Variations on a theme of neutrinos

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UC HIPECC 2014 International Summer
School on Astrocomputing

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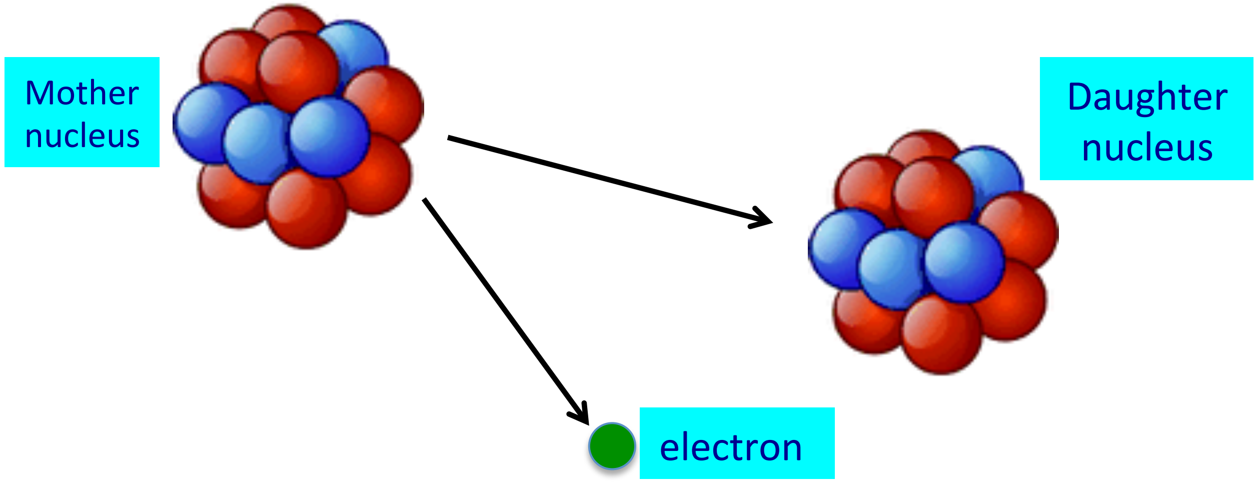
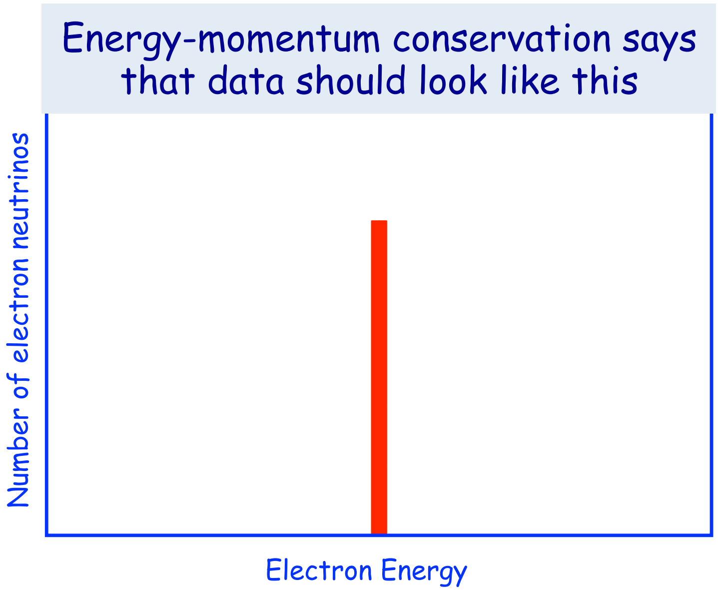
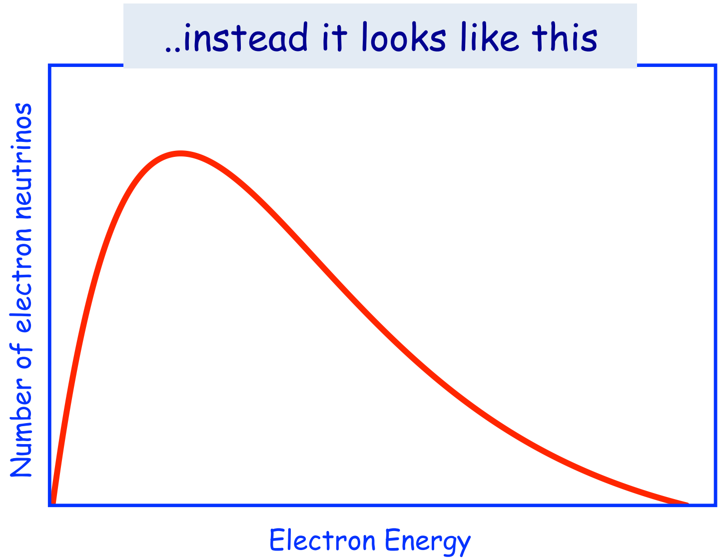
Neutrinos are fascinating particles as they are the only neutral fermions

- What is a neutrino?
- What is a particle?
- Why are they fascinating?

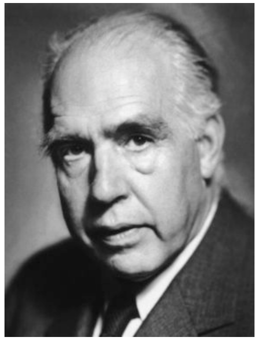
Neutrino came out of a puzzle about the radioactive decay in the early 1920's:



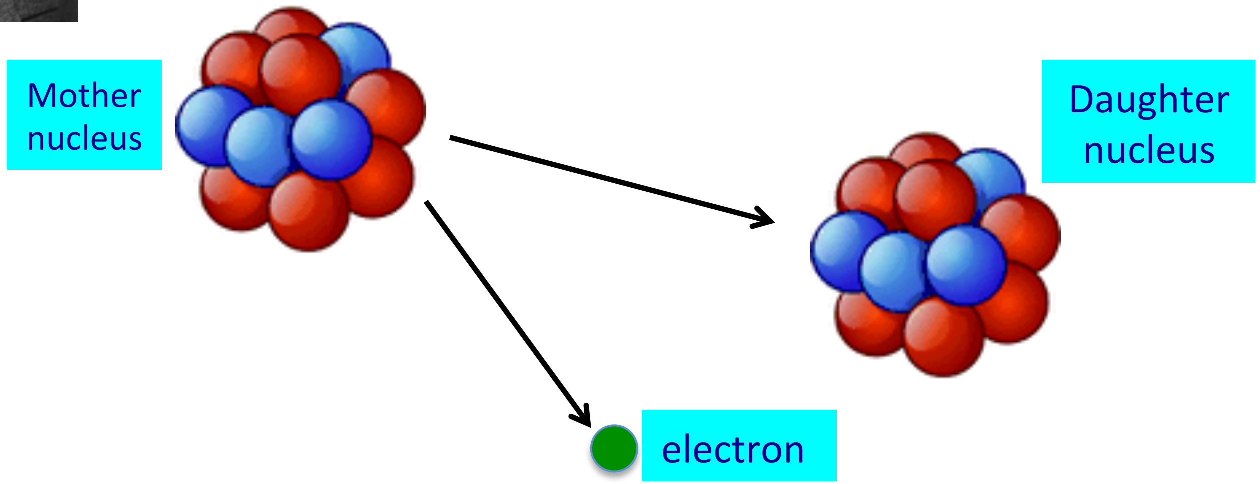




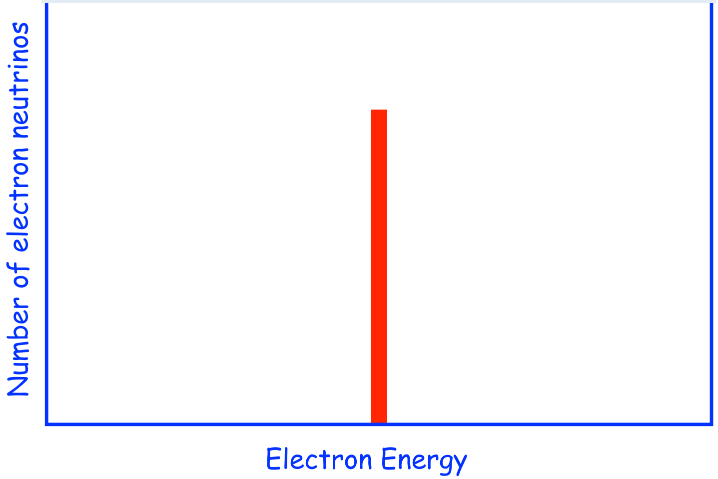
Niels Bohr



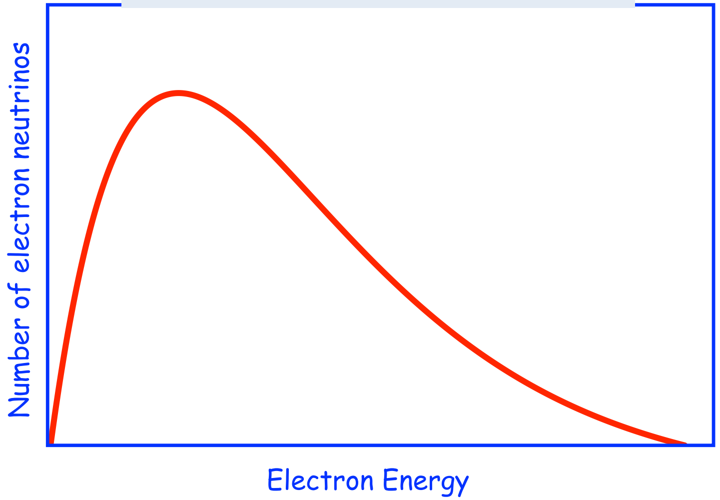
In radioactive decays energy-momentum conservation no longer holds!



Energy-momentum conservation says that data should look like this

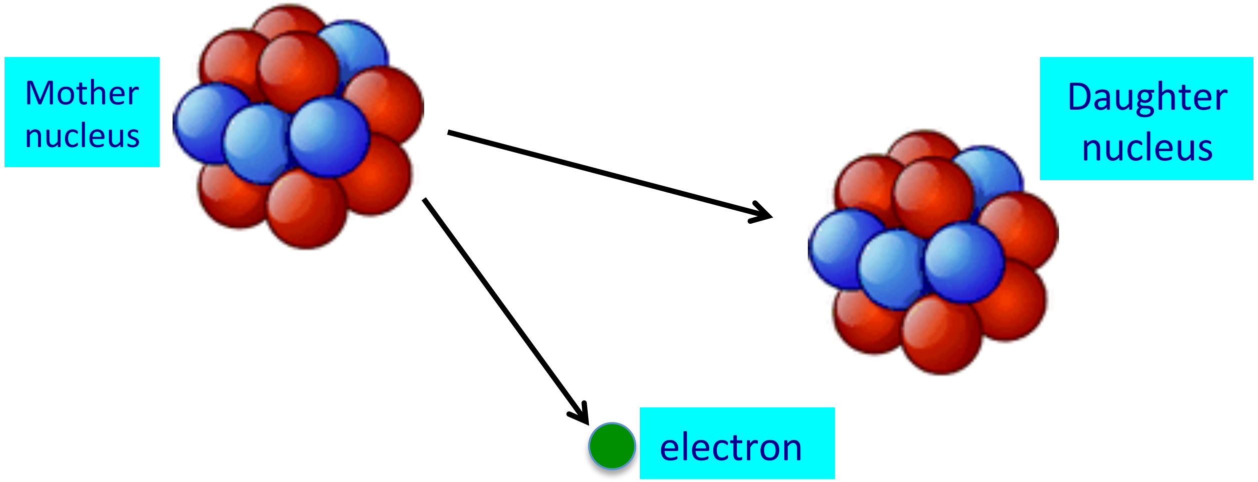


..instead it looks like this



Wolfgang Pauli

In this reaction there is a third particle produced that you cannot (yet) see!



