Nuclear fusion catalyzed by doubly charged scalars:

Implications for energy production

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Doubly charged scalar particles $X^{\pm\pm}$

Predicted by a number of popular extensions of the SM:

- Type II seesaw
- Zee-Babu model of neutrino mass
- Left-Right model
- Georgi-Mahacek model
- The 3-3-1 model
- Little Higgs model
- Simplified models (doubly charged scalars in various representations of $SU(2)_L$ added to the SM)

Can be long-lived or even stable!

Alimena *et al.* 1903.04497; Acharya *et al.* 2004.11305; Hirsch, Maselek and Sakurai, 2103.05644;...

Possible reasons: new (approximately) conserved quantum number; weak coupling; limited phase space in any allowed decay.

Simplest example: add to the SM an uncolored $SU(2)_L$-singlet scalar field X with $Y = 2$. Can interact

- with γ and Z^0
- with the SM Higgs through $(H^\dagger H)(X^\dagger X)$ term in the Higgs potential
- with RH charged leptons through $h_X l_R l_R X$+$h.c.$ Yukawa coupling

Only the last term leads to instability of X.

X will be long-lived if h_X is small; stable if Yukawa coupling is forbidden by symmetry (e.g. Z_2: $X \to -X$).

Long-lived doubly charged particles:

- ♢ Actively looked for experimentally
- ♢ Up to now have not been found

Expts. like MoEDAL should have enhanced sensitivity

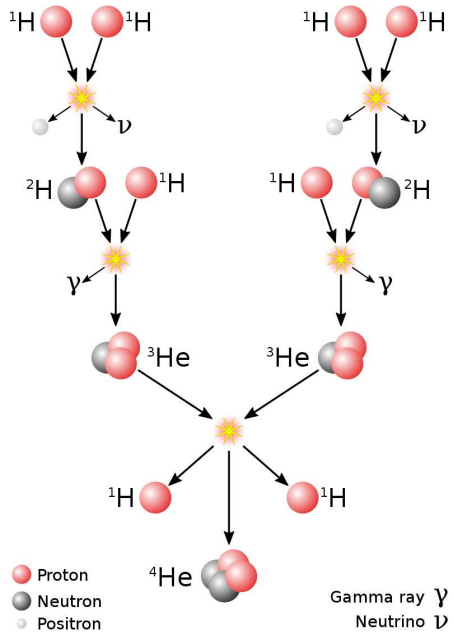
If found: May have unexpected and important uses!

⇒ Catalysis of fusion of light nuclei with possible implications for energy production and cosmology

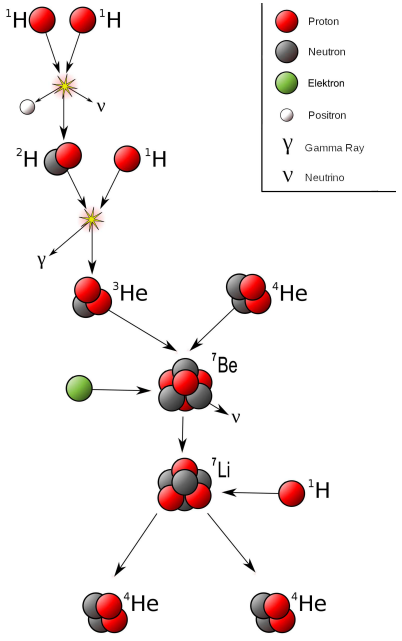
Nuclear fusion reactions

Source of stellar energy

Thermonuclear reactions in the Sun and other similar-size stars: $p - p$ cycle



Branch 1



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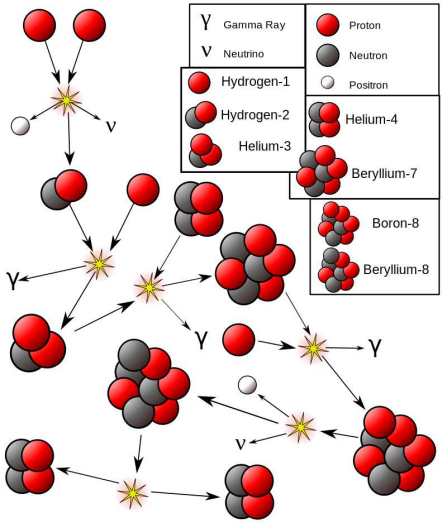


Branch 3

Net effect: $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}.$

Controlled thermonuclear fusion

Most often considered reaction:

$$d + {}^3\mathrm{H} \to {}^4\mathrm{He} + n + 17.6\,\mathrm{MeV}$$

(larger cross section and higher energy yield than for $d - d$ fusion reactions)

Deuterium: 1.5 ml of D_2O in every 10 l of natural water.

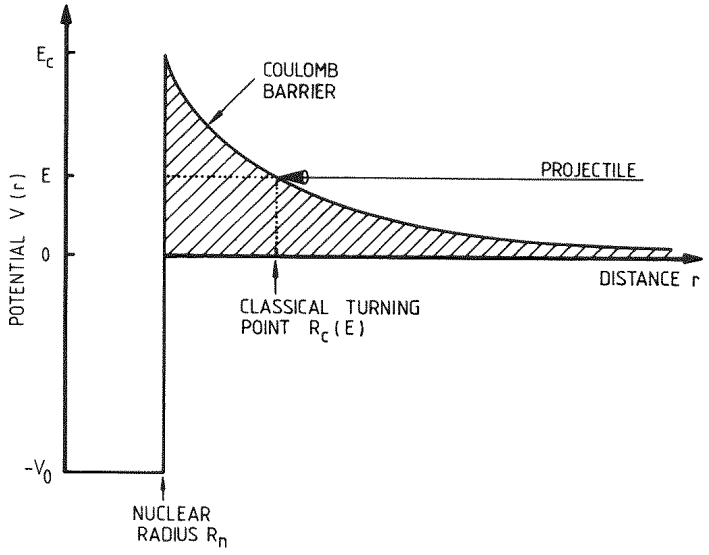
Tritium: Natural abundance at the Earth (10^{-18} of hydrogen) due to interactions of cosmic rays with the atmosphere. Most efficiently produced in nuclear reactors through ${}^6\mathrm{Li} + n \to {}^4\mathrm{He} + {}^3\mathrm{H}$, ${}^7\mathrm{Li} + n \to {}^4\mathrm{He} + {}^3\mathrm{H} + n$.

Many advantages over fission: Reduced radioactivity in operation, little high-level nuclear waste, ample fuel supplies, increased safety.

But: necessary combination of temperature, pressure, and duration is difficult to achieve in practice.

Why is high T necessary?

Coulomb repulsion between positively charged nuclei



$$E_{\mathrm{C}} = \frac{Z_1 Z_2 e^2}{R_1 + R_2} \simeq 1.2\,\mathrm{MeV}\,\frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}}$$

$$(R \simeq 1.2 A^{1/3}\,\mathrm{fm})$$

For $d - d$ fusion: $E_{\mathrm{C}} \simeq 0.47\,\mathrm{MeV}$

In the center of the Sun: $T_c \simeq 1.3\,\mathrm{keV}$
$= 15.6 \times 10^6\,\mathrm{K}$.

