GRAVITATION

ELECTROMAGNETISM

NEW LONG-RANGE FORCES

and their action on ANTIMATTER

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4 kinds of interactions

Strong, electromagnetic, weak and gravitational

with rather different properties

subject of the meeting:

How does GRAVITY act on ANTIMATTER ?

we think we know, but we should test ...

and a related subject:

Are there other kinds of interactions ?

it would be presomptuous to pretend that we know all of them !

NEW INTERACTIONS MAY EXIST

and remain unknown to us ...

how could we know about that ?

Can we anticipate something about how these new interactions could act

on various forms of matter

ordinary matter,

ANTIMATTER

and DARK MATTER ?

Electromagnetic and gravitational interactions are long-ranged

due to the exchanges of massless particles.

The spin-1 ***photon*** *is the massless particle associated with*

the quantization of A^μ

the massless $U(1)$ ***gauge field*** *of (quantum) electrodynamics*

Weak, Electromagnetic and Strong interactions invariant under

$SU(3) \times SU(2) \times U(1)$ **gauge group of STANDARD MODEL**

spin-1 gauge quanta, ***associated with symmetries****, responsible for interactions:*

$$\begin{cases} \textit{photon} & \textit{massless} \\ W^\pm \textit{ and } Z & m_{W,Z} \simeq 80, 91 \text{ GeV} \\ \textit{gluons} & \textit{massless} \end{cases}$$

What about gravitational interactions ?

Lorentz and Poincaré symmetries of Relativity in flat spacetime

Space-time may be curved $\longrightarrow$ *gravitation*

Equivalence principle: all (free) particles fall in the same way

(In the absence of other forces)

all particles behave in the same way in a gravitational field, independently of their nature

Gravitational interactions described (at classical level) by general relativity

believed to be associated, at quantum level, to exchanges of

massless spin-2 GRAVITONS

Electromagnetism acts on electric charges, opposite for particles and antiparticles

Electromagnetic force changes sign when replacing a particle by its antiparticle

$$\boxed{\text{coupling } \; e\,Q\,J_\mu\,A^\mu}$$

Universal coupling to CHARGE

Particles and antiparticles behave in opposite ways in electromagnetic field

Gravitation acts on mass (for particles or objects at rest) or more precisely energy and momentum, given by the energy-momentum tensor $T^{\mu\nu}$

$$\boxed{\text{coupling } \; \kappa\,T_{\mu\nu}\,h^{\mu\nu}}$$

Universal coupling to MASS *(through $T_{\mu\nu}$)*

Particles and antiparticles behave in the same way in gravitational field

According to quantum field theory

PARTICLES and ANTIPARTICLES have the SAME MASS

They should behave exactly in the same way in a gravitational field

(in the absence of other forces) **in agreement with equivalence principle**

but it is certainly good to verify experimentally this is indeed the case

as there are occasionnal claims that

antiparticles may have "negative masses" ; and "fall upwards".

Imagining antiparticles with "negative masses" would be extremely problematic

especially also in view of existence of self-conjugate massive particles :

π°, η, ψ *or* Υ = **massive self-conjugate** $q\bar{q}$ **states**

or positronium e^+e^-.

Indeed

$$m(\Upsilon) \simeq 2\,m_b = m_b + m_{\bar{b}}$$

$$m(\textit{positronium}) \simeq 2\,m_e = m_{e^-} + m_{e^+}$$

make it

very hard to see how one could have $m_{\bar{q}} = -\,m_q$, **or** $m_{e^+} = -\,m_{e^-}$ **!**

which don't seem to make sense !

Still this may look like theoretical prejudice, and is worth being tested experimentally

even if simply to comfort the validity of our general ideas on ***Equivalence Principle***

and description of particles and antiparticles through ***Quantum Field Theory***

(as one may like to check whether a neutrino travels at $v_\nu \leq c$, or not ... !)

In addition to checking these general principles

we have to consider the possible existence of new interactions.

Action of gravity may be effectively modified by

an EXTRA NEW FORCE

adding its effects to those of gravity.