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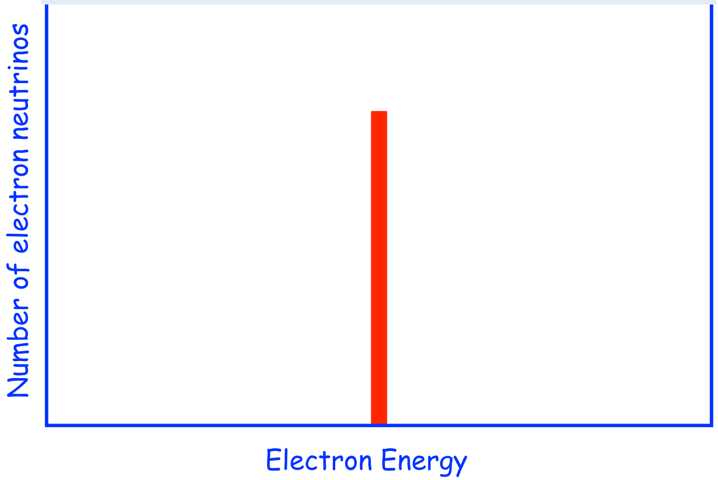

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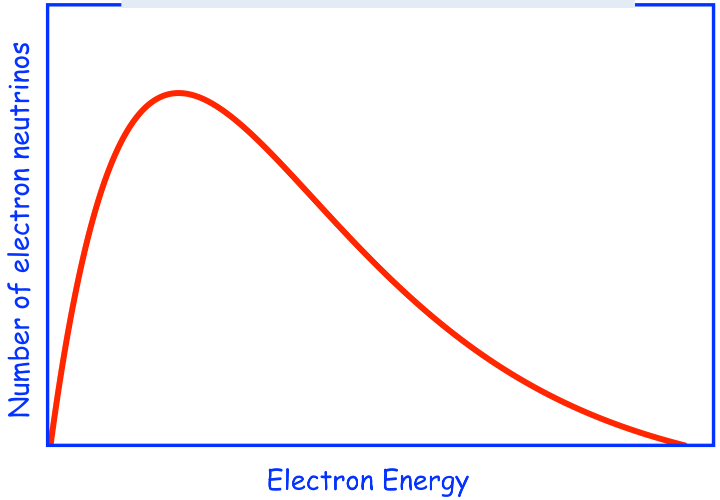

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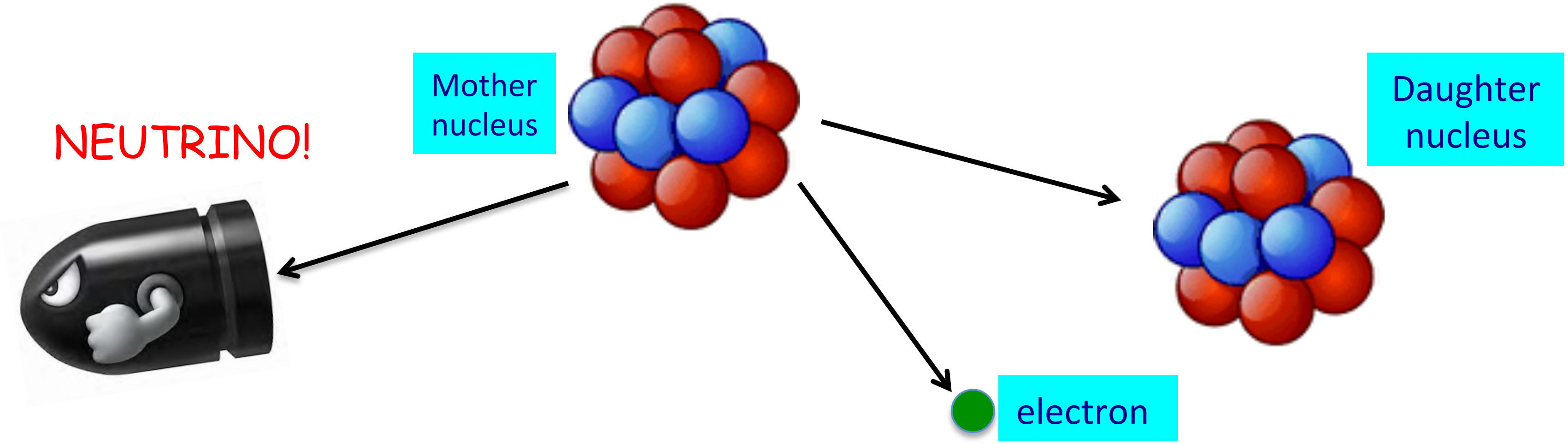

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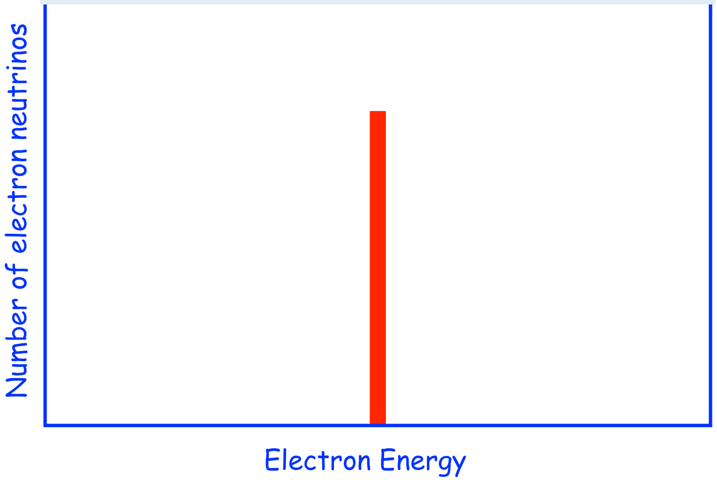

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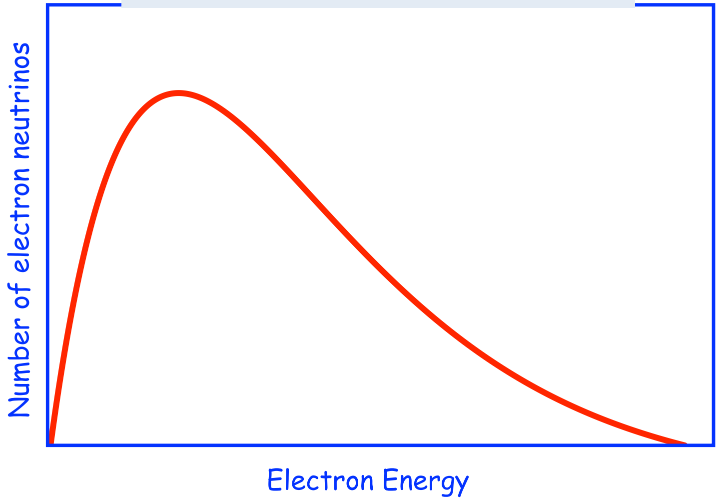


Wolfgang Pauli,
father of the neutrino
and Pauli exclusion
principle

Physicist goes to a ball

or

Mystery of Missing Energy

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

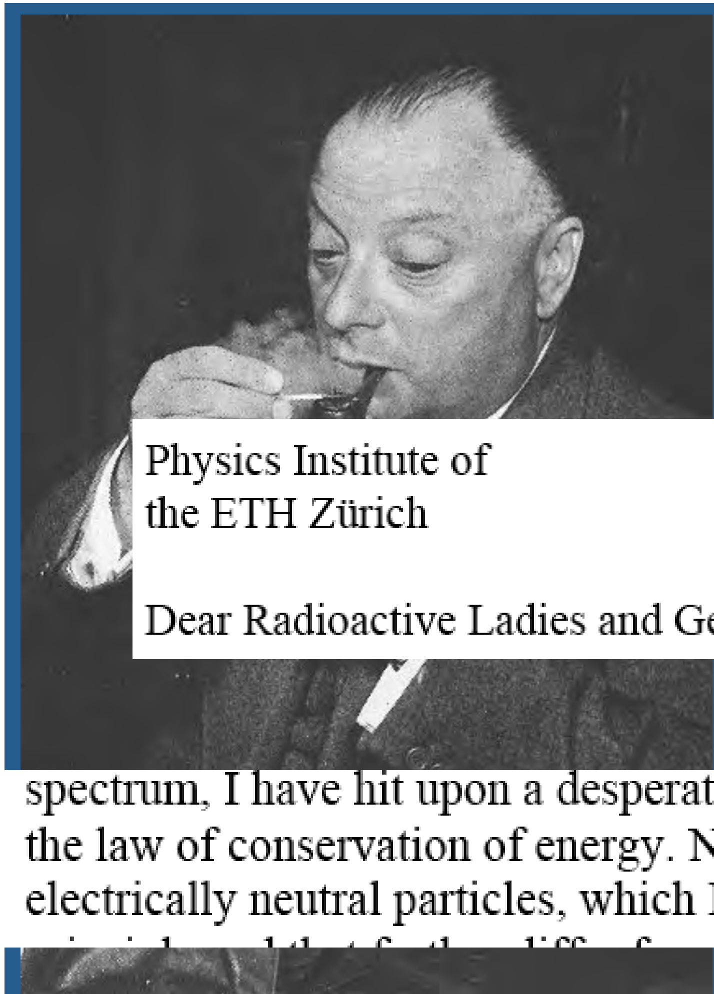
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Physicist goes to a ball

or



Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion

Wolfgang Pauli

way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble

principle

Pauli

Fermi

Majorana

Pontecorvo

Neutrino Timeline

Goeppert-Meyer

We will find out how neutrinos oscillate, why they play an important role in astrophysics/ cosmology and what they have to do with element production.

What is a particle?

The best answer follows from symmetry arguments!

What is a particle?

Wigner: A particle is an irreducible representation of the Poincare group.

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Recall the quantities Lorentz transformations leave invariant:

$$t^2 - \mathbf{r}^2 = \tau^2$$

$$E^2 - \mathbf{p}^2 = m^2$$

$$\mathbf{E}^2 - \mathbf{B}^2$$

$$\mathbf{E} \cdot \mathbf{B}$$

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Poincare group is the group including Lorentz boosts, translations and rotations.

Next let us explore the concept of mass

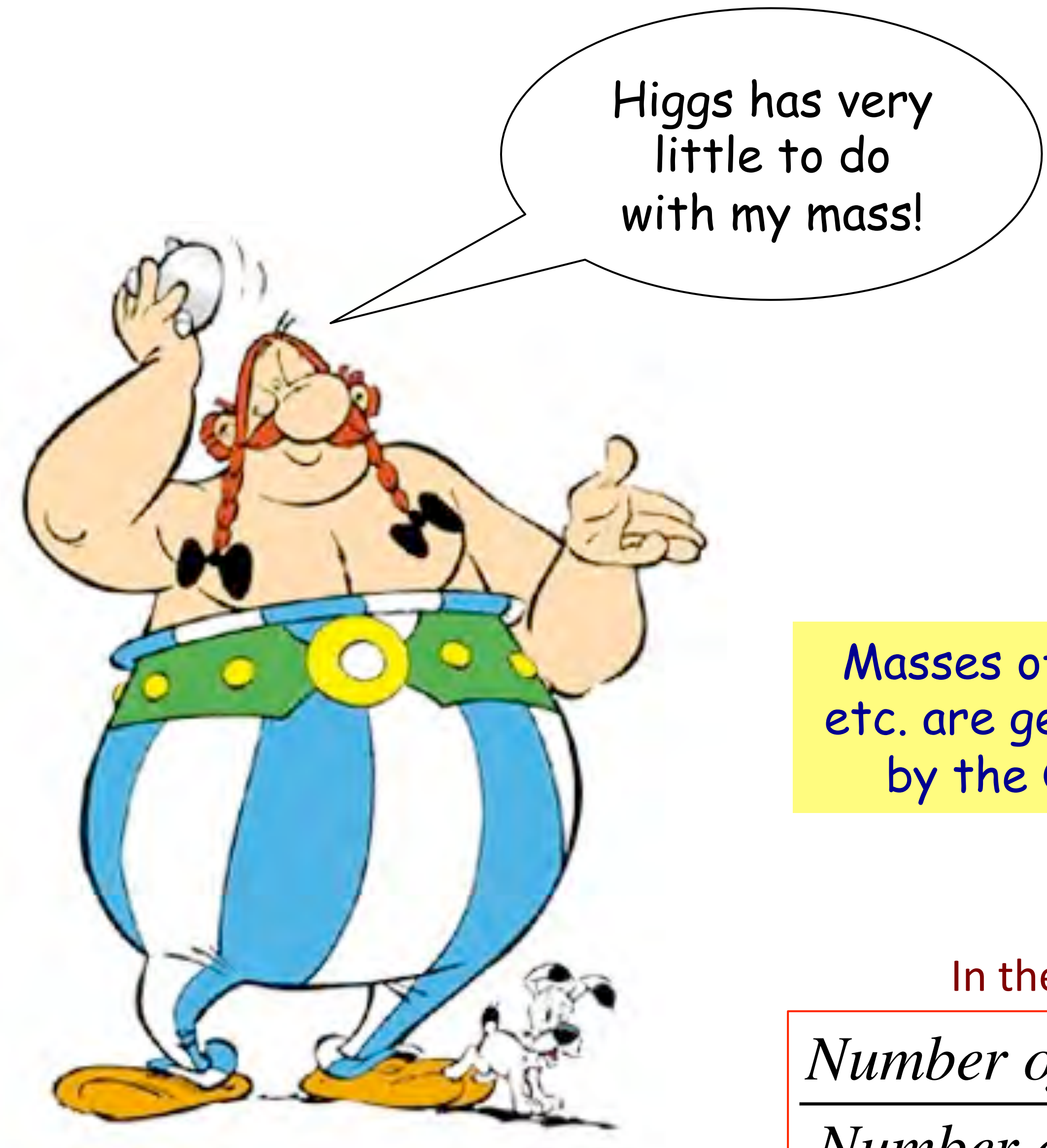
What is mass?

$$\Psi_L = \frac{1}{2}\left(1-\gamma_5\right)\Psi$$

$$\Psi_R = \frac{1}{2}\left(1+\gamma_5\right)\Psi$$

$$L = m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_l\right)$$

In the Standard Model all elementary masses possibly except those for neutrinos are generated by the Yukawa couplings of the Higgs.



Masses of protons, neutrons, etc. are generated dynamically by the QCD interactions!