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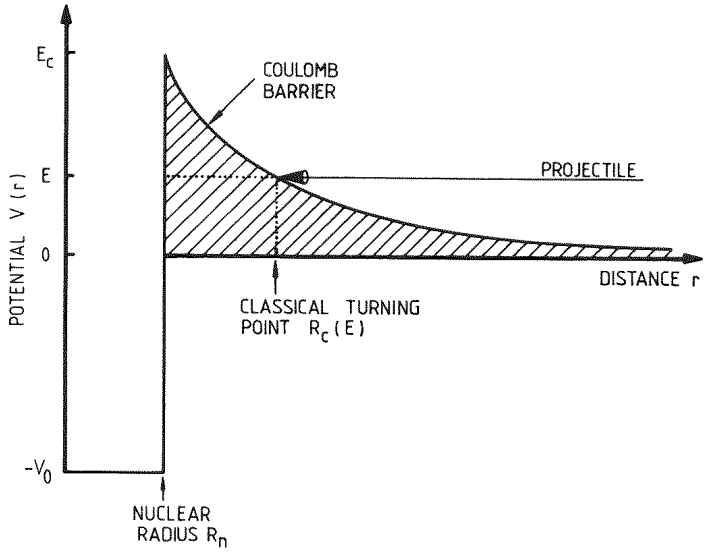

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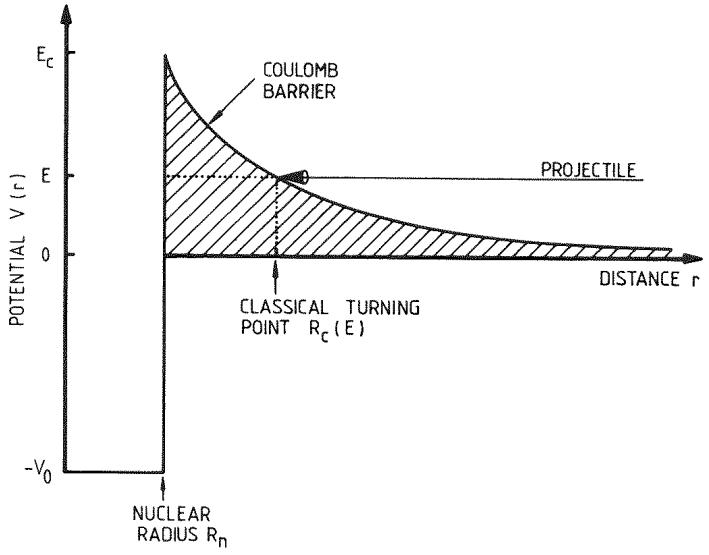

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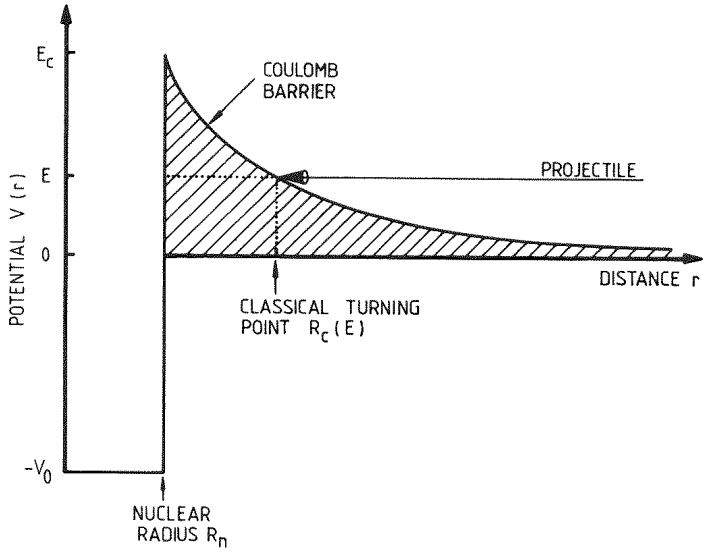

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P quickly increases with T ($\Rightarrow$ increasing $\bar{E}$).

Controlled fusion studies

Various approaches:

- Magnetic confinement (TOKAMAK, Stellarator, ...)
- Inertial confinement (lasers, electron beams, ion beams)
- Electrostatic confinement . . .

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Country	Organization	Device Name	Device Configurati..	Device Type	Device Status	Design	Ownership
Australia	HB11 Energy	HB11	Laser/Inertial	Laser Fusion	Planned	Exp	Private
Brazil	Federal University of Espírito Santo	NOVA-FURG	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	National Institute for Space Research-IN..	ETE	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	University of São Paulo	TCABR	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Canada	General Fusion Inc	General Fusion	Altern. Concepts	Magnetized Target Fusi..	Under construc..	Exp	Private
	University of Saskatchewan	STOR-M	Tokamaks	Conventional Tokamak	Operating	Exp	Public
China	Chinese Consortium	CFETR	Tokamaks	Conventional Tokamak	Planned	Demo	Public
	ENN	EXL-50	Tokamaks	Spherical Tokamak	Operating	Exp	Private
	Hefei Institutes of Physical Science	HT-7	Tokamaks	Conventional Tokamak	Operating	Exp	Public

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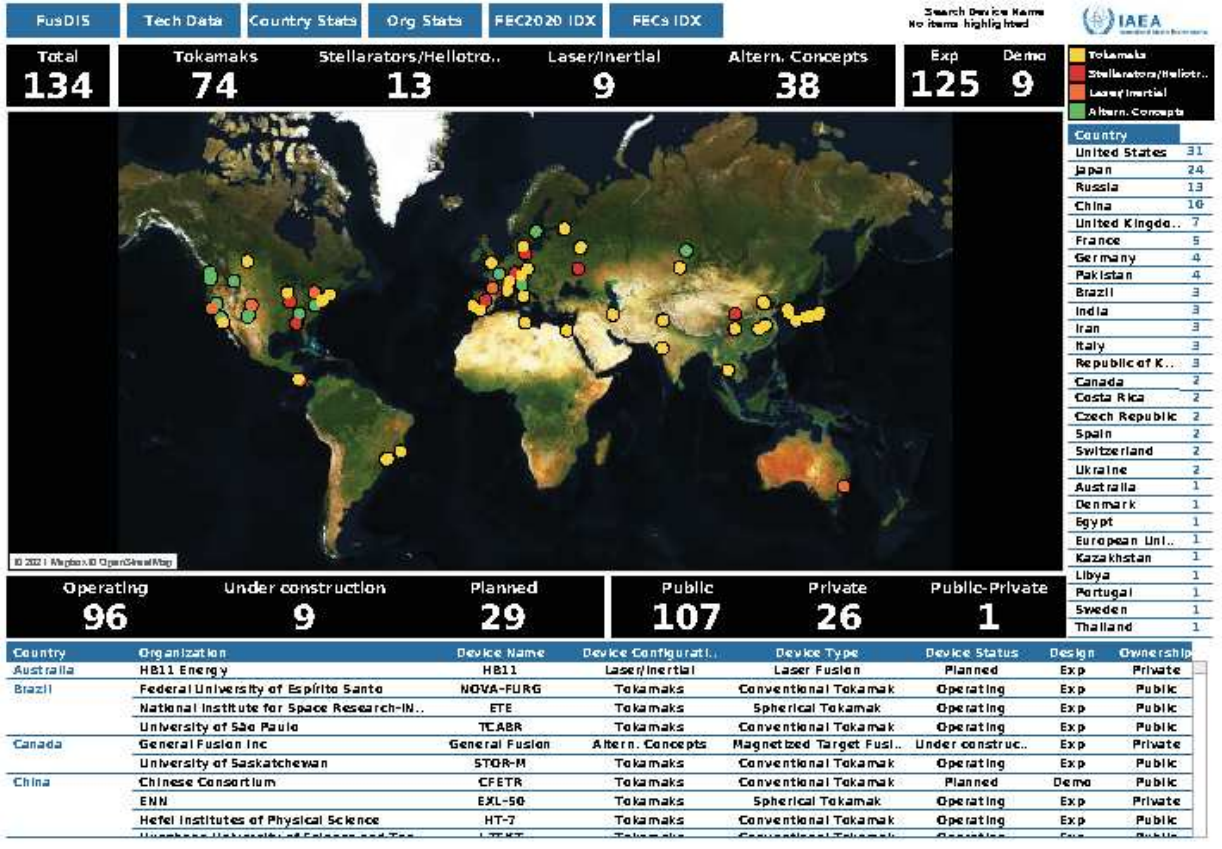