This would lead to

(apparent) violations of the equivalence Principle

(these are already very strongly constrained, for a new long-range force)

Then, in principle:

Particles and antiparticles could effectively "fall" in different ways

if a new force distinguishes between them

very much as two bodies of different compositions

could effectively "fall" in slightly different ways

discuss whether significant violations of EP might occur,

when comparing action of "effective gravity" on particles and antiparticles,

or are in fact already practically excluded, given the very high precision of EP tests ...

also having in mind that things may be different when comparing

$$e^+ \leftrightarrow e^- , \qquad \bar{p} \leftrightarrow p$$

$$\bar{n} \leftrightarrow n , \qquad \bar{H} \leftrightarrow H$$

Additional interactions may be due to new (spin-0 or spin-1) messengers

as expected in unified theories

cf. **Brout-Englert-Higgs... boson** responsible for particle masses

expected to be discovered soon at LHC

with m practically constrained between 114 $\leftrightarrow$ 145 GeV

(only missing part in Standard Model)

corresponding interaction short-ranged, $\simeq \mathbf{10^{-16}}$ cm, as for weak interactions

advantage of considering

spin-1 rather than spin-0 messengers *(other than SM Higgs boson)*:

spin-1 messengers can be coupled universally through the gauge principle

using a local symmetry

which symmetry ??

SM cannot be the end of the story, there must be

NEW PHYSICS beyond the Standard Model

what sort of new physics ?

maybe with an extended gauge group, beyond $SU(3) \times SU(2) \times U(1)$?

In **grand-unified theories** ($SU(5)$, ...)

new gauge bosons $X^{\pm 4/3}$, $Y^{\pm 1/3}$, with $m_X, m_Y \approx 10^{16}$ GeV

$\longrightarrow$ very short-ranged ($\sim 10^{-30}$ cm) interaction leading to **proton decay** ...

or

$$\boxed{SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times SU(2) \times U(1) \times \underline{\text{extra-}U(1)}}$$

as discussed in **Supersymmetric extensions of Standard Model** (USSM)

since 1977 *PL 69B (1977) 489*

Practically all extensions of the standard model, supersymmetric or not, involve **new spin-1 or spin-0 particles**.

Some may be neutral and light, very light or even massless mediating new long-range forces.

spin-0 exchanges: particles and antiparticles behave in the same way

(attractive spin-0 induced force)

spin-1 exchanges with vector couplings: particles and antiparticles behave oppositely

(attractive or repulsive spin-1 induced force)

most interesting case

massless or very light spin-1 bosons called U bosons

naturally obtained from **extra-$U(1)$ gauge symmetry**

(spin-1 exchanges with axial couplings: particles and antiparticles behave in the same way)

Where can **extra-$U(1)$ come from ?**

how a light U could be detected ?

Light U, *possibly leading to effective modifications of gravity,*

discussed since 1980 *PLB 95 (1980)285, NPB 187 (1981)184, ...*

from **SUSY SM with 2 doublet Higgs (super)fields** $\begin{pmatrix} h_1^0 \\ h_1^- \end{pmatrix}, \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}$

allowing for the possibility of rotating independently the two doublets

thanks to **extra-$U(1)_A$ symmetry** $h_1 \to e^{i\alpha}\, h_1, \;\; h_2 \to e^{i\alpha}\, h_2$ *of 2 HD models*

possibly combined with B, L *and* Y *symmetries* *general discussion, under simple hypothesis* *NPB 347 (1990) 743*

extra-$U(1)$ acts *(on SM particles) as*

combination of $B, L, Y,$ with $U(1)_A$ generator *(if 2 Higgs doublets as in SUSY)*

After mixing between neutral gauge bosons: U *current =*

AXIAL part *(depending on Higgs sector, 2 doublets + possible singlet ...)*

+ **VECTOR part** *c.l. of* B, L *(or $B - L$) and* **electromagnetic** *currents*

+ *possible* **DARK MATTER** *contribution* **(if Light DM particle)**

Axial part may exist, but strongly constrained from particle physics experiments
not discussed here

quite interesting effects in

$$\psi \to \gamma\, U\,,\ \Upsilon \to \gamma\, U\,, K^+ \to \pi^+ U\,, e^+e^- \to \gamma U\,,$$

$$g_\mu - 2,\ g_e - 2,$$

parity-violation effects in atomic physics, ...