In the Early Universe

$$\frac{Number\ of\ neutrons}{Number\ of\ protons} = \frac{e^{-m_n/T}}{e^{-m_p/T}}$$

Chiral representation of Dirac matrices

$$\gamma^0 = \beta = \begin{pmatrix} 0 & -I \\ -I & 0 \end{pmatrix}, \quad \vec{\alpha} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & -\vec{\sigma} \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

Helicity and chirality

Chirality: γ_5, Helicity: $\dfrac{\vec{\Sigma}\cdot\vec{k}}{\left|\vec{k}\right|}$, $\left[\gamma_5, \dfrac{\vec{\Sigma}\cdot\vec{k}}{\left|\vec{k}\right|}\right] = 0$

$$\gamma_5 \left|\lambda, \chi\right\rangle = \lambda \left|\lambda, \chi\right\rangle$$

$$\frac{\vec{\Sigma}\cdot\vec{k}}{\left|\vec{k}\right|}\left|\lambda, \chi\right\rangle = \chi \left|\lambda, \chi\right\rangle$$

$$\lambda = \pm 1, \quad \chi = \pm 1$$

These operators act on the fermion fields:

$$\Psi_s(\vec{r}) = \sum_{\vec{k}} \left\langle \vec{r} \middle| \vec{k} \right\rangle a_s(\vec{k}), \quad s = 1,2,3,4$$

$$b^\dagger\left(\vec{k},\chi\right)=\sum_s a^\dagger\left(\vec{k}\right)\langle s|\chi,\chi\rangle$$

$$d\left(-\vec{k},\chi\right)=\sum_s a^\dagger\left(\vec{k}\right)\langle s|-\chi,\chi\rangle$$

Free, massless particle Hamiltonian:

$$H=\int d^3\vec{r}\ \Psi^\dagger(\vec{r})\vec{\alpha}\cdot\hat{p}\Psi(\vec{r})$$

$$=\sum_{\vec{k},\chi}\left|\vec{k}\right|\left[b^\dagger\left(\vec{k},\chi\right)b\left(\vec{k},\chi\right)-d\left(-\vec{k},\chi\right)d^\dagger\left(-\vec{k},\chi\right)\right]$$

"Dirac" mass term:

$$m_D\int d^3\vec{r}\ \Psi^\dagger(\vec{r})\beta\Psi(\vec{r})$$

$$=-\sum_{\vec{k},\chi}m_D\left[b^\dagger\left(\vec{k},\chi\right)d^\dagger\left(-\vec{k},-\chi\right)-d\left(-\vec{k},-\chi\right)b\left(\vec{k},\chi\right)\right]$$

Hence the total Hamiltonian is

$$H = \sum_{\vec{k},\chi} \left\{ \left|\vec{k}\right| \left[b^\dagger_{k\chi} b_{k\chi} - d_{-k\chi} d^\dagger_{-k\chi} \right] - m_D \left[b^\dagger_{k\chi} d^\dagger_{-k\chi} - d_{-k\chi} b_{k\chi} \right] \right\}$$

This Hamiltonian can be diagonalized by the transformation

$$\begin{pmatrix} B_{k\chi} \\ D^\dagger_{-k\chi} \end{pmatrix} = \begin{pmatrix} \cos\vartheta & -\sin\vartheta \\ \sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} b_{k\chi} \\ d^\dagger_{-k\chi} \end{pmatrix}$$

$$H = \sum_{k\chi} \sqrt{\vec{k}^2 + m_D^2} \left(B^\dagger_{k\chi} B_{k\chi} - D_{-k\chi} D^\dagger_{-k\chi} \right)$$

$$\cos 2\vartheta = \frac{\left|\vec{k}\right|}{\sqrt{\vec{k}^2 + m_D^2}} \qquad \sin 2\vartheta = \frac{m_D}{\sqrt{\vec{k}^2 + m_D^2}}$$

Majorana mass term:

$$m_M \left(\left(\Psi_L \right)^C \right)^\dagger \beta \, \Psi_L$$

• Such a mass term violates lepton number conservation since it implies that neutrinos are their antiparticles.

Neutrino mass eigenstates are a combination of weak-interaction eigenstates: neutrinos mix!

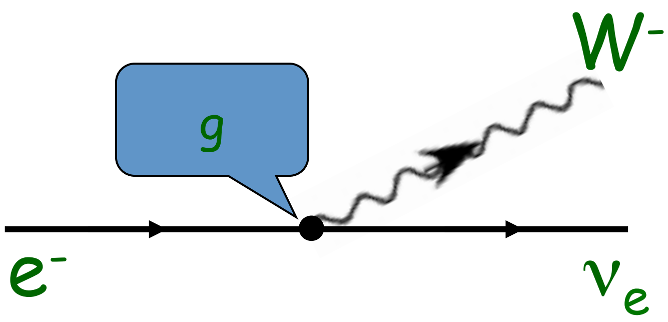
$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i$$

$\alpha = e, \mu, \tau$

$i = 1,2,3,..$

U is unitary: $U^\dagger U = UU^\dagger = 1$

If the neutrino mass were zero this would be nothing more than a change of basis in the Standard Model:



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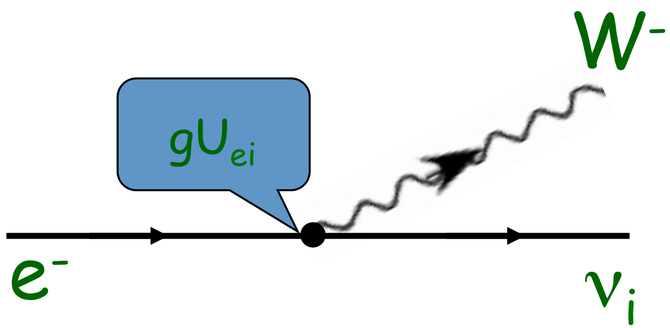

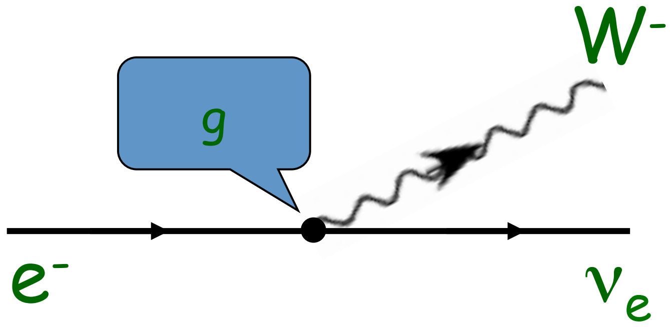

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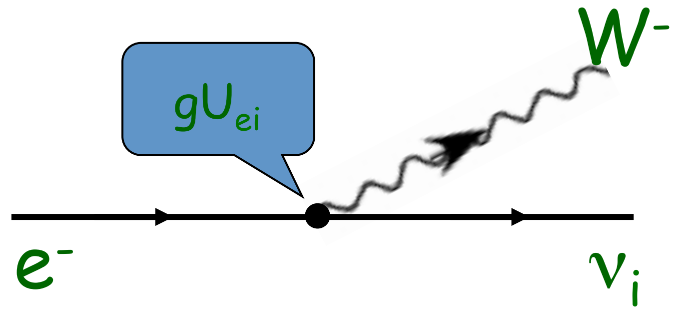


$$L_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\bar{\ell}_{L\alpha}\gamma^{\lambda}\nu_{L\alpha}W_{\lambda}{}^{-} + \bar{\nu}_{L\alpha}\gamma^{\lambda}\ell_{L\alpha}W_{\lambda}{}^{+} \right)$$

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha}\gamma^{\lambda}U_{\alpha i}\nu_{Li}W_{\lambda}{}^{-} + \bar{\nu}_{Li}\gamma^{\lambda}U_{\alpha i}{}^{*}\ell_{L\alpha}W_{\lambda}{}^{+} \right)$$

Left-handed

- Symmetries, in particular weak isospin invariance, define the Standard Model. The symmetry is $SU(2)_W xU(1)$.

- In the Standard Model, the left-handed and the right-handed components of the neutrino are treated differently: ν_L sits in an weak-isospin doublet (I_W =1/2) together with the left-handed component of the associated charged lepton, whereas ν_R is an weak-isospin singlet (I_W=0).

SU(2) × U(1) Standard Model

Weak isospin

$$SU(2)_W : \;\; I^{(W)} = \frac{1}{2} \;\Rightarrow \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \;\; \begin{matrix} I_3^{(W)} = +\frac{1}{2} \\ I_3^{(W)} = -\frac{1}{2} \end{matrix}$$

Weak singlets

$$I^{(W)} = 0 : \;\; \nu_R, \; e_R$$

Higgs Field sits in a weak doublet with $I_3^{(W)} = -\frac{1}{2}$.

• Symmetries, in particular weak isospin invariance, define the Standard Model. The symmetry is $SU(2)_W \times U(1)$.

• In the Standard Model, the left-handed and the right-handed components of the neutrino are treated differently: ν_L sits in an weak-isospin doublet (I_W =1/2) together with the left-handed component of the associated charged lepton, whereas ν_R is an weak-isospin singlet (I_W=0).

• A mass term connects left- and right-handed components. The usual Dirac mass term is $L = m\overline{\psi}\psi = m(\overline{\psi_L}\psi_R + \overline{\psi}_R\psi_L)$. But such a neutrino mass term requires a right-handed neutrino, hence it is not in the Standard Model.

• The right-handed component of the neutrino carries no weak isospin quantum numbers. This permits *Majorana neutrino mass* in the Standard Model if one only uses right-handed neutrinos.

A very brief introduction to the effective field theories

A note on dimensional counting

- Lagrangian, L, has dimensions of energy (or mass).
- $L = \int d^3x\, \mathcal{L} \Rightarrow$ Lagrangian density, $\mathcal{L}$, has dimensions of energy/volume or M^4.
- Define the scaling dimension of x, [x] to be -1 $\Rightarrow$ scaling dimension of momentum (or mass) is [m] = +1 (recall that (p.x/h) is dimensionless and we take [h]=0).
- Clearly $[\mathcal{L}] = 4$. This should be true for any Lagrangian density of any theory.
- Consider the mass term for fermions, $\mathcal{L}_m = m\, \overline{\Psi}\Psi$. Then $[\overline{\Psi}\Psi] = 3$ or $[\Psi] = 3/2$.
- In the Standard Model the Higgs field vacuum expectation value gives the particle mass: $\mathcal{L} = H\, \overline{\Psi}\Psi$. Hence $[H] = 1$.

An example for the effective field theories

Euler-Heisenberg correction to the Q.E.D. Lagrangian

$$L = \frac{1}{2}(\mathbf{E}^2-\mathbf{B}^2) + \underbrace{\text{terms which are higher order in fields}}_{\text{Consistent with the symmetries of the system}}$$

Symmetries of the Electromagnetism

Lorentz Invariants: $\mathbf{E}^2 - \mathrm{B}^2$ and $\mathbf{E} \cdot \mathrm{B}$

$$\underbrace{\begin{gathered} \mathbf{E} \to \mathbf{E} \\ \mathrm{B} \to -\mathrm{B} \\ \mathbf{E}^2 - \mathrm{B}^2 \to \mathbf{E}^2 - \mathrm{B}^2 \\ \mathbf{E} \cdot \mathrm{B} \to -\mathbf{E} \cdot \mathrm{B} \end{gathered}}_{Under\ time-reversal}$$

Since we want the Lagrangian density to be *invariant* under *both* Lorentz *and* time-reversal transformations we pick $\mathbf{E}^2 - \mathrm{B}^2$.

An example for the effective field theories

Euler-Heisenberg correction to the Q.E.D. Lagrangian

$$L = \frac{1}{2}(\mathbf{E}^2-\mathbf{B}^2) + \frac{2\alpha^2}{45 m_e^4}\left[(\mathbf{E}^2-\mathbf{B}^2)^2 + 7\,(\mathbf{E}\cdot\mathbf{B})^2\right]$$

Using the Standard Model degrees of freedom one can parameterize the neutrino mass by a dimension 5 operator. (Recall that $I_3^W = 1/2$ for the ν_L and -1/2 for H_{SM}).

$$L = X_{\alpha\beta} H_{SM} H_{SM} \overline{\nu_{L\alpha}^{\,c}} \nu_{L\beta} / \Lambda$$

$$\boxed{v^2 X_{\alpha\beta} / \Lambda = U m_\nu^{\text{diagonal}} U^T}$$

This term is not renormalizable! It is the only dimension-five operator one can write using the Standard Model degrees of freedom. Hence the neutrino mass is the most accessible new physics beyond the Standard Model!

There are other ways to obtain neutrino mass:

$$L = H_{I=1}\,\overline{\nu_{L\alpha}{}^{C}}\,\nu_{L\beta}$$

Note: This Higgs is not in the Standard Model!