- ◇ Significant progress in recent years
- ◇ Still far from practical implementation for energy production

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Inject μ^- into e.g. $d - t$ mixture:

Muons push away electrons and form muonic atoms with t (or d)

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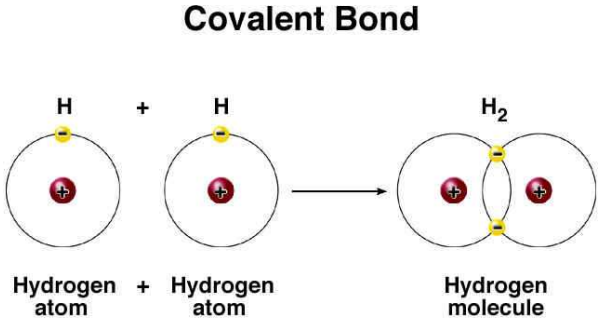
Muons are not consumed; may participate in further fusion reactions $\Rightarrow$ muon catalyzed fusion (μCF).

Much faster fusion reactions

Formation of μ-molecules (or μ-molecular ions) and subsequent fusion.
Hydrogen molecule: distance between protons of order of a_e.



μ-molecules (or molecular ions): Distance between nuclei $\sim a_\mu \quad \Rightarrow$

$$(dt\mu) \to {}^3\mathrm{He} + n + \mu.$$

Compared to "in-flight" fusion, the rate is enhanced by a factor $(\bar{r}/a_\mu)^3 \sim 10^6$ (average distance between atoms in gas $\bar{r} \sim 5 \cdot 10^{-9}\,\mathrm{cm}$).

Similarly for $p-d$, $d-d$, $p-t$ and $t-t$ fusion reactions.

Rise and fall of μCF

- First discussed by C. Frank in 1946 in connection with interpretation of expt. by Lattes, Occhialini & Powell ($\pi \to \mu\nu$ decay discovery; proved π and μ are different particles). Considered and rejected μ-catalyzed $p - d$ fusion as a possible interpretation.
- First discussion of μCF for energy production by Sakharov in 1947 (Lebedev Inst. report)
- More detailed analyses: Zeldovich (1954); Sakharov and Zeldovich (1957)
- Experimental discovery (by accident, but correct interpretation) Alvarez *et al.*, 1957
- First detailed analysis, including prospects for energy production: Jackson (1957)

. . .

Once considered a prospective candidate for cold fusion.

Experimental studies in many labs throughout the world (LANL, PSI, Dubna, LNPI, KEK, RAL...)

Several hundreds of publications in the 1960s – 1990s.

Many dedicated conferences.
Dedicated journal *Muon catalyzed fusion* published in Basel (Switzerland) in 1987-1992.

Rise and fall of μCF – contd.

An obstacle for energy production by μCF (Jackson 1957, Zeldovich 1957):
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$\Rightarrow$ μCF cannot be used as a viable source of energy.

Other heavy long-lived charged particles?

Possibility of energy generation through the catalysis of nuclear fusion by hypothetic long-lived or stable singly charged particles: Zeldovich (1957); Rafelski (1989); Ioffe, Okun, Shifman & Voloshin (1979); Hamaguchi, Hatsuda & Yanagida (2006).
By fractionally charged particles (heavy quarks): Zweig (1978).

It was found that these processes suffer from the same problem of catalytic poisoning as μCF and cannot be useful sources of energy.

In particular, Ioffe *et al.* showed that reactivation of catalyst particles by irradiating their atomic bound states with He nuclei by neutron beams (suggested by Zweig) would require beams $\sim$9 orders of magnitude higher than currently produced by most powerful nuclear reactors.

X-catalyzed fusion (XCF)

X-particles may catalyze nuclear fusion in deuterium!

Can only stick to ^{6}Li nuclei produced in stage III fusion reactions downstream the catalytic cycle

Sticking probability is tiny

Each X-particle can catalyze $\sim 3.5 \cdot 10^9$ fusion cycles and produce $\sim 7 \cdot 10^4\,\mathrm{TeV}$ of energy before it sticks to ^{6}Li

If sufficiently long-lived, X particles bound to ^{6}Li nuclei can be re-activated multiple times

X^{--} in deuterium environments:

Dissociate D_2 and ionize D, lose energy and get moderated to velocities of order of atomic velocities $v_{\rm at} \simeq 2e^2/\hbar \sim 10^{-2}c$

Capture deuterons on atomic orbits and form $(dX)^-$ ions $\longrightarrow (ddX)$ atoms.

m_X should be $\gg$ masses of light nuclei; unlike for μCF, an atomic system rather than a molecule is formed: (ddX) similar to (anti)-helium atom (X^{--} as a "nucleus", two d in $1s$ atomic state instead of two positrons).

Binding energy is obtained to a very good accuracy by rescaling
$E_b(^4{\rm He}) = 79.005\,{\rm eV} \quad \Rightarrow \quad E_b(ddX) = 0.290\,{\rm MeV}$

Reduced mass $m_d m_X/(m_d + m_X) \simeq m_d \quad \Rightarrow$
Bohr radius $a_d = \hbar^2/(Z_X Z_d e^2 m_d) \simeq 7.2\,{\rm fm}$.
Very small object – X can catalyze fusion more efficiently than μ.

Fusion rates are many orders of magnitudes faster than rates of atomic formation processes $\Rightarrow$

Once (ddX) [or similar $(NN'X)$] atoms are formed, fusion occurs practically instantaneously

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Time scale of XCF determined by the X moderation time
$(t_{\rm mod} \sim 10^{-10}\,{\rm s}$ at liquid hydrogen density $N_0 = 4.25 \times 10^{22}\ {\rm nuclei/cm^3})$
and rates of $({\rm He}dX)^+$ formation through dissociative attachment,
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Rates of fusion reactions, however, determine the branching ratios of various fusion channels, which are important for kinetics of the catalytic cycle.