If no axial part (or ignoring axial part),

U coupled to SM particles through a VECTOR current, e.g.

$$J_U^\mu \; = \; \alpha \, J_B^\mu + \; \beta_i \, J_{L_i}^\mu + \gamma \, J_{em}^\mu + \; J_{dark}^\mu$$

or, taking constraints from grand-unification into account

$$\boxed{J_U^\mu \; = \; \alpha \, J_{B-L}^\mu + \; \gamma \, J_{em}^\mu + \; J_{dark}^\mu}$$

For **ordinary neutral matter (or antimatter)**:

new force acts on combination of B and L, i.e. effectively of Z and N

may lead to (apparent) violations of the Equivalence Principle,

must be very small for a long range force

with a new interaction constrained typically $<$ *(roughly* 10^{-9} *to* 10^{-10}*) strength of gravity*

(will be tested in space by MICROSCOPE, testing the EP at 10^{-15}, down to roughly 10^{-12})

given the very strong existing constraints,

no significant effect expected between neutral matter and antimatter

In addition, taking into account **grand-unification constraints**:

$\boxed{\textbf{expected } U \textbf{ coupling to } B-L \textit{ (combined with } Q\textit{)}, \textbf{ which vanishes for } H \textbf{ and } \bar{H}}$

PLB 172(1986)363, 227(1989)127 ...

no differential effect $H/\bar{H}$ expected at all !

More fun with positrons and electrons ?

no such extremely strong constraints exist on the possible

contribution of electromagnetic current to $\boldsymbol{U}$ *current*

as EP tests have been performed with neutral particles or bodies !

An extreme toy-model situation to contemplate

is one for which **positrons** (or electrons) would

“fall upwards”

(in a vanishing electromagnetic field, a difficult thing to realize)

their antiparticles falling downwards with enhanced acceleration

(if they experience a sufficient U*-field generated by Earth proportionnally to a combination of* Q *(*$\simeq 0$*) and (with a very small coefficient)* B *and* L *or* $(B-L)$ *)*

(Tests of fund. laws in physics, Moriond Proc. M60 (Jan. 1989) 561;

“ General characteristics of a spin-1-induced “fifth force” ”

cf. part “**Grand-unification and the fall of antimatter**”)

Interesting extreme case,

$\boldsymbol{U}$ coupled to SM through **electromagnetic current**

(NPB 347 (1990) 743)

$$\boxed{\boldsymbol{U} = \text{“dark photon”}}$$

couples (very weakly) to charged SM particles (and dark matter particles)

CONCLUSIONS

Comparing the behavior of particles and antiparticles in a gravitational field

would allow to further establish the validity of the Equivalence Principle

and of the basic principles of Quantum Field Theories

One should also be attentive to possible new long-range forces,

as mediated by a massless or light U boson gauging an extra-$U(1)$ symmetry

Hard to imagine how H and $\bar{H}$ would fall

or could be measured to effectively fall differently

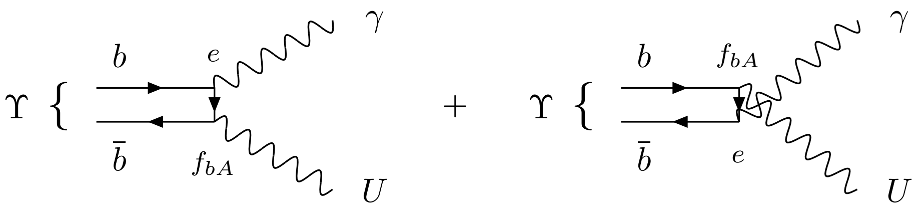
(but more room for surprises with charged particles, especially electrons and positrons)

The action of gravity on antimatter is worth being tested

Les transparents auxquels vous avez échappé ...