At lower energies, Beyond Standard Model physics is described by local operators

$$L = L_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \ldots$$

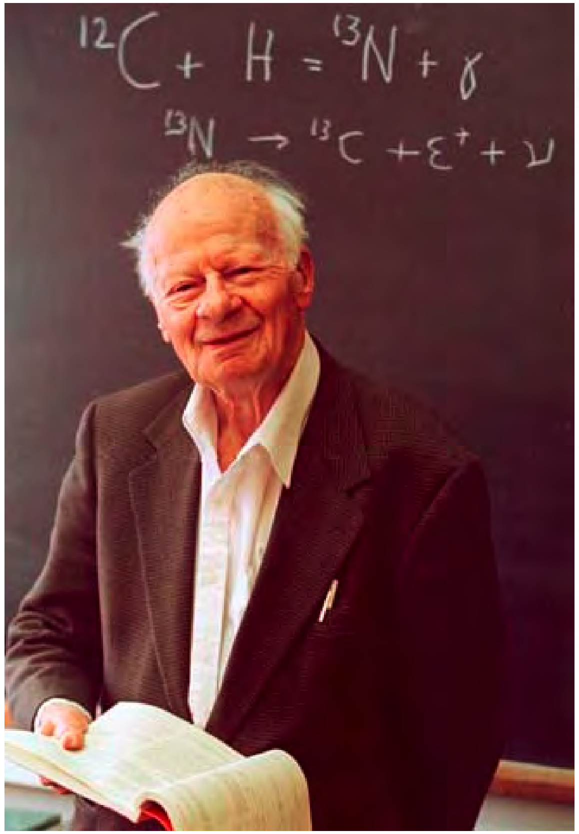
Majorana neutrino mass (unique)

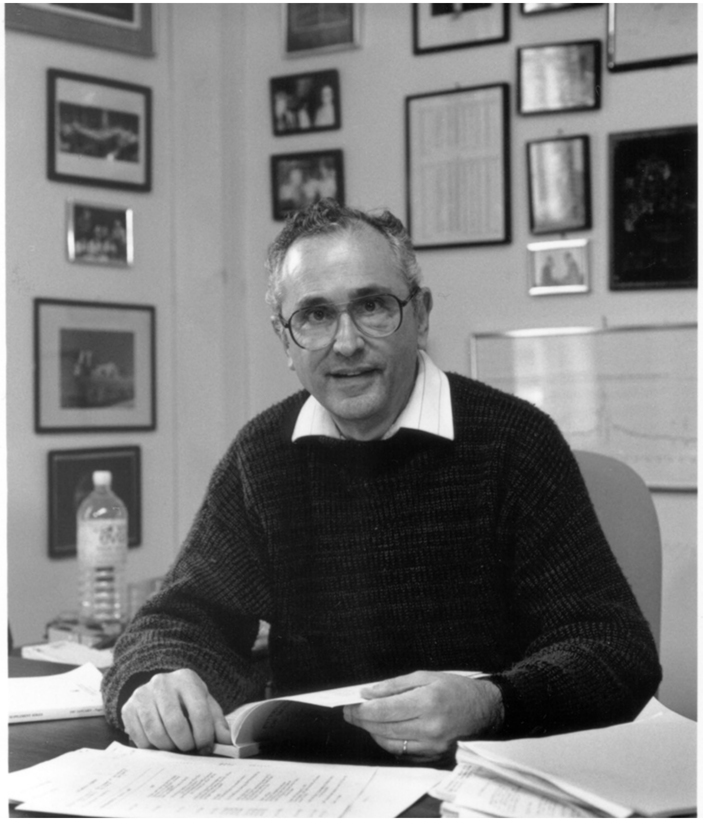
Includes Majorana neutrino magnetic moment

Majorana mass term:

$$m_M \left((\Psi_L)^C \right)^\dagger \beta \, \Psi_L$$

- Such a mass term violates lepton number conservation since it implies that neutrinos are their antiparticles.
- It is permitted by the weak-isospin invariance of the Standard Model.
- Neutrino mass terms are not included in the fundamental Lagrangian of the Standard Model. They arise from new physics. Of course it is possible to write down an *effective* Lagrangian for the neutrino mass in terms of only the Standard Model fields if you give up renormalizability.

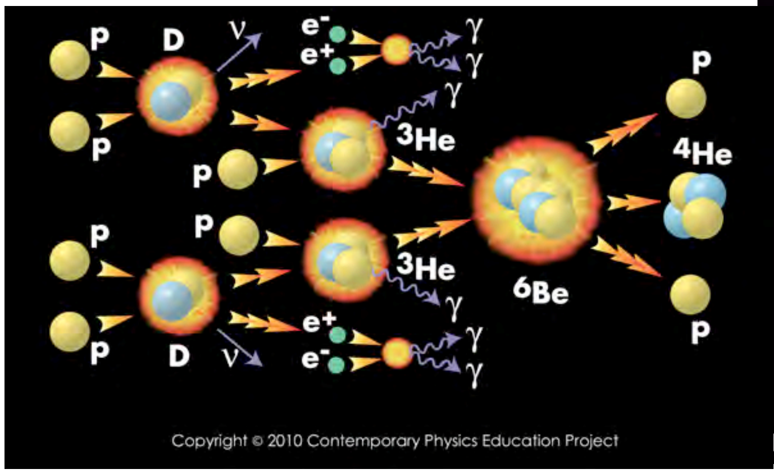


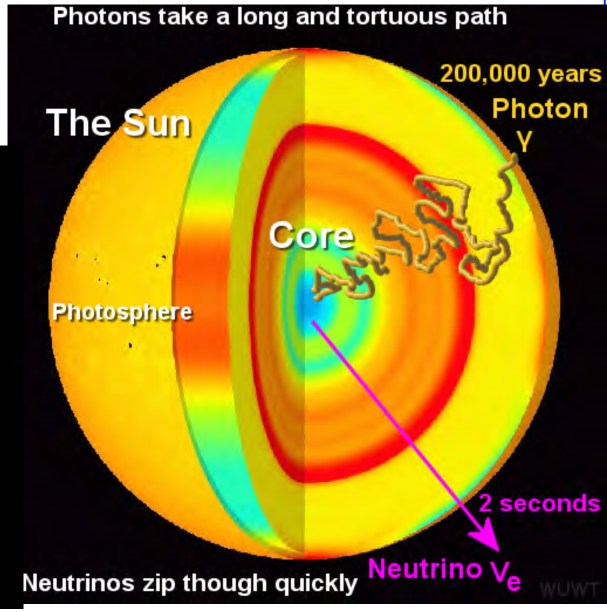


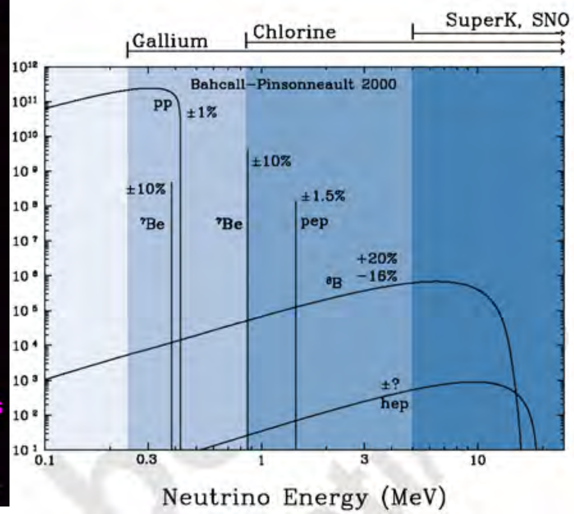
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

Bahcall and Davis, 1964

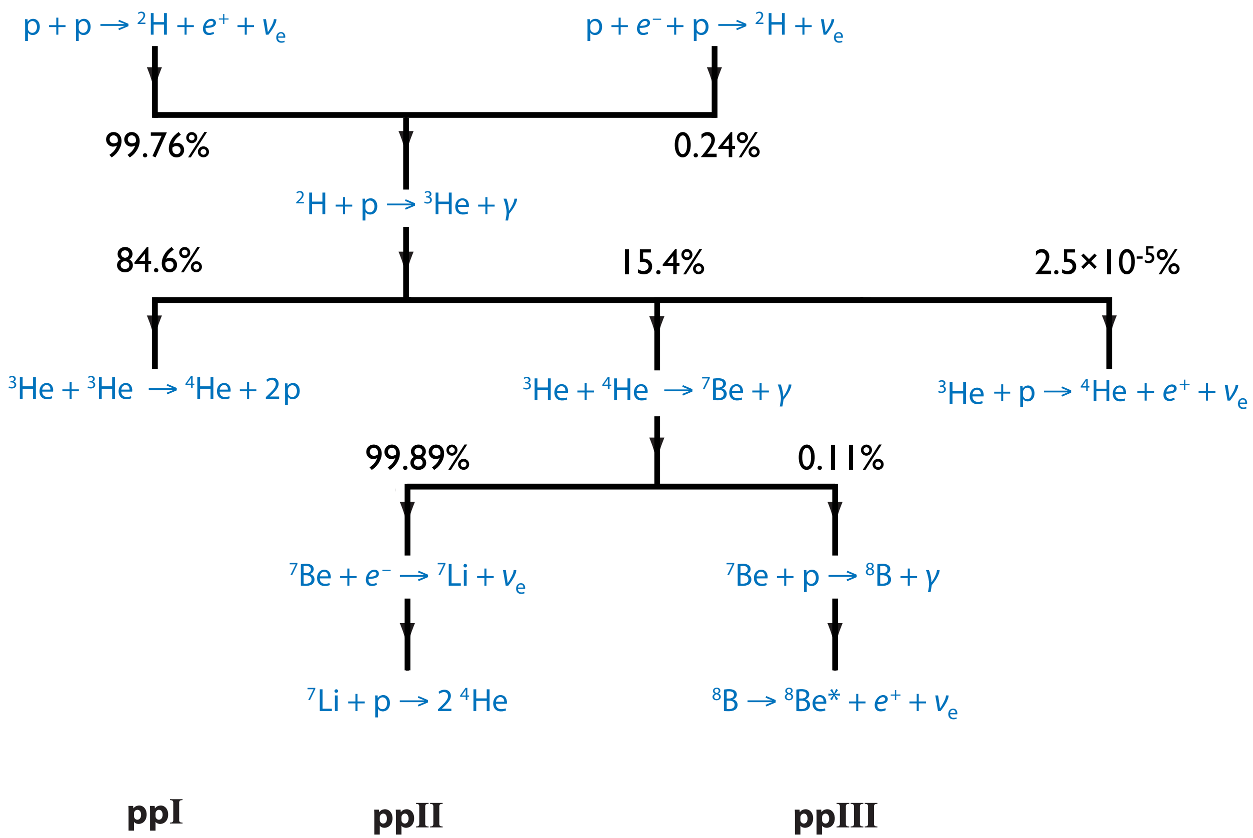
Solar Neutrinos

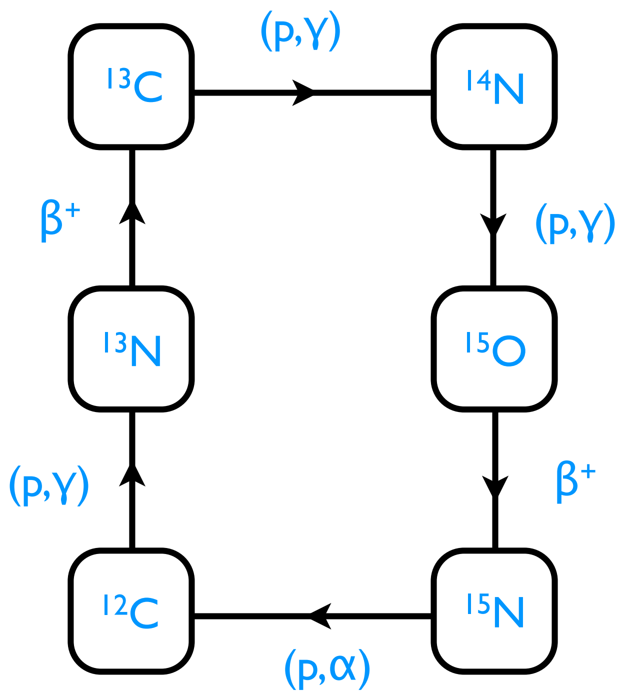






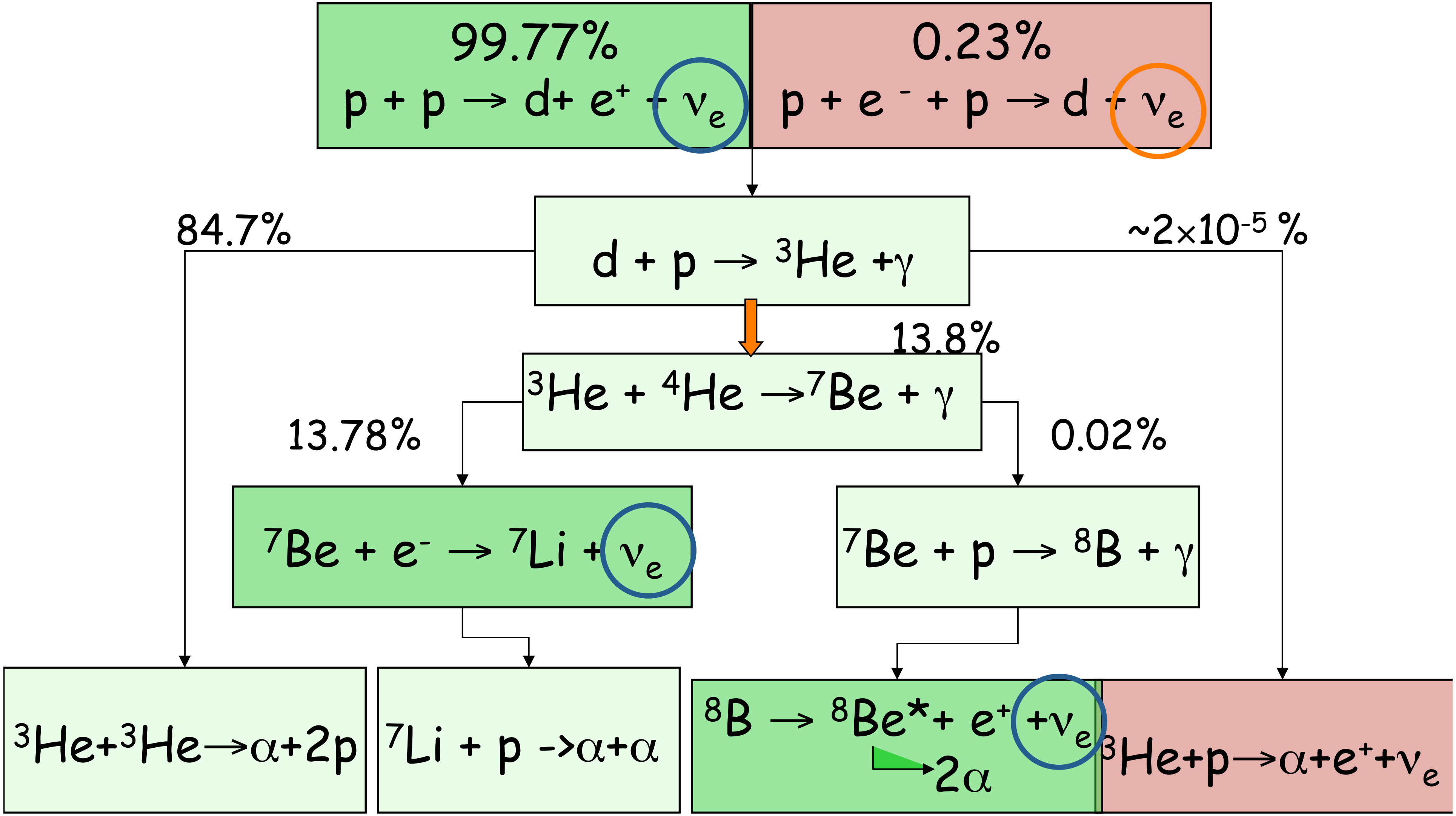
Neutrino producing reactions in the Sun





CN cycle

Nuclear reaction network in the Sun



Three paths leading to neutrinos are called pp-I, pp-II and pp-III chains, respectively.