Stage I XCF reactions in deuterium

$$(ddX) \to {}^3\mathrm{He} + n + X \qquad (Q = 2.98\ \mathrm{MeV},\ 29.1\%)$$
$$(ddX) \to ({}^3\mathrm{He}X) + n \qquad (Q = 3.89\ \mathrm{MeV},\ 19.4\%)$$

$$(ddX) \to {}^3\mathrm{H} + p + X \qquad (Q = 3.74\ \mathrm{MeV},\ 34.4\%)$$
$$(ddX) \to ({}^3\mathrm{H}X) + p \qquad (Q = 4.01\ \mathrm{MeV},\ 6.2\%)$$
$$(ddX) \to {}^3\mathrm{H} + (pX) \qquad (Q = 3.84\ \mathrm{MeV},\ 0.5\%)$$

$$(ddX) \to {}^4\mathrm{He} + \gamma + X \qquad (Q = 23.6\ \mathrm{MeV},\ 4{\cdot}10^{-9})$$
$$(ddX) \to ({}^4\mathrm{He}X) + \gamma \qquad (Q = 24.7\ \mathrm{MeV},\ 3{\cdot}10^{-8})$$
$$(ddX) \to {}^4\mathrm{He} + X \qquad (Q = 23.6\ \mathrm{MeV},\ 10.4\%)$$

Q-values depend on binding!

Rates of reactions with bound X in final states are $\propto$ corresp. sticking probabilities ω_s.

Radiative reactions with $^4\mathrm{He}$ in the final states have tiny branching ratios. Reason: for $d + d \to {}^4\mathrm{He} + \gamma$ transitions of E1 type are strictly forbidden due to identical nature of the two fusing nuclei.

[Effective E1 charge after separation of the irrelevant c.m. motion is $q_{\mathrm{eff}} \propto (q_1/m_1 - q_2/m_2)$].

Reaction $(ddX) \to {}^4\mathrm{He} + X$ is an internal conversion process. Its X-less version does not exist: the process $d + d \to {}^4$He is forbidden by kinematics.

Free X in the final states can again form (ddX) atoms and catalyze further stage I fusion reactions.

Also true for (pX): X transfered to d through fast charge exchange reaction

$$(pX) + d \to (dX) + p\,, \qquad Q \simeq 50\,\mathrm{keV}.$$

$(^3\mathrm{H}X)$ and $(^3\mathrm{He}X)$: cannot directly pariticipate in stage I $d-d$ fusion reactions.
But: can pick up deuterons of the medium and form atomic bound states $(^3\mathrm{H}dX)$ and $(^3\mathrm{He}dX)$ which can give rise to stage II fusion reactions.

$(^3\mathrm{H}X)$ is singly negatively charged ion – can obviously pick up a positively charged d to form an $(^3\mathrm{H}dX)$ atom.

$(^3\mathrm{He}X)$ is neutral. Can still capture positively charged d and form positive ion $(^3\mathrm{He}dX)$ due to atomic polarization effects (analog of H^-). Similarly for $(^4\mathrm{He}X) \to (^4\mathrm{He}dX)$.

Stability of $(^3\mathrm{He}dX)$ and $(^4\mathrm{He}dX)$ follows from general analysis of three-body Coulomb systems [Martin (1998); Krikeb *et al.* (2000); Armour *et al.* (2005)].

Stage II fusion reactions

$$({}^3\mathrm{He}dX) \to {}^4\mathrm{He} + p + X \qquad (Q = 17.4\ \mathrm{MeV},\ 94\%)$$
$$({}^3\mathrm{He}dX) \to ({}^4\mathrm{He}X) + p \qquad (Q = 18.6\ \mathrm{MeV},\ 6\%)$$
$$({}^3\mathrm{He}dX) \to {}^4\mathrm{He} + (pX) \qquad (Q = 17.5\ \mathrm{MeV},\ 3{\cdot}10^{-4})$$

$$({}^3\mathrm{H}dX) \to {}^4\mathrm{He} + n + X \qquad (Q = 17.3\ \mathrm{MeV},\ 96\%)$$
$$({}^3\mathrm{H}dX) \to ({}^4\mathrm{He}X) + n \qquad (Q = 18.4\ \mathrm{MeV},\ 4\%)$$

Most of previously bound X are liberated – free to form (ddX) states and catalyze again stage I reactions. Same is true for X in (pX) states.

Remaining final-state X: bound in $({}^4\mathrm{He}X)$ atoms. Together with $({}^4\mathrm{He}X)$ produced at stage I pick up d from the medium and form $({}^4\mathrm{He}dX)$, which undergo stage III XCF reactions.

Stage III fusion reactions

$$(^4\mathrm{He}dX) \to {}^6\mathrm{Li} + \gamma + X \qquad (Q = 0.32\ \mathrm{MeV},\ 10^{-13})$$

$$(^4\mathrm{He}dX) \to (^6\mathrm{Li}X) + \gamma \qquad (Q = 2.4\ \mathrm{MeV},\ 2{\cdot}10^{-8})$$

$$(^4\mathrm{He}dX) \to {}^6\mathrm{Li} + X \qquad (Q = 0.32\ \mathrm{MeV},\ \simeq 100\%)$$

Radiative processes have tiny BR because E1 transitions are strongly suppressed (^{4}He and d not identical but have nearly the same q/m).
(N.B.: Source of cosmological lithium problem!)

New channel $(^4\mathrm{He}dX) \to {}^6\mathrm{Li} + X$ (internal conversion) dominates by far.

Almost all previously bound X are liberated in stage III reactions. Can catalyze again nuclear fusion through XCF reactions of stages I and II.

Remaining tiny fraction of X-particles end up in $(^6\mathrm{Li}X)^+$ states; cannot form bound state with positively charged nuclei $\Rightarrow$ catalytic poisoning occurs.

Stage III fusion reactions

$\Rightarrow$ Though very small, this fraction is important!

Fraction of the initial X that goes to $({}^4\mathrm{He}dX) \rightarrow$ stage III reactions: $\sim 1.4\%$
Fraction of the initial X that ends up bound to ^{6}Li: $\sim 2.8 \cdot 10^{-10}$

$\Rightarrow$ Each X can catalyze $\sim 3.5 \times 10^9$ fusion cycles before catalytic poisoning occurs.

Independently of which sub-channels were involved, the net effect of stage I, II and III XCF reactions:

$$4d \rightarrow {}^6\mathrm{Li} + p + n + 23.1\,\mathrm{MeV}.$$

$\Rightarrow$ Each initial X will produce about 7×10^4 TeV of energy before it gets knocked out of the catalytic process.

A caveat:

This is only true if X-particles are sufficiently long-lived to survive during 3.5×10^9 fusion cycles!

Estimates: the slowest processes in XCF cycle are formation of positive ions $(^3\mathrm{He}dX)$ and $(^4\mathrm{He}dX)$ with $t_{\mathrm{form}} \sim 10^{-8}\,\mathrm{s}$.