SEARCHING FOR A LIGHT U in quarkonium decays

$$\Upsilon \to \gamma U \,, \; \psi \to \gamma U$$



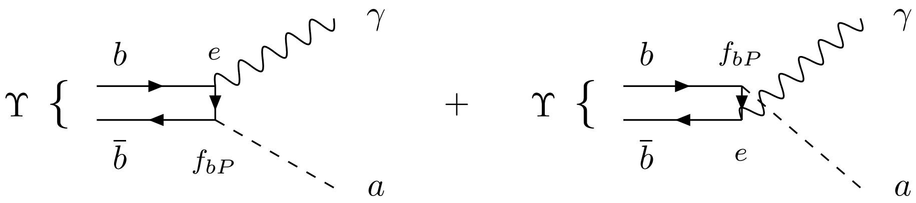
does not vanish even if U *couplings to* b *(*f_{bA} *and* f_{bV}*)* $\to 0$ *!!*

very light U *behaves as spin-0 pseudoscalar with* **effective pseudoscalar coupling:**

$$\boxed{f_{q,l\;P} \;=\; f_{q,l\;A}\,\frac{2\,m_{q,l}}{m_U}}$$

NPB 187, 184, 1981, ... ,

(equivalence theorem , as in SUSY where very light spin-$\frac{3}{2}$ gravitino $\leftrightarrow$ spin-$\frac{1}{2}$ goldstino)



Amplitude for producing U proportional to gauge coupling

$$\mathcal{A}\,(\,A\ \longrightarrow\ B\ +\ U_{\text{long}}\,)\ \ \propto\ \ g\text{''}\ \ \ldots$$

$$\uparrow$$

may be very small !!

but longitudinal polarisation $\epsilon_L^\mu \simeq \dfrac{k^\mu}{m_U}$ *singular when* $g\text{''} \longrightarrow 0$, *as* $m_U \propto g\text{''}\ \ldots \longrightarrow 0$ *!*

$$\boxed{\mathcal{A}\,(\,A\ \longrightarrow\ B\ +\ U_{\text{long}}\,)\ \ \propto\ \ g\text{''}\ \frac{k_U^\mu}{m_U}\ <B\,|J_{\mu\,U}|\,A>\ =\ \frac{1}{F_U}\ k_U^\mu\ <B\,|J_{\mu\,U}|\,A>}$$

F_U = *symmetry-breaking scale* $\qquad k^\mu\,\bar\psi\,\gamma_\mu\gamma_5\,\psi\ \longrightarrow 2\,m_q\,\psi\,\gamma_5\,\psi$

Interaction proportional to $\dfrac{2\,m_q}{F_U}$

A very light U *does not decouple for very small gauge coupling !*

behaves as "eaten-away" pseudoscalar Goldstone boson a

effective pseudoscalar coupling: $\quad f_{q,l\ P}\ =\ f_{q,l\ A}\ \dfrac{2\,m_{q,l}}{m_U}$

$$\Rightarrow \quad \boxed{\boldsymbol{B(\Upsilon \to \gamma\, U) \;\simeq\; B(\Upsilon \to \gamma\, a)}}$$

same experiments can search for light spin-1 gauge boson, or spin-0 pseudoscalar, or scalar

$$\textit{decays:} \quad \begin{cases} \boldsymbol{U} \;\longrightarrow\; \boldsymbol{\nu\bar{\nu}} \;\; \textit{(or light dark matter particles)} \\ \boldsymbol{U} \;\longrightarrow\; \boldsymbol{e^+e^-,\; \mu^+\mu^-,\; q\bar{q},\; \tau^+\tau^-} \;\; \textit{(depending on } m_U\textit{)} \end{cases}$$

$$\Rightarrow \textit{search for} \quad \boxed{\begin{cases} \boldsymbol{\Upsilon \;\to\; \gamma \;+\; invisible} \\ \boldsymbol{\Upsilon \;\to\; \gamma \;+\; e^+e^- \;\; (\text{or} \;\; \mu^+\mu^-,\; \tau^+\tau^-),\; \ldots\,)} \end{cases}}$$

Light U behaves very much as spin-0 "axionlike" (eaten-away) pseudoscalar a

$\psi(\Upsilon) \to \gamma + inv.$ *excluded standard axion in the 80's ...*

to avoid excluding a U with invisible decays having "eaten away" an axionlike pseudoscalar

break $U(1)_A$ symmetry through 2 doublets h_1, h_2 + extra singlet with much larger v.e.v.