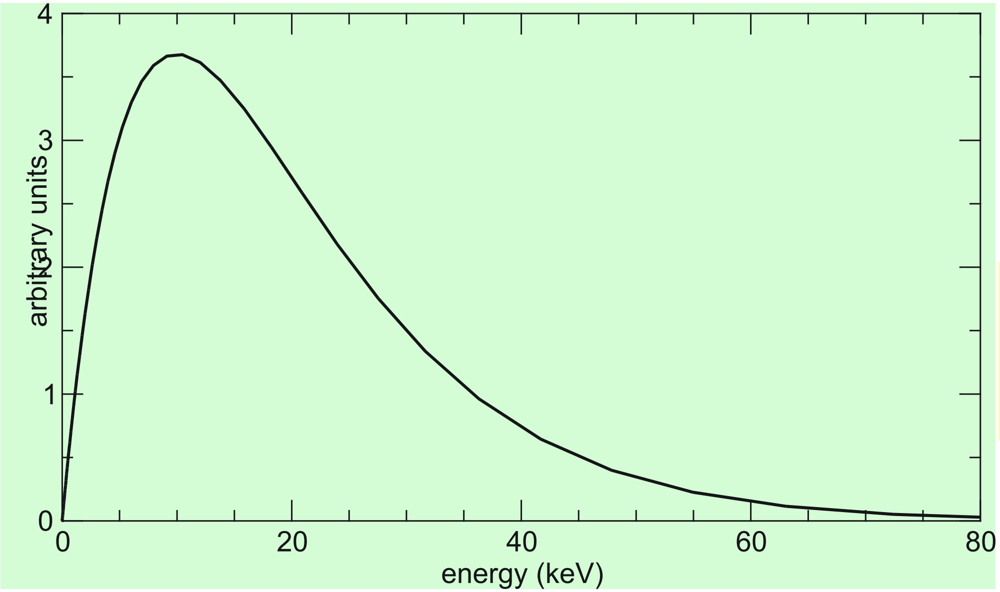
Reaction rates in astrophysical environments

Number of reactions per target nucleus per second: $\lambda = \sigma n_p v$

Total number of reactions per second when the number of target nuclei per unit volume is n_T: $R = \sigma n_p v n_t V$

Reaction rate per second and per unit volume:

$$r = \frac{1}{1+\delta_{pt}} n_p n_t \sigma v$$



The probability $\Phi(v)$ to find a particle with a velocity between v and v+dv

$$\Phi(v) = 4\pi \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 \, \mathrm{e}^{-\frac{m v^2}{2 \mathrm{kT}}}, \int \Phi(v)\, dv = 1$$

Stellar reaction rates has to be averaged over this distribution

$$r = \frac{1}{1+\delta_{pt}} n_p n_t \int \sigma(v) \Phi(v) v \, dv = \frac{1}{1+\delta_{pt}} n_p n_t < \sigma v >$$

Initial Reaction Network for the pp Chain in the Sun

$$\begin{aligned}
\frac{d[H]}{dt} &= -2\lambda_{11}\frac{[H]^2}{2} - \lambda_{12}[H][D] + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{17}[H][Be^7] - \lambda'_{17}[H][Li^7] \\
\frac{d[D]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - \lambda_{12}[H][D] \\
\frac{d[He^3]}{dt} &= \lambda_{12}[H][D] - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] + 2\lambda_{17}[H][Be^7] + 2\lambda'_{17}[H][Li^7] \\
\frac{d[Be^7]}{dt} &= \lambda_{34}[He^3][He^4] - \lambda_{17}[H][Be^7] - \lambda_{e7}[e][Be^7] \\
\frac{d[Li^7]}{dt} &= \lambda_{e7}[e][Be^7] - \lambda'_{17}[H][Li^7]
\end{aligned}$$

Reaction Network After the Deuterium Equilibrium

$$\begin{aligned}
\frac{d[H]}{dt} &= -3\lambda_{11}\frac{[H]^2}{2} + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{17}[H][Be^7] - \lambda'_{17}[H][Li^7] \\
\frac{d[He^3]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] + 2\lambda_{17}[H][Be^7] + 2\lambda'_{17}[H][Li^7] \\
\frac{d[Be^7]}{dt} &= \lambda_{34}[He^3][He^4] - \lambda_{17}[H][Be^7] - \lambda_{e7}[e][Be^7] \\
\frac{d[Li^7]}{dt} &= \lambda_{e7}[e][Be^7] - \lambda'_{17}[H][Li^7]
\end{aligned}$$

Reaction Network After the Li and Be Equilibrium

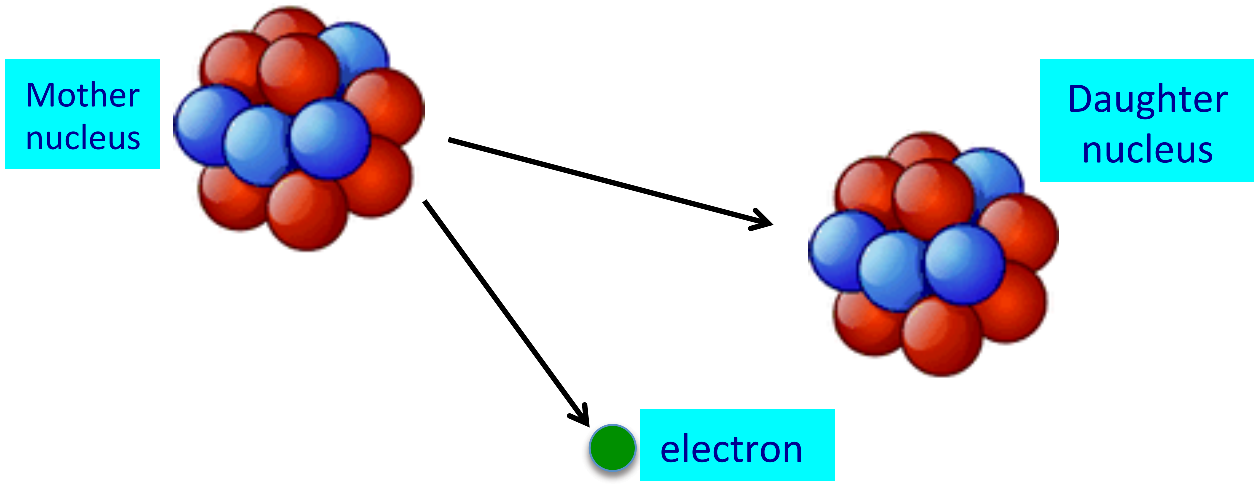
$$
\begin{aligned}
\frac{d[H]}{dt} &= -3\lambda_{11}\frac{[H]^2}{2} + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^3]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} + \lambda_{34}[He^3][He^4]
\end{aligned}
$$

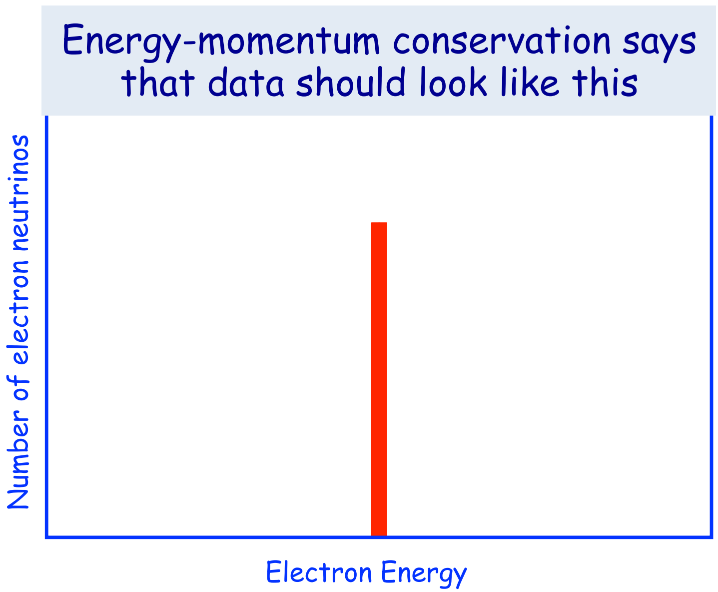
Reaction Network After the He^3 Equilibrium

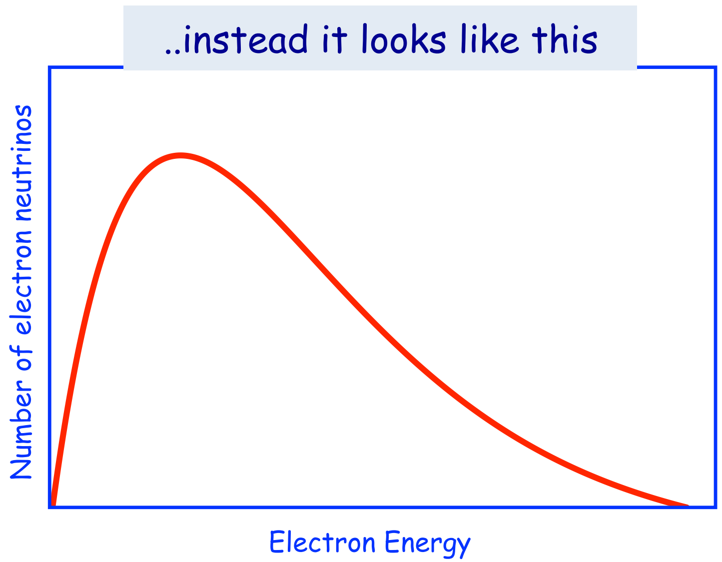
$$
\begin{aligned}
\frac{d[H]}{dt} &= -\lambda_{11}[H]^2 - 2\lambda_{34}[He^3]_{eq}[He^4] \\
\frac{d[He^4]}{dt} &= \frac{1}{4}\lambda_{11}[H]^2 + \frac{1}{2}\lambda_{34}[He^3]_{eq}[He^4]
\end{aligned}
$$

$$
\frac{d[He^4]}{dt} = -\frac{1}{4}\frac{d[H]}{dt}
$$

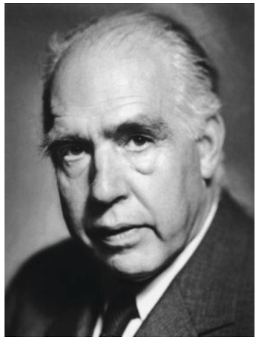
Neutrino came out of a puzzle about the radioactive decay in the early 1920's:



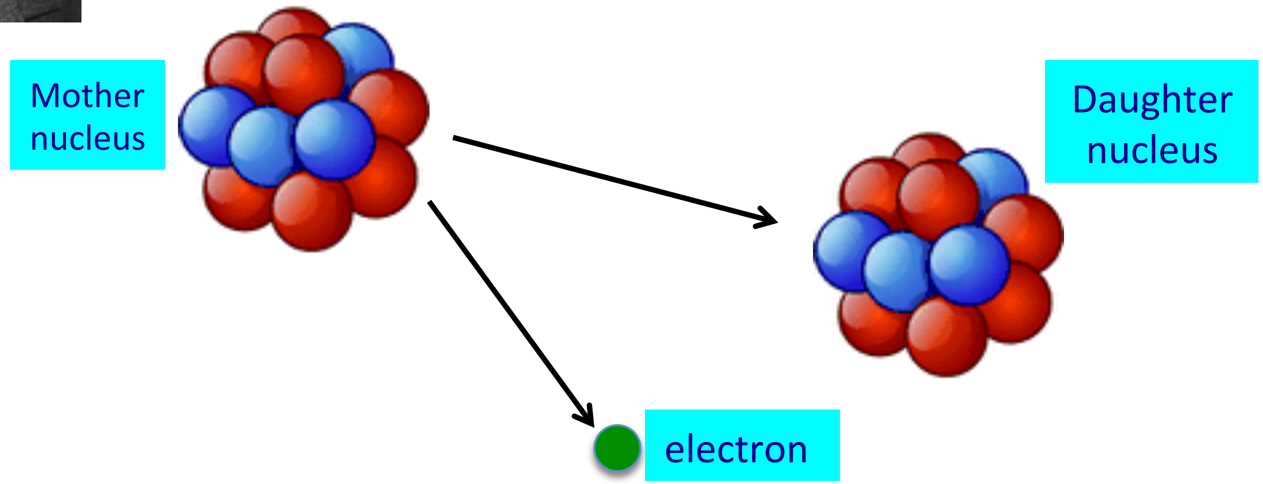




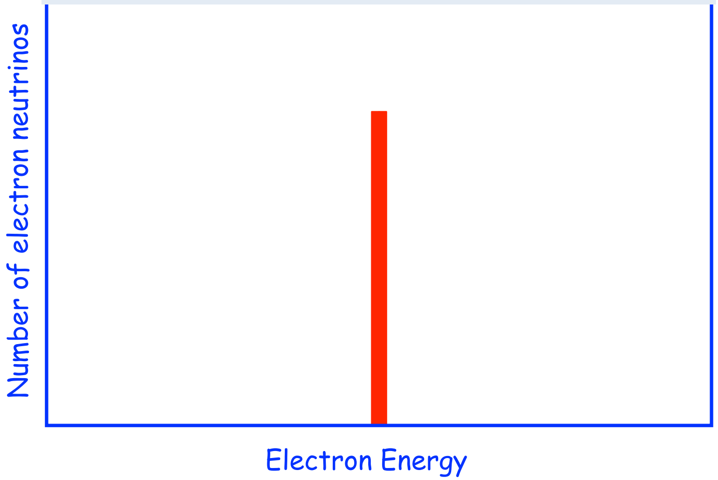
Niels Bohr



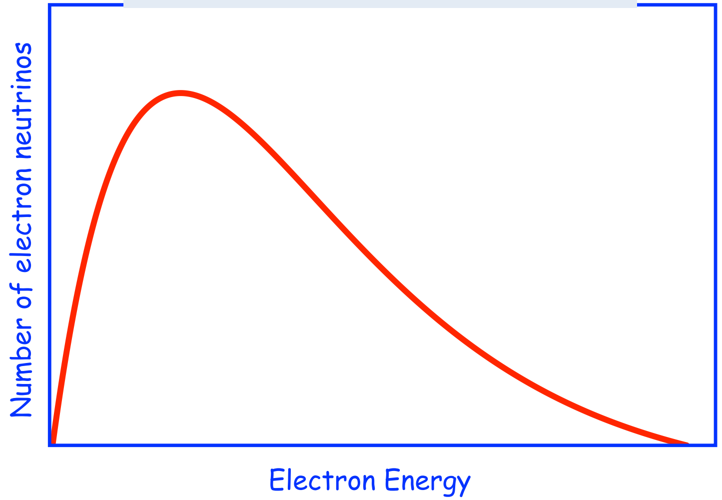
In radioactive decays energy-momentum conservation no longer holds!



Energy-momentum conservation says that data should look like this

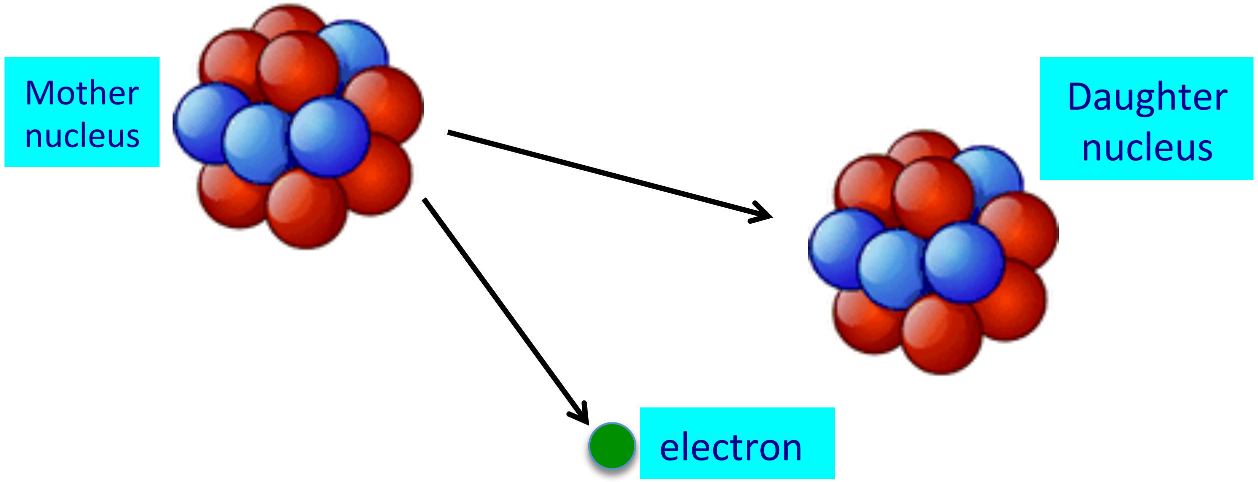


..instead it looks like this



Wolfgang Pauli

In this reaction there is a third particle produced that you cannot (yet) see!



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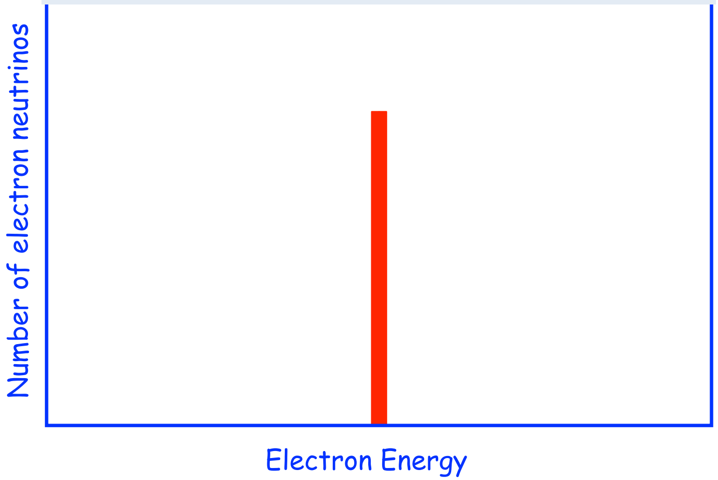

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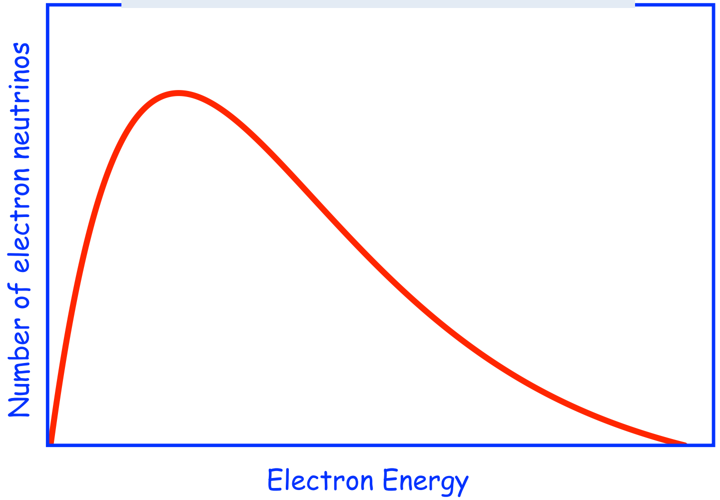

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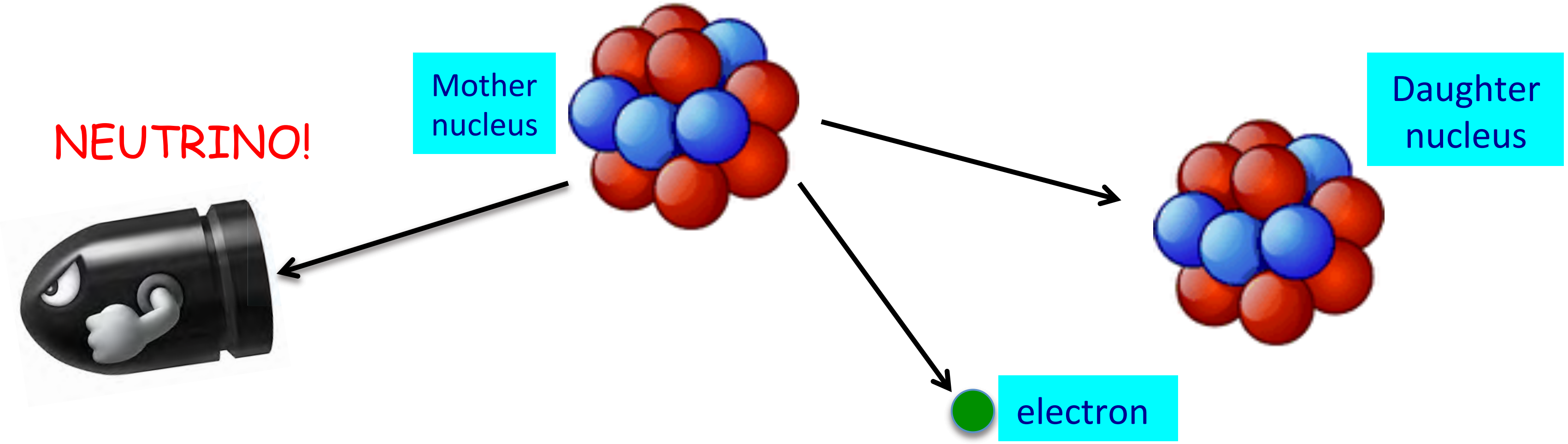
NEUTRINO!



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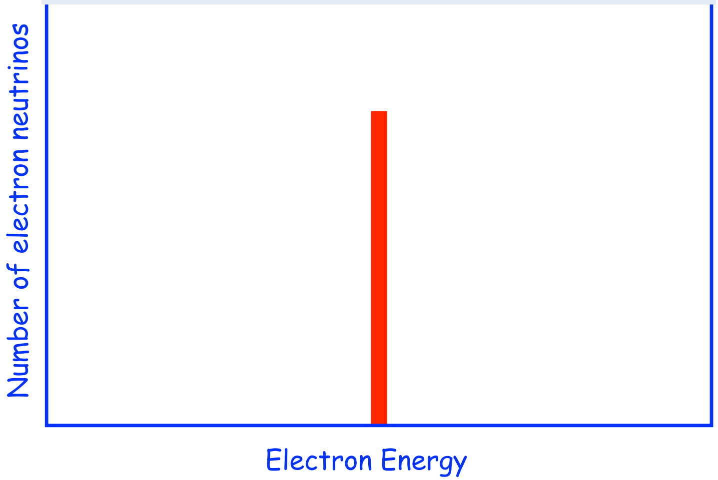

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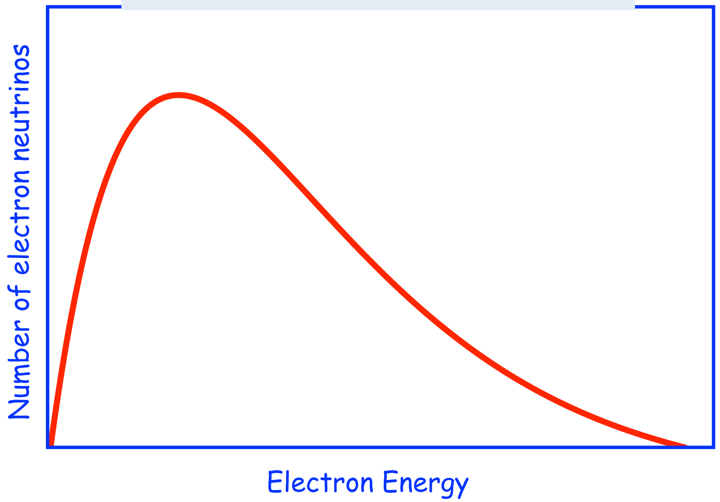


Wolfgang Pauli,
father of the neutrino
and Pauli exclusion
principle

Physicist goes to a ball

or

Mystery of Missing Energy

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

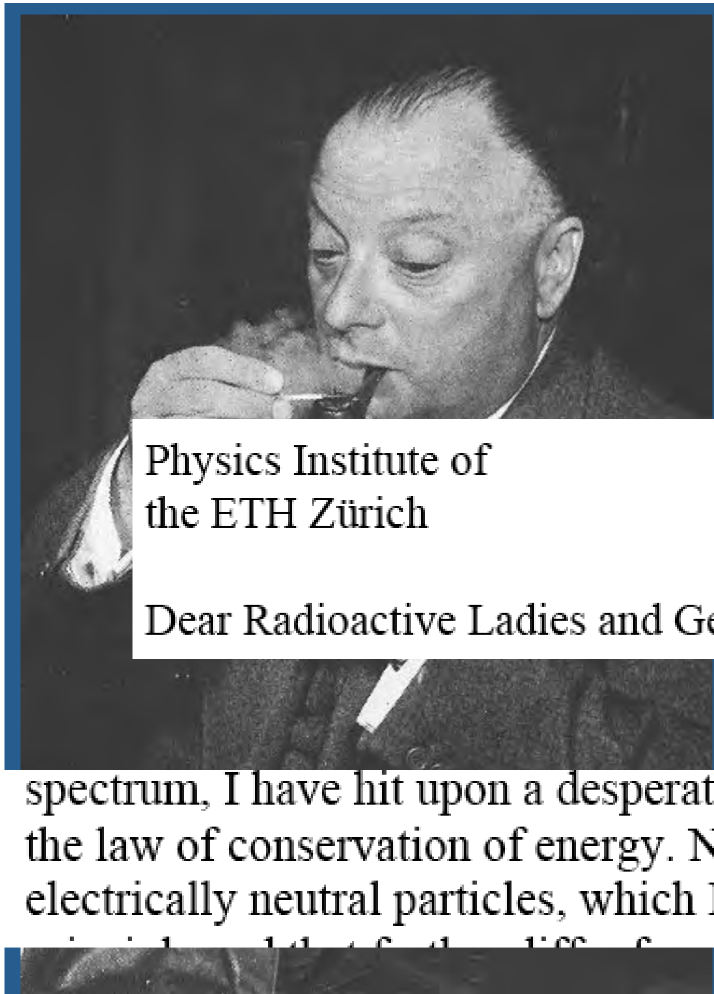
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
müsste von derselben Grössenordnung wie die Elektronenmasse sein und
jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche
beta- Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.