$\Rightarrow$ For X-particles to survive during 3.5×10^9 fusion cycles and produce $\sim 7 \times 10^4\,\mathrm{TeV}$ of energy, their lifetime τ_X should exceed $\sim 10^2\,\mathrm{s}$.

For shorter lifetimes the energy produced by a single X-particle before it gets stuck to a ^{6}Li nucleus is reduced accordingly.

Ingredients:

- X-atomic physics
  - Formation times of X-atoms and ions
  - Atomic binding energies
  - Atomic wave functions ($\rightarrow \rho_0$, ρ_1, $E \equiv E_{\rm rel}$)
- Sticking probabilities
- Reaction rates and branching ratios
  - Astrophysical S-factors
  - Direct calculation of internal conversion rates
- Acquisition and reactivation of X-particles
- Energy considerations

Finite nuclear size

For most nuclei N Bohr radii of the (NX) atomic states are either comparable to or smaller than nuclear radii $\Rightarrow$ approximation of pointlike nuclei not valid.

Take finite nuclear size into account by making use of variational approach with test wave function of Flügge:

$$\psi(r) = N(\lambda)\left(1+\frac{\lambda r}{2R}\right)e^{-\frac{\lambda r}{2R}}$$

(correct asymptotics both for large and small r).

Bound st.	Bohr rad. a	r_{Nc}	$R_N = 1.2A^{1/3}$	R_{Nc}	$E_b(R_N)$	$E_b(R_{Nc})$	E_b^0
(pX)	14.4	0.8783	1.20	1.134	0.096	0.096	0.100
(dX)	7.20	2.142	1.51	2.765	0.189	0.183	0.200
$(^3\mathrm{H}X)$	4.81	1.759	1.73	2.271	0.276	0.268	0.299
$(^3\mathrm{He}X)$	2.41	1.966	1.73	2.538	1.00	0.905	1.196
$(^4\mathrm{He}X)$	1.81	1.676	1.905	2.163	1.202	1.153	1.588
$(^6\mathrm{Li}X)$	0.805	2.589	2.18	3.342	2.680	2.069	5.369

Bohr radii, rmc charge radii r_{Nc}, $R_N = 1.2A^{1/3}$ and $R_{Nc} = (5/3)^{1/2}r_{Nc}$ in fm; energies in MeV.

Sticking probabilities

Characteristic time of X-atomic processes $t_{\rm at} \sim a_d/v_{at} \simeq 1.6 \times 10^{-21}\,{\rm s}$.
Fusion reactions of XCF occur on nuclear time scales $t_{\rm nuc} \lesssim 10^{-23}\,{\rm s}$ $\Rightarrow$
One can find X-sticking probabilities ω_s using the sudden approximation (Migdal's approach).

Consider $(N_1 N_2 X) \to N_3 + N_4 + X$; N_3 produced with velocity v.
The sticking probability of X to N_3 is

$$\diamondsuit \qquad \omega_s = \sum_\alpha \left| \int \psi^*_{f\alpha} \psi_i e^{-i\vec{q}\vec{r}} d^3 r \right|^2 .$$

Main contribution to ω_s comes from the transition to the ground state of $(N_3 X)$.
$\Rightarrow$ ψ_i and ψ_f are wave functions of $1s$ states of hydrogen-like atoms with masses and charges of the atomic particles $m_i = m_1 + m_2$, $Z_i = Z_1 + Z_2$ and $m_f = m_3$, $Z_f = Z_3$, respectively; $\vec{q} = m_3 \vec{v}/\hbar$.

Fusion cross sects. and astroph. S-factor

The cross section of a fusion reaction of nuclei N_1 and N_2:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta_{12}}\,, \qquad E = \frac{\mu v^2}{2}$$

$S(E)$ is astrophysical factor, E is the c.m.s. energy, v is relative velocity, η_{12} is Sommerfeld parameter:

$$\eta_{12} = \frac{Z_1 Z_2 e^2}{\hbar v} = Z_1 Z_2 \alpha \sqrt{\frac{\mu c^2}{2E}}\,, \qquad \mu = \frac{m_1 m_2}{m_1 + m_2}\,.$$

For catalyzed fusion from the relative s-wave state of N_1 and N_2: define the reaction factor $A(E)$ as $A(E) = \sigma(E) v C_0^{-2}$ (Jackson). C_0^2 is s-wave Coulomb barrier penetration probability factor:

$$C_0^2 = \frac{2\pi\eta_{12}}{e^{2\pi\eta_{12}} - 1} \qquad \Rightarrow$$

$$A(E) = \frac{S(E)}{\pi Z_1 Z_2 \alpha \mu c} \left(1 - e^{-2\pi\eta_{12}}\right).$$

Transition from $S(E)$ to $A(E)$ takes into account the fact that the catalyst particle screens the Coulomb fields of the fusing nuclei and essentially eliminates the Coulomb barrier.

Barrier penetration factor depends exponentially on the distance between N_1 and N_2; in atomic systems average distance between N_1 and N_2 is $\sim a_B$ but the probability that N_1 and N_2 come close together to nearly zero distance is only power-suppressed. $\Rightarrow$

It is preferable for nuclei to fuse from close distance. For atomic w.f. $\Psi_i(\vec{r}_1,\, \vec{r}_2)$: go to variables $\vec{r},\, \vec{R}$ with r the distance between N_1 and N_2 and R the distance between their c.m. and X. Define

$$\rho_0 = \int |\Psi_i(\vec{r}=0,\, \vec{R})|^2 d^3R.$$

Then the rates λ of XCF reactions are related to the corresponding $A(E)$-factors as

$$\lambda = A(E)\rho_0$$

ρ_0 plays the same role as the number density n of the target particles in the usual expression for the reaction rates $\lambda = \sigma n v$.

For the model atomic w.f. $\Psi_i(\vec{r}_1, \vec{r}_2) = \frac{1}{\pi(a_1 a_2)^{3/2}} e^{-\frac{r_1}{a_1} - \frac{r_2}{a_2}}$,

$$\rho_0 = \frac{1}{\pi(a_1 + a_2)^3}.$$

In muonic molecules: energies of relative motion of nuclei very low, $\eta_{12} \gg 1$; in evaluating the cross sections of μCF reactions usually sufficient to consider $S(E \to 0)$.
[Extrapolation to small E also necessary for astrophysics implications!]

In XCF: kinetic energies E of relative motion of N_1 and N_2 in (XN_1N_2) atoms not negligible, must be taken into account.

Virial theorem: $2\bar{T} = -\bar{U} \quad \Rightarrow \quad E_b = |\bar{T} + \bar{U}| = \bar{T}$. On the other hand,

$$\bar{T} = \bar{T}_{\rm c.m.} + \bar{T}_{\rm rel}$$

$\Rightarrow$ For (ddX) atom, $E = E_b/2 = 145\,\mathrm{keV}$, for other (N_1N_2X) systems $E \simeq E_b m_2/(m_1 + m_2)$, where m_2 is the smaller of the two masses.

No need for extrapolation of exp. data to small E!