(as in U(N)MSSM with $\lambda H_1 H_2 S$ superpotential) *PF, PLB 95, 285, 1980; NPB 187, 184, 1981*

$$h_1 \to e^{i\alpha} h_1, \quad h_2 \to e^{i\alpha} h_2, \quad s \to e^{-2i\alpha} s$$

A gets mixed with "almost inert" singlet s

U behaves as almost "invisible" axionlike pseudoscalar a

$$a = \boxed{\cos\zeta} \; \underbrace{\left(\sqrt{2}\ \mathrm{Im}\,(\sin\beta\, h_1^\circ + \cos\beta\, h_2^\circ)\right)}_{A} + \sin\zeta \; \underbrace{(\sqrt{2}\ \mathrm{Im}\, s)}_{\text{singlet}}$$

$r = \cos\zeta$ = **INVISIBILITY PARAMETER**

(reduces strength or effective strength of U or a interactions, cf. "invisible axion")

$\psi \to \gamma U$, $\Upsilon \to \gamma U$ *decay rates* $\propto r^2 = \cos^2\zeta$

ψ and Υ decays provide strong limits on axial couplings f_A of U to c or b

$$f_{q,l\ A} \simeq \underbrace{2^{-\frac{3}{4}}\ {G_F}^{\frac{1}{2}}\ m_U}_{2\ 10^{-6}\ m_U(\mathrm{MeV})} \times \begin{cases} \cos\zeta\ \cot\beta & (u,c,t) \\ \cos\zeta\ \tan\beta & (d,s,b;\ e,\mu,\tau) \end{cases}$$

or equivalent pseudoscalar couplings f_p of a

$$f_{q,l\ P} \simeq \underbrace{2^{\frac{1}{4}}\ {G_F}^{\frac{1}{2}}\ m_{q,l}}_{4\ 10^{-6}\ m_{q,l}(\mathrm{MeV})} \times \begin{cases} \cos\zeta\ \cot\beta & (u,c,t) \\ \cos\zeta\ \tan\beta & (d,s,b;\ e,\mu,\tau) \end{cases}$$

For invisibly decaying U (with $B_{inv} \simeq 1$): $\psi \to \gamma U < 1.4\ 10^{-5}$, $\Upsilon \to \gamma U < 4\ 10^{-6}$

$$\boxed{\begin{array}{l} r x = \cos\zeta\ \cot\beta < .75 \ \Leftrightarrow\ |f_{cA}| < 1.5\ \ 10^{-6}\ m_U(\mathrm{MeV}) \ \Leftrightarrow\ |f_{cP}| < 5\ \ 10^{-3} \\ r/x = \cos\zeta\ \tan\beta < .2 \ \Leftrightarrow\ |f_{bA}|\ <\ 4\ \ 10^{-7}\ m_U(\mathrm{MeV}) \ \Leftrightarrow\ |f_{bP}| < 4\ \ 10^{-3} \end{array}}$$

(limits to be divided by $\sqrt{B_{inv}}$)

requires a to be mostly singlet

	doublet fraction	$r^2 = \cos^2\zeta < 15\%\ /B_{inv}$
or: Υ *limit*	$\Rightarrow$ *doublet fraction*	$r^2 = \cos^2\zeta <\ 4\%\ /(\tan^2\beta\ B_{inv})$

if large $\tan\beta$**,** Υ ***limit*** $\Rightarrow$ ***not much chance to see*** $\psi \rightarrow \gamma U_{inv}$ **...**

$$B(\psi \rightarrow \gamma U)\; B_{inv} \;\lesssim\; 10^{-6}/\tan^4\beta$$

independently of B_{inv}

Furthermore, with $f_{eA} = f_{bA}$ *from universality constraints,*

$\Upsilon \to \gamma + U_{inv}$ *decays constrain* ***axial U couplings to electron***

$$|f_{eA}| < 4 \; 10^{-7} \; m_U(\mathrm{MeV}) \, / \sqrt{B_{\mathrm{inv}}(U)} \,, \qquad |f_{eP}| < 4 \; 10^{-7} / \sqrt{B_{\mathrm{inv}}(U)}$$