Physicist goes to a ball

or

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion

Wolfgang Pauli

way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble

principle

Pauli

Fermi

Majorana

Pontecorvo

Goeppert-Meyer

Neutrino Timeline

What is a particle?

Wigner: A particle is an irreducible representation of the Poincare group.

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Recall the quantities Lorentz transformations leave invariant:

$$t^2 - \mathbf{r}^2 = \tau^2$$

$$E^2 - \mathbf{p}^2 = m^2$$

$$\mathbf{E}^2 - \mathbf{B}^2$$

$$\mathbf{E} \cdot \mathbf{B}$$

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Poincare group is the group including Lorentz boosts, translations and rotations.

Next let us explore the concept of mass

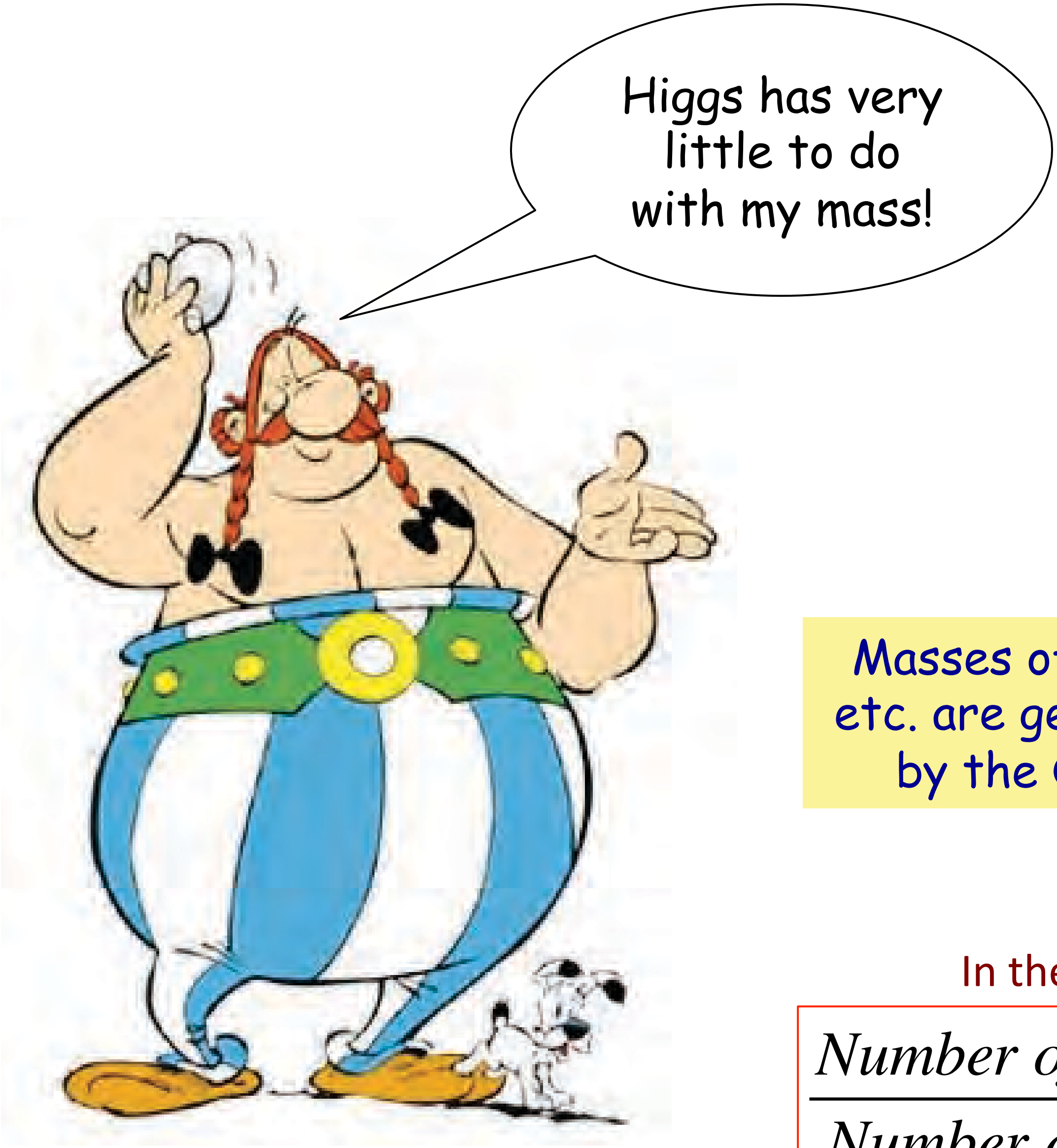
What is mass?

$$\Psi_L = \frac{1}{2}\left(1-\gamma_5\right)\Psi$$

$$\Psi_R = \frac{1}{2}\left(1+\gamma_5\right)\Psi$$

$$\mathcal{L} = m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_l\right)$$

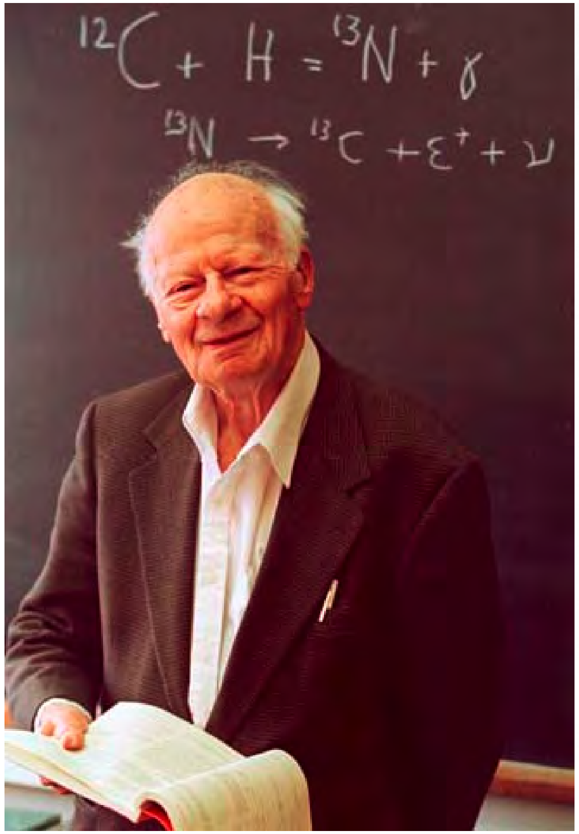
In the Standard Model all elementary masses possibly except those for neutrinos are generated by the Yukawa couplings of the Higgs.

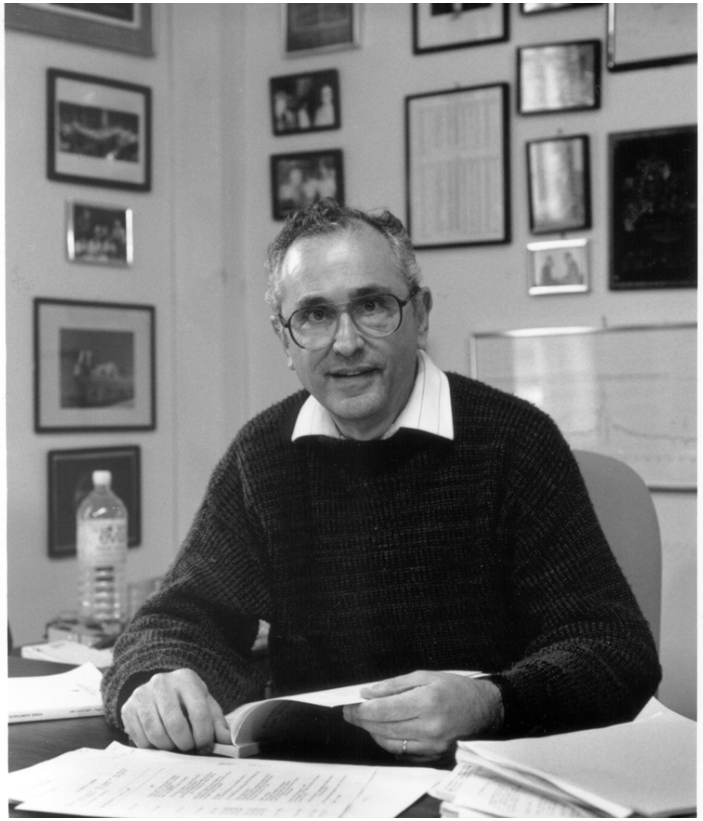


Masses of protons, neutrons, etc. are generated dynamically by the QCD interactions!

In the Early Universe

$$\frac{Number\ of\ neutrons}{Number\ of\ protons} = \frac{e^{-m_n/T}}{e^{-m_p/T}}$$

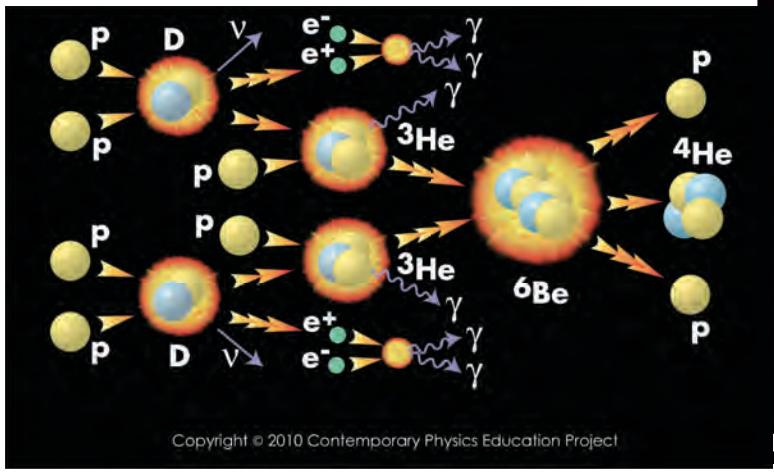


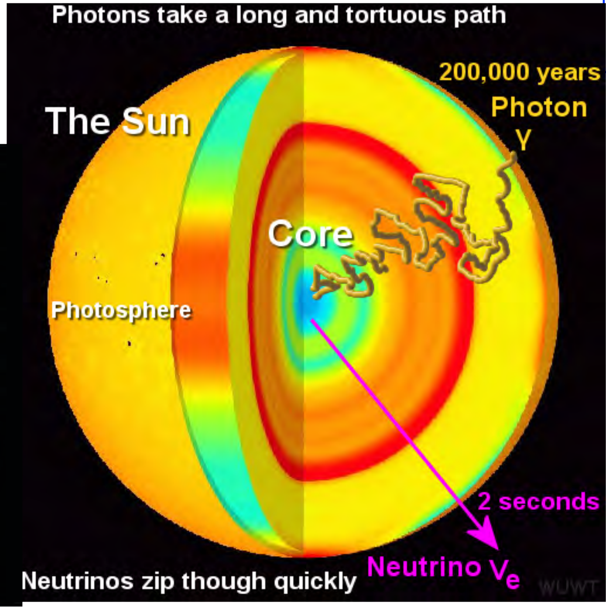


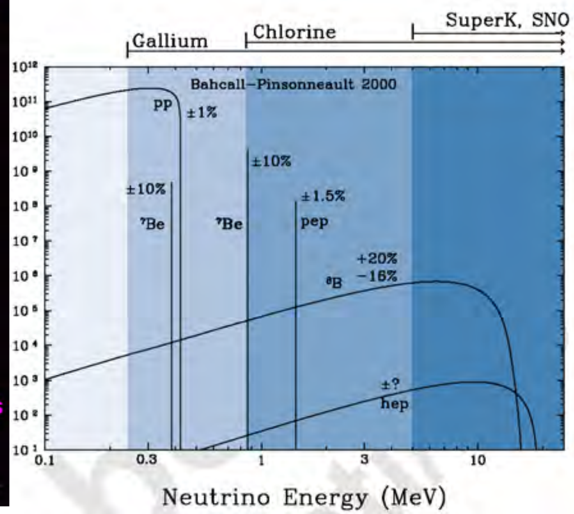
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