Internal conversion (IC) processes

At low energies predominantly proceed through electric monopole (E0) transitions whenever this is allowed by angular momentum and parity selection rules. This holds for reactions

$$\diamondsuit \qquad (ddX) \to {}^4\mathrm{He} + X\,, \qquad ({}^4\mathrm{He}dX) \to {}^6\mathrm{Li} + X\,.$$

The rates:

$$\lambda_{\mathrm{IC}} = g_s \frac{8\pi}{9} Z_X^2 \alpha^2 \left(\frac{mc}{\hbar}\right)^2 c \sqrt{\frac{E_0}{2mc^2}}\, \left|\tilde{Q}_0\right|^2 F(Z_X Z, E_0)\, \rho_1\,.$$

g_s is stat. weight factor, m is the mass of the final-state nucleus N, $E_0 (\simeq Q)$ is its kinetic energy.

$$F(Z_X Z, E_0) = \frac{|\psi_f(0)|^2_Z}{|\psi_f(0)|^2_{Z=0}}$$

takes into account deviation of w.f. of the final-state nucleus N of charge Z in the electric field of X-particle from the plane wave (similar to the Fermi function used in the theory of β-decay).

$$F(Z_X Z, E_0) = \frac{2\pi\eta}{1 - e^{-2\pi\eta}}\,, \qquad \eta = Z_X Z \alpha \sqrt{\frac{mc^2}{2E_0}}\,.$$

Accounts for enhancement of λ_{IC} due to increase of the atomic w.f. of N at $r = 0$ due to Coulomb attraction (Sommerfeld enhancement).

ρ_1 is the squared modulus of the atomic w.f. of the compound nucleus in the initial state of IC reaction, taken at zero separation between the nucleus and the X-particle.

$\tilde{Q}_0$ is the transition matrix element of the nuclear charge radius operator between the initial and final nuclear states:

$$\tilde{Q}_0 = \langle f | \sum_{i=1}^{Z} r_{pi}^2 | i \rangle \, .$$

We estimate it as

$$\tilde{Q}_0 \simeq r_i r_f \, .$$

Here: $r_f \equiv \langle r_c^2 \rangle_f^{1/2}$ is the rms charge radius of the final-state nucleus, r_i is the rms charge radius of the compound nucleus in the initial state, which we express through the rms charge radii $r_{N_1 c}$ and $r_{N_2 c}$ of the fusing nuclei N_1 and N_2 according to

$$r_i \simeq (r_{N_1 c}^3 + r_{N_2 c}^3)^{1/3}$$

(corresponds to the liquid drop model of nucleus).

$\Rightarrow$ We actually estimate the transition matrix element of the charge radius operator $\tilde{Q}_0$ as the geometric mean of the charge radii of the initial and final nuclear states.

To assess the accuracy: compared our result for the $(^4\mathrm{He}dX) \to {}^6\mathrm{Li} + X$ with the existing calculations carried out in the catalyzed BBN framework for the case of a singly charged catalyst particle C using a simple scaling law [Pospelov, 2006] and within a sophisticated coupled-channel nuclear physics approach [Hamaguchi *et al.*, 2007]. Re-calculated our result taking $Z_X = 1$, $Q = 1.3$ MeV and the c.m. energy $E = 10$ keV.

For the astrophysical S-factor of the $d + (^4\mathrm{He}C) \to {}^6\mathrm{Li} + C$ process we found $S(E)$=0.19 MeV b. Has to be compared with the results of Pospelov (0.3 MeV b) and Hamaguchi *et al.* (0.043 MeV).

Our result between these two numbers: a factor of 1.6 smaller than the former and a factor of 4.4 larger than the latter.

Acquisition and reactivation of X-particles

X-particles: can be produced in pairs in accelerator experiments – in l^+l^- annihilation at lepton colliders or through the Drell-Yan processes at hadronic machines.

Energy produced by one X-particle before catalytic poisoning occurs: $E \sim 7 \times 10^4\,\mathrm{TeV}$. Large on microscopic scale, but is only about 10 mJ! $\Rightarrow$

At least 10^8 X-particles are needed to generate 1 MJ of energy.
1MJ: kinetic energy of 1 tonne moving w/ velocity 100 mph (161 kmph).

Colliders are well suited for discovery of new particles, but for production of large numbers of X-particles fixed-target accelerator experiments are more suitable $\Rightarrow$ beam energy must exceed the mass of the X-particle significantly. Currently plans for building 100 TeV machines discussed.

The problem: X-particle production cross section is very small

$$\sigma_p \simeq \frac{4\pi}{3}\frac{\alpha^2}{s}\beta^3$$

For $m_X \sim 1\mathrm{TeV}$ and $\beta \sim 0.3$, $\sigma_p \sim 1\,\mathrm{fb}$. $\Rightarrow$

Energy spent on production of one $X^{++}X^{--}$ pair will be by far larger than the energy that can be generated by one X^{--} before it gets bound to ^{6}Li $\Rightarrow$

Reactivating and re-using the bound X-particles multiple times would be mandatory for accelerator-produced X.

Only X-particles with $\tau_X \gtrsim 3 \times 10^4\,\mathrm{yr}$ will be suitable for energy production.

To reactivate X-particles: dissociate $(^6\mathrm{Li}X)$ ions. Could be achieved by irradiating them with particle beams [as suggested for reactivation of lower-charge catalyst particles by Zweig].

But: it would be much more efficient to use instead $(^6\mathrm{Li}X)$ ions as projectiles and irradiate a target with their beam! [a]

Coulomb binding energy of X to $^6\mathrm{Li}$ $\sim 2\,\mathrm{MeV}$; to strip X off on target with average $A \simeq 40$ need to accelerate $(^6\mathrm{Li}X)$ to $\beta \simeq 0.01$ (beam energy $\sim 0.05\,\mathrm{GeV}$). Cross section of stripping reaction $\gtrsim 0.1\,\mathrm{b}$ $\Rightarrow$ X-particles can be liberated with high efficiency in small targets.

Energy spent on reactivation of one X-particle is only about 10^{-9} of energy it can produce before sticking to a ^{6}Li nucleus.

[a] Suggested by M. Pospelov

If X-particles are stable or practically stable: there may exist a terrestrial population of relic X-particles bound to nuclei or (in the case of X^{++}) to electrons.

Possibility of the existence of exotic bound states containing charged massive particles suggested by Cahn & Glashow (1980) and De Rujula, Glashow & Sarid (1990). Studied by many authors.

A number of searches for superheavy exotic isotopes has been carried out using a variety of experimental techniques; upper limits on their concentrations established.

Exotic helium atoms $(X^{++}ee)$ were searched for in the Earth's atmosphere with laser spectroscopy technique; for the mass range $20 - 10^4$ TeV/c^2 concentration limit $10^{-12} - 10^{-17}$ per atom established.

For X^{--}, their Coulomb binding to nuclei of charge Z would produce superheavy exotic isotopes with nuclear properties of original nuclei but chemical properties of atoms with nuclear charge $Z - 2$. Could have accumulated in continental crust and marine sediments.

