^0, M^-)$, $g^2/4\pi \approx 3.4$, $\sin\theta = 1/\sqrt{3}$ and $k_{ab} = \pm 1$ for the case of p or n. Here, we used approximate relations $m_p \approx m_n$, $m(M^0) \approx m(M^-)$ and $m_v = m_\rho \approx m_\omega$.

As a result, we get large value of cross-section, for example $\sigma(pM^0 \to pM^0) \approx 0.9$ barn.

The expressions for non-elastic scattering of type $N_a M_b \to N_c M_d$, where $N_a = (p, n)$ and $M_b = (M^0, M^-)$

$$\sigma(N_a M_b \to N_c M_d) = \frac{g^4 m_N^2}{8\pi m_v^4}[1 - \frac{\Delta_{ab}}{E_p}]^{1/2}$$

Here, $E_p \approx m_p v_r^2/2$ and $\Delta_{ab} = m(M^-) - m(M^0) \pm (m_n - m_p)$ for $p \to n (n \to p)$

Consider the reaction $pM^0 \to nM^+$ From the threshold kinetic energy $E_p^{thr} = \Delta M + \Delta m \equiv \Delta_{11}$ it follows the value of velocity at the threshold $v_r^{thr} = \sqrt{2\Delta_{11}/m_p}$. For the case $\Delta_{11} = 10$ MeV we get rather large relative velocity $v_r^{thr} = 0.1 >> v_r \sim 10^{-3}$. The reaction $nM^0 \to pM^-$ can be threshold and non-threshold depending on the value $\Delta M/\Delta m$. We should note that this reaction lead to the final states with unstable particles, they go through two stage, $nM^0 \to pM^- \to pM^0 e^- \bar{\nu}_e$.

Interaction of hadronic DM with standard leptons

Charge transition $M^0 \to M^- W$ is described by effective vertex in the form:

$$L^{eff}(WMM) = iG_{WM} W^{+\mu}(\bar{M}^0 \partial_\mu M^- - \partial_\mu \bar{M}^0 M^-) + h.c.$$

The value of effective constant G_{WM} is determined by matching the expressions for width of decay $M^- \to M^0 W^- \to M^0 e^- \bar{\nu}_e$ with help of standard form-factor method and using the model Lagrangian:

$$\Gamma(M^- \to M^0 e^- \bar{\nu}_e) \approx \frac{g^2 G_{WM}^2}{15 \cdot 2^4 \pi^3} \frac{(\Delta M)^5}{M_W^4}.$$

The comparison of this expression with standard one leads to the relation

$$G_{WM}^2 = g^2 |U_{ud}|^2 / 2^3 \text{ or } G_{WM} = g U_{ud} / 2\sqrt{2}$$

Low-energy interaction of M-particles with Z-boson can be represented in the same form:

$$L^{eff}(ZMM) = iG_{ZM}(\bar{M}_q \partial_\mu M_q - \partial_\mu \bar{M}_q M_q)$$

In contrast to charge vertex, effective coupling G_{ZM} is generated by interactions of Z with both quarks Q and q. So, it is defined by the coupling $g_1 \sin\theta_w$ in vertex ZUU and $g_2 c_a / 4\cos\theta_w$ in standard vertex Zqq, which are different.

Cross-sections of DM-Lepton scattering

$$\sigma(l^- M^0 \to \nu_l M^-) = \frac{3g^4|U_{ud}|^2}{2^{10}\pi M_W^4} s(1 - \frac{M^2}{s})^2$$

$l = e, \mu, \tau$ $\sqrt{s}$ is full energy in the center of mass system

Full process $lM^0 \to \nu_l M^- \to \nu_l M^0 e\bar{\nu}_e$

Convolution formula for the process $lM^0 \to \nu_l M^0 e\bar{\nu}_e$:

$$\sigma(lM^0 \to \nu_l M^0 e\bar{\nu}_e) = \int_a^b dq^2 \sigma(lM^0 \to \nu_l M^-(q^2)) \frac{q\Gamma(M^-(q^2))}{\pi|q^2 - M_0^2 + iq\Gamma(M^-(q^2))|^2}$$

At $q^2 = M_-^2$ the cross-section has acute peak and the process pass through at small momenta transfer from lepton.

Conclusions

- HDM is not excluded by EW and CC restrictions.
- Large mass of DM hadrons (10 TeV and upper).
- Signals of charge M-decay: metastable charge particle and low-energy leptons.
- Hyperfine mass-splitting in M-M*: signals - low-energy photons (KeV) and luminosity of DM.
- Analysis of HDM scenario with account of M*, co-annihilation, absorbtion and thermalization.
- Description of DM interaction with usual matter.