For invisible decays:

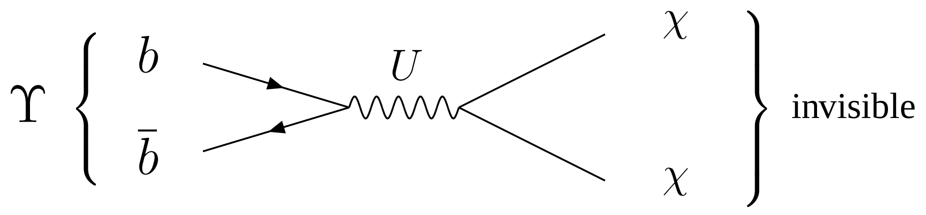
$|f_{eP}| < \frac{1}{5}$ **[standard Higgs coupling to electron** $(2 \; 10^{-6})$**]**

PRD 75, 115017 (2007);PLB 675, 267 (2009); PRD 81, 054025 (2010)

(also limits for $U \to e^+e^-, \; \mu^+\mu^-, \ldots$**)**

(not discussed here)

LIGHT DARK MATTER in Υ DECAYS



Invisible Υ decay into LDM particles

$$\begin{cases} \Upsilon \to \quad \chi\,\chi \;= \quad \textbf{invisible} & \textit{(V coupling)} \\ \Upsilon \to \gamma\;\chi\,\chi = \gamma + \textbf{invisible} & \textit{(A coupling)} \end{cases}$$

could be sizeable, for DM particles with relatively large cross sections*: PLB 269 (1991) 213*

$\Upsilon \to \chi\,\chi$ **and** $\gamma\;\chi\chi$ **test vector and axial couplings to** b

(no decay $\Upsilon \to$ invisible mediated by spin-0 exchanges)

What may be the expected rates ?

For Light DM particles

Invisible Υ BR cannot be "predicted" from DM annihilation cross section !

different processes involved, $b\bar{b} \to \chi\chi$ and $\chi\chi \to f\bar{f}$, at different energies ....

(and if LDM interactions due to spin-0 exchanges, invisible Υ decay forbidden)

For invisible Υ decays mediated by a light U,

$$\Upsilon \to \underbrace{\chi\,\chi}_{\text{inv}} < 3\ 10^{-4} \ \textit{(BABAR)} \Rightarrow \qquad |c_\chi\, f_{bV}| < 5\ 10^{-3}$$

and from ψ decays,

$$\psi \to \underbrace{\chi\,\chi}_{\text{inv}} < 7.2\ 10^{-4} \ \textit{(BES II)} \Rightarrow \qquad |c_\chi\, f_{cV}| < .95\ 10^{-2}$$

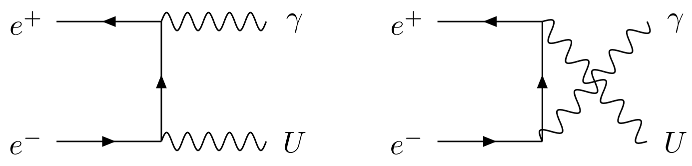
PRD 74(2006)054034, ... , PRD 81(2010)054025

Other processes (and constraints)

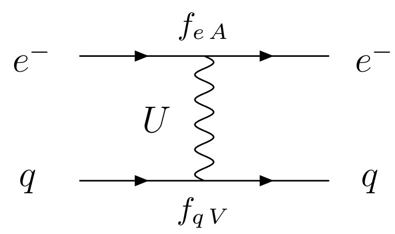
Dark Matter annihilations, 511 keV annihilation line, $g_e - 2$, $g_\mu - 2$,

ν scatterings, supernovae explosions, ...

Production in $e^+ e^- \to \gamma U$



Parity violations in atomic physics



strong limit : $\sqrt{|f_{eA}\, f_{qV}|} \; < \; 10^{-7}\, m_U(\mathrm{MeV})$

With constraints from ψ, Υ *and* K^+ *decays,*

may favor **vector U coupling to SM particles** *through* $\boxed{\alpha\,(B-L) + \gamma\, Q}$

possibly through electromagnetic current **(→ "dark photon" searches, with $U \equiv A'$)**