Singly positively charged ions ($^6\mathrm{Li}X$) and ($^7\mathrm{Li}X$) behave chemically as superheavy protons; can capture electrons and form anomalously heavy hydrogen atoms. From exp. searches for anomalous hydrogen in normal water: upper limits on concentration $\sim 6 \times 10^{-15}$ for masses between 10 and $10^5\ \mathrm{TeV/c^2}$.

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To estimate the required energy: assume (conservatively) that it is twice the energy needed to vaporize the matter sample. E.g., it takes $\sim$ 10 kJ to vaporize 1 g of granite; $\Rightarrow$ energy necessary to extract one X-particle is $\sim 2.3 \times 10^{-18}\ \mathrm{J}/c_X$ [c_X is the concentration of X-particles in granite (number of X per molecule)].

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Requiring that it does not exceed the energy one X-particle can produce before getting stuck to ^{6}Li $\Rightarrow$ $c_X \gtrsim 2.3 \times 10^{-16}$. If it is satisfied, extracting X-particles from granite would allow XCF to produce more energy than it consumes, even without reactivation and recycling of the X-particles.

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Another advantage of the extraction of relic X-particles from minerals compared to their production at accelerators is that it could work even for X-particles with mass $m_X \gg 1$ TeV/c^2.

Cosmological implications?

Existence of long-lived charged particles may have important cosmological consequences. Pospelov (2006) suggested that singly negatively charged heavy metastable particles C^- may catalyze nuclear fusion reactions at the BBN era, possibly solving the cosmological lithium problem.

Doubly charged scalars X may also catalyze nuclear fusion reactions in the early Universe, with significant impact on primordial nucleosynthesis.

On the other hand, cosmology may provide important constraints on the XCF mechanism. A comprehensive study of cosmological implications of the existence of $X^{\pm\pm}$ particles would be of great interest.

Conclusions

If long-lived doubly charged scalar particles exist, they may have very important practical applications for energy production (and probably interesting implications for cosmology).

If is the key word!

Strong additional motivation for continuing and extending experimental searches for $X^{\pm\pm}$.

Backup slides

The moderation time of X-particles from $\beta \equiv v/c \simeq 0.1$ to atomic velocities $v \simeq 2e^2/\hbar \simeq 1.5 \times 10^{-2} c$ is

$$\tau \simeq 6 \times 10^{-11}\,\mathrm{s}$$

at liquid hydrogen density $N_0 = 4.25 \times 10^{22}$ nuclei/cm^3 and $T \simeq 20$K. It is about 4.8×10^{-8} s in deuterium gas at 0°C and pressure of one bar.

The cross section of the charge exchange reaction $d + (pX) \to (dX) + p$:

$$\sigma_c \simeq 4\pi a_p^2 f v_*/v\,.$$

Here $a_p = \hbar/(2\alpha m_p c) = 1.44 \times 10^{-12}$ cm is the Bohr radius of (pX) atom, v and v_* are the relative velocities of the involved particles in the initial and final states, respectively, and f is a constant of order unity. Taking into account that the relative velocities of the initial-state particles are very small and the Q-value of the reaction $d + (pX) \to (dX) + p$ is $\simeq 90$ keV, we find $v_* \simeq 1.4 \times 10^{-2} c$, which gives

$$\sigma_c v \simeq 10^{-14}\,\mathrm{cm}^3/\mathrm{s}\,.$$

The rate λ_c and the characteristic time t_c of this reaction at liquid hydrogen density $N_0 = 4.25 \times 10^{22}$ nuclei/cm^3:

$$\lambda_c = \sigma_c v N_0 \simeq 4 \times 10^8\,\mathrm{s}^{-1}\,, \qquad t_c = \lambda_c^{-1} \simeq 2.5 \times 10^{-9}\,\mathrm{s}\,.$$

Estimates of the properties of positive ions

To assess their properties we use semi-quantitative methodfs. In doing that, we will be using the properties of negative ion H^- as a starting point, but will also take into account the peculiarities of $(^3\mathrm{He}dX)$ and $(^4\mathrm{He}dX)$ ions. In the case of H^-, the radius of the outer electron's orbit is about a factor 3.7 larger than that of the inner electron, and the binding energy of the outer electron (electron affinity) is about 18 times smaller than that of the inner one. Taking into account tighter binding of the inner core in the case of the positive ions we consider, we rather arbitrarily assume the radii a of their external orbits and the deuteron binding energies E_{bd} to be, respectively, a factor of ~ 30 larger and three orders of magnitude smaller than those of the corresponding $(\mathrm{He}X)$ atoms. We therefore choose

$$(^3\mathrm{He}dX): \qquad a \simeq 7\times 10^{-12}\,\mathrm{cm}\,, \qquad E_{bd} \simeq 1.2\,\mathrm{keV}\,, \tag{1}$$

$$(^4\mathrm{He}dX): \qquad a \simeq 5\times 10^{-12}\,\mathrm{cm}\,, \qquad E_{bd} \simeq 1.6\,\mathrm{keV}\,. \tag{2}$$

The formation of $(^3\mathrm{He}dX)$ and $(^4\mathrm{He}dX)$ ions can proceed as follows. An $(^3\mathrm{He}X)$ atom collides with the neighboring D_2 molecules, dissociating them and picking up one of their deuterons through the exothermic reaction

$$(^3\mathrm{He}X) + \mathrm{D}_2 \to (^3\mathrm{He}dX) + d + 2e^-\,.$$

This is the dissociative attachment (DA) mechanism, analogous to the one by which H^- ions are produced in e^-+H_2 $\rightarrow$$H^-$+H reactions. An important difference is that what is attached is now a nucleus (deuteron) rather than an electron. The formation of $(^4\mathrm{He}dX)$ ions from $(^4\mathrm{He}X)$ atoms proceeds similarly. [Note that a tiny fraction of $(^4\mathrm{He}dX)$ ions is produced directly in stage I].

As the Q-values of the formation reactions of $(^3\mathrm{He}dX)$ and $(^4\mathrm{He}dX)$ ions are about two orders of magnitude larger than the dissociation energy of D_2 molecules and the ionization potential of D atoms, these processes are actually similar to the usual charge exchange reactions on free particles, except that most of the released energy is now carried away by the final-state electrons. The rates and characteristic times of these processes can therefore be estimated using the expressions similar to those reaction $d + (pX) \rightarrow (dX) + p$. This gives, at the liquid hydrogen density,

$$\lambda_{\mathrm{DA}} \sim 5 \times 10^7\,\mathrm{s}^{-1}\,, \qquad t_{\mathrm{DA}} = \lambda_{\mathrm{DA}}^{-1} \sim 2 \times 10^{-8}\,\mathrm{s}\,.$$