Bahcall and Davis, 1964

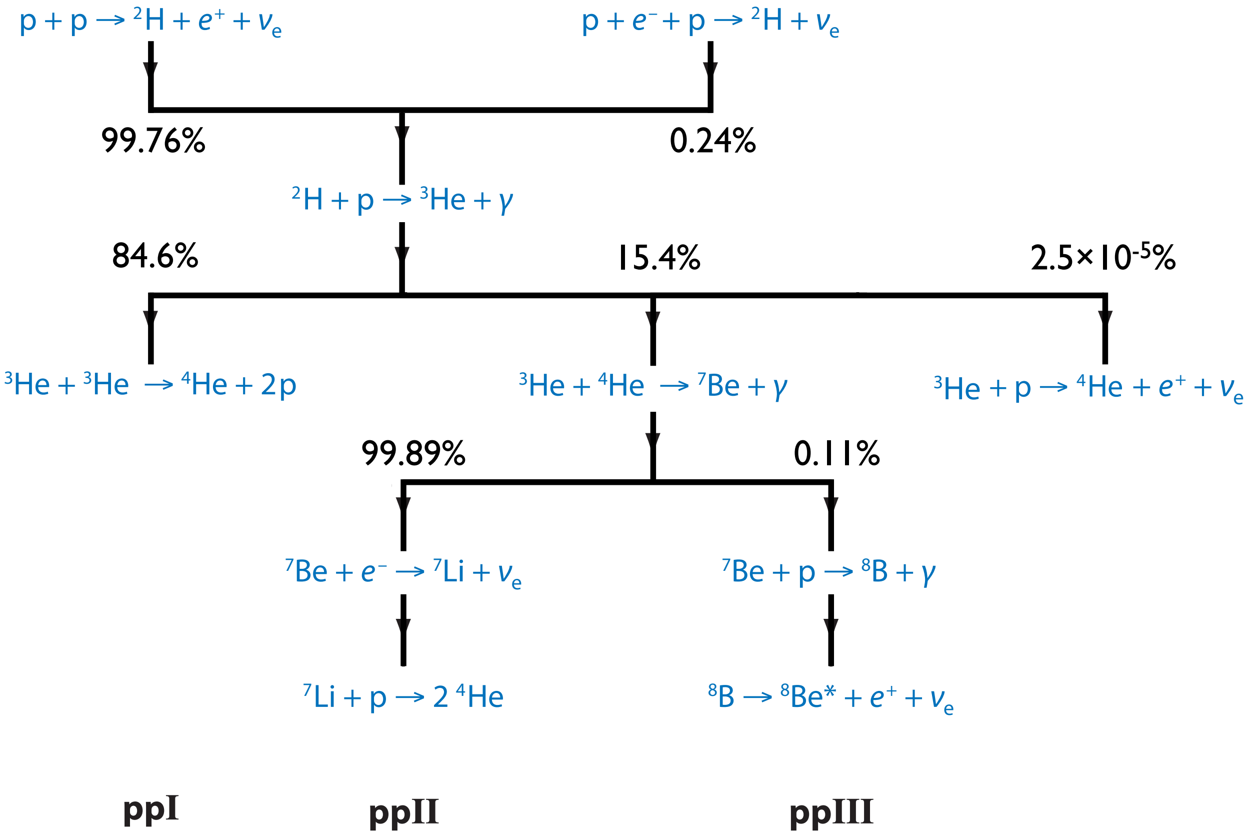
Solar Neutrinos

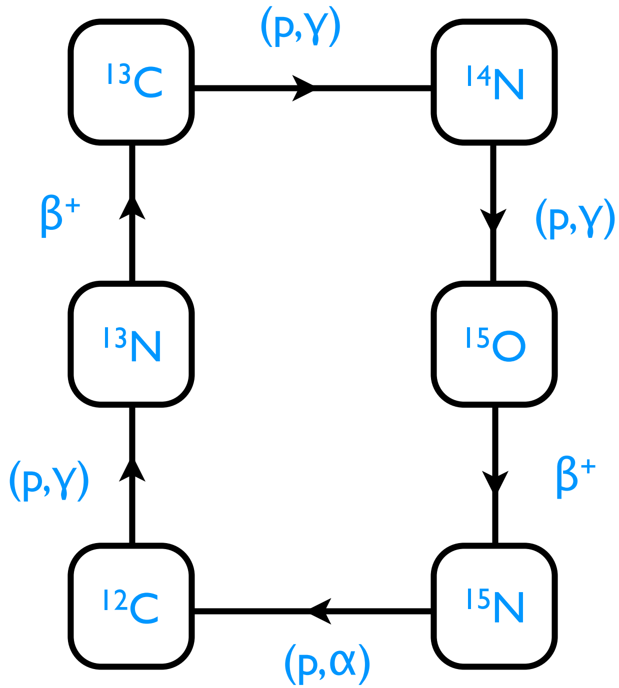






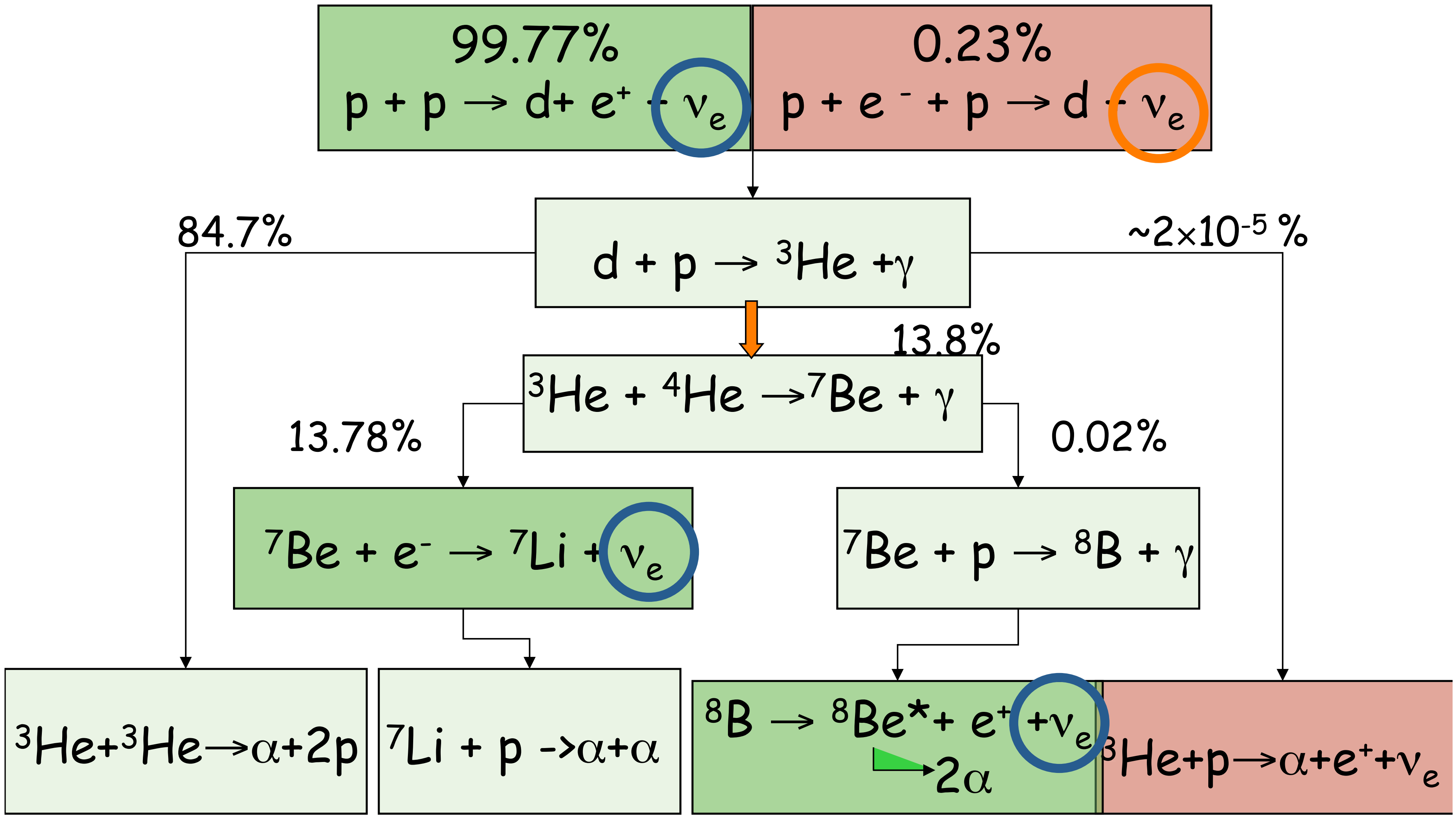
Neutrino producing reactions in the Sun





CN cycle

Nuclear reaction network in the Sun



Three paths leading to neutrinos are called pp-I, pp-II and pp-III chains, respectively.

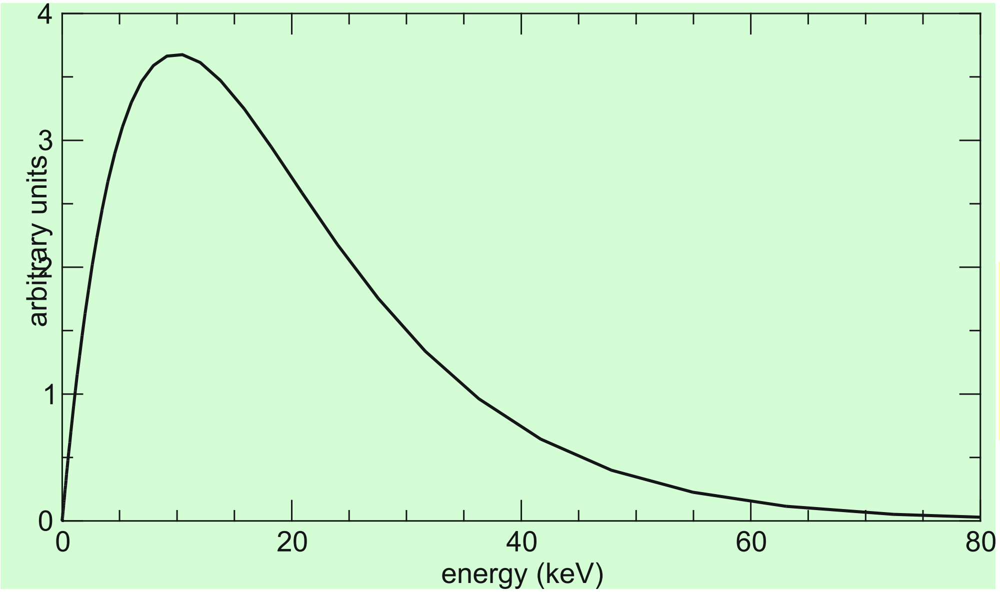
Reaction rates in astrophysical environments

Number of reactions per target nucleus per second: $\lambda = \sigma n_p v$

Total number of reactions per second when the number of target nuclei per unit volume is n_T: $R = \sigma n_p v n_t V$

Reaction rate per second and per unit volume:

$$r = \frac{1}{1+\delta_{pt}} n_p n_t \sigma v$$



The probability Φ(v) to find a particle with a velocity between v and v+dv

$$\Phi(v) = 4\pi \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 \, \mathrm{e}^{-\frac{m v^2}{2\mathrm{kT}}}, \int \Phi(v)\, dv = 1$$

Stellar reaction rates has to be averaged over this distribution

$$r = \frac{1}{1+\delta_{pt}} n_p n_t \int \sigma(v) \Phi(v) v \, dv = \frac{1}{1+\delta_{pt}} n_p n_t < \sigma v >$$

Initial Reaction Network for the pp Chain in the Sun

$$\begin{aligned}
\frac{d[H]}{dt} &= -2\lambda_{11}\frac{[H]^2}{2} - \lambda_{12}[H][D] + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{17}[H][Be^7] - \lambda'_{17}[H][Li^7] \\
\frac{d[D]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - \lambda_{12}[H][D] \\
\frac{d[He^3]}{dt} &= \lambda_{12}[H][D] - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] + 2\lambda_{17}[H][Be^7] + 2\lambda'_{17}[H][Li^7] \\
\frac{d[Be^7]}{dt} &= \lambda_{34}[He^3][He^4] - \lambda_{17}[H][Be^7] - \lambda_{e7}[e][Be^7] \\
\frac{d[Li^7]}{dt} &= \lambda_{e7}[e][Be^7] - \lambda'_{17}[H][Li^7]
\end{aligned}$$

Reaction Network After the Deuterium Equilibrium

$$
\begin{aligned}
\frac{d[H]}{dt} &= -3\lambda_{11}\frac{[H]^2}{2} + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{17}[H][Be^7] - \lambda'_{17}[H][Li^7] \\
\frac{d[He^3]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] + 2\lambda_{17}[H][Be^7] + 2\lambda'_{17}[H][Li^7] \\
\frac{d[Be^7]}{dt} &= \lambda_{34}[He^3][He^4] - \lambda_{17}[H][Be^7] - \lambda_{e7}[e][Be^7] \\
\frac{d[Li^7]}{dt} &= \lambda_{e7}[e][Be^7] - \lambda'_{17}[H][Li^7]
\end{aligned}
$$

Reaction Network After the Li and Be Equilibrium

$$\begin{aligned}
\frac{d[H]}{dt} &= -3\lambda_{11}\frac{[H]^2}{2} + 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^3]}{dt} &= \lambda_{11}\frac{[H]^2}{2} - 2\lambda_{33}\frac{[He^3]^2}{2} - \lambda_{34}[He^3][He^4] \\
\frac{d[He^4]}{dt} &= \lambda_{33}\frac{[He^3]^2}{2} + \lambda_{34}[He^3][He^4]
\end{aligned}$$

Reaction Network After the He^3 Equilibrium

$$\begin{aligned}\frac{d[H]}{dt} &= -\lambda_{11}[H]^2 - 2\lambda_{34}[He^3]_{eq}[He^4] \\ \frac{d[He^4]}{dt} &= \frac{1}{4}\lambda_{11}[H]^2 + \frac{1}{2}\lambda_{34}[He^3]_{eq}[He^4]\end{aligned}$$

$$\frac{d[He^4]}{dt} = -\frac{1}{4}\frac{d[H]}{dt}$$