Reaction	E_b	E	$S(E)$	$A(E)$	$\rho_{0,1}$	λ
$(ddX) \to {}^3\mathrm{He} + n + X$	0.290	0.145	0.102	$1.31 \cdot 10^{-16}$	0.64	$8.4 \cdot 10^{18}$
$(ddX) \to {}^3\mathrm{H} + p + X$	"	"	$8.6 \cdot 10^{-2}$	$1.11 \cdot 10^{-16}$	"	$7.1 \cdot 10^{18}$
$(ddX) \to {}^4\mathrm{He} + \gamma + X$	"	"	$7 \cdot 10^{-9}$	$9.0 \cdot 10^{-24}$	"	$5.8 \cdot 10^{11}$
$(ddX) \to {}^4\mathrm{He} + X$	"	"	$1.9 \cdot 10^{-2}$	$2.5 \cdot 10^{-17}$	0.73	$1.8 \cdot 10^{18}$
$({}^3\mathrm{He}\, dX) \to {}^4\mathrm{He} + p + X$	0.91	0.36	7.1	$4.0 \cdot 10^{-15}$	$7.6 \cdot 10^{-3}$	$3.0 \cdot 10^{18}$
$({}^3\mathrm{H} dX) \to {}^4\mathrm{He} + n + X$	0.32	0.13	5.6	$6.2 \cdot 10^{-15}$	0.88	$5.5 \cdot 10^{20}$
$({}^4\mathrm{He}\, dX) \to {}^6\mathrm{Li} + \gamma + X$	1.16	0.39	$1.3 \cdot 10^{-8}$	$6.6 \cdot 10^{-24}$	1.8×10^{-2}	$1.2 \cdot 10^{10}$
$({}^4\mathrm{He}\, dX) \to {}^6\mathrm{Li} + X$	"	"	1.55	$7.9 \cdot 10^{-16}$	0.14	$1.1 \cdot 10^{19}$

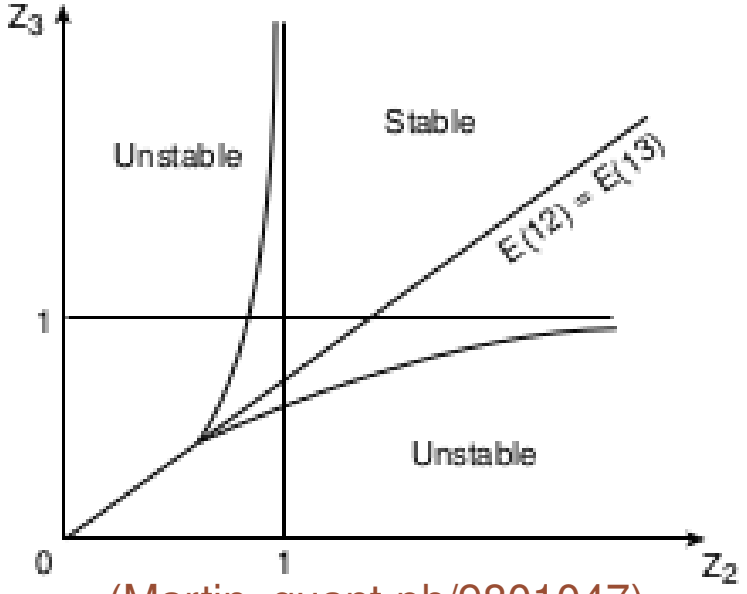
Energies in MeV, $S(E)$ in MeV b, $A(E)$ in cm^3/s, ρ_0 and ρ_1 in $10^{35}\,\mathrm{cm}^{-3}$, reaction rates λ in s^{-1}. Rates are inclusive of all sub-channels with either free or bound X-particles in the final state.

Reaction	Q_0	Q	ω_{s0}	ω_s	Br_0	Br
$(ddX) \to {}^3\mathrm{He} + n + X$	3.27	2.98	–	–	54.2%	29.1%
$(ddX) \to ({}^3\mathrm{He}X) + n$	–	3.89	0.61	0.40	–	19.4%
$(ddX) \to {}^3\mathrm{H} + p + X$	4.03	3.74	–	–	45.8%	34.4%
$(ddX) \to ({}^3\mathrm{H}X) + p$	–	4.01	0.22	0.15	–	6.2%
$(ddX) \to {}^3\mathrm{H} + (pX)$	–	3.84	$1.9 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	–	0.5%
$(ddX) \to {}^4\mathrm{He} + \gamma + X$	23.85	23.56	–	–	$3.7 \cdot 10^{-8}$	$4 \cdot 10^{-9}$
$(ddX) \to ({}^4\mathrm{He}X) + \gamma$	–	24.71	0.95	0.87	–	$3 \cdot 10^{-8}$
$(ddX) \to {}^4\mathrm{He} + X$	–	23.56	–	–	–	10.4%
$({}^3\mathrm{He}\, dX) \to {}^4\mathrm{He} + p + X$	18.35	17.44	–	–	100%	94%
$({}^3\mathrm{He}\, dX) \to ({}^4\mathrm{He}X) + p$	–	18.60	0.29	0.06	–	6%
$({}^3\mathrm{He}\, dX) \to {}^4\mathrm{He} + (pX)$	–	17.54	$2.3 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	–	$3.0 \cdot 10^{-4}$
$({}^3\mathrm{H}dX) \to {}^4\mathrm{He} + n + X$	17.59	17.27	–	–	100%	96%
$({}^3\mathrm{H}dX) \to ({}^4\mathrm{He}X) + n$	–	18.42	0.23	$4.0 \cdot 10^{-2}$	–	4.0%
$({}^4\mathrm{He}\, dX) \to {}^6\mathrm{Li} + \gamma + X$	1.475	0.32	–	–	100%	10^{-13}
$({}^4\mathrm{He}\, dX) \to ({}^6\mathrm{Li}X) + \gamma$	–	2.39	$1 - 1.2 \cdot 10^{-6}$	$1 - 1.2 \cdot 10^{-3}$	–	$1.9 \cdot 10^{-8}$
$({}^4\mathrm{He}\, dX) \to {}^6\mathrm{Li} + X$	–	0.32	–	–	–	$\simeq$100%

Stability of 3-body Coulomb systems

$$q_1 < 0, \quad q_{2,3} > 0; \qquad Z_i \equiv 1/|q_i|.$$

As only ratios of charges matter, $|q_1|$ set equal to 1.



(Martin, quant-ph/9801047)

Our case:

$$q_2 = 1, \quad q_3 = 1/2 \qquad \Rightarrow \qquad z_2 = 1, \quad z_3 = 2.$$

Cosmological lithium problem(s) and CBBN

Observed abundance of ^{7}Li is below the BBN prediction by a factor ~ 3, abundance of ^{6}Li is above the prediction by a factor $\gtrsim 1000$.

Explanations within CBBN (catalyzed BBN with long-lived heavy single-charged C^-) (Pospelov, 2006 followed by many others):

At $T_9 \sim 0.3$: C^- captures ^{7}Li to form $(^7\mathrm{Li}C^-)$; then

$$(^7\mathrm{Li}C^-) + p \to \alpha + \alpha + C^-$$

(^{7}Li destruction).

At $T_9 \sim 0.1$: C^- captures ^{4}He to form $(^4\mathrm{He}C^-)$; $\Rightarrow$

$$(^4\mathrm{He}C^-) + d \to {}^6\mathrm{Li} + C^-$$

Cross section several orders of magnitude larger than that of the usual ^{6}Li production process $^4\mathrm{He} + d \to {}^6\mathrm{Li} + \gamma$; $\Rightarrow$ enhanced production of ^{6}Li.

X^{--} can play similar role in CBBN.