Nuclear Astrophysics

An Introduction

Lecture 2

F. De Oliveira Santos

GANIL spiral2

laboratoire commun CEA/DSM CNRS/IN2P3

Short summary of the previous lecture

Gamow energy

$$E_0 = 1.22\,(Z_1^2 Z_2^2\, \mu\, T_6^2)^{\frac{1}{3}} \quad \text{keV}$$

Gamow window

$$\Delta E = 0.749\left(Z_1^2 Z_2^2 \mu T_6^5\right)^{1/6} \quad \text{keV}$$

Astrophysical factor

$$\sigma(E) = \frac{S}{E}\exp(-2\pi\,\eta)$$

Sommerfeld parameter

$$2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2}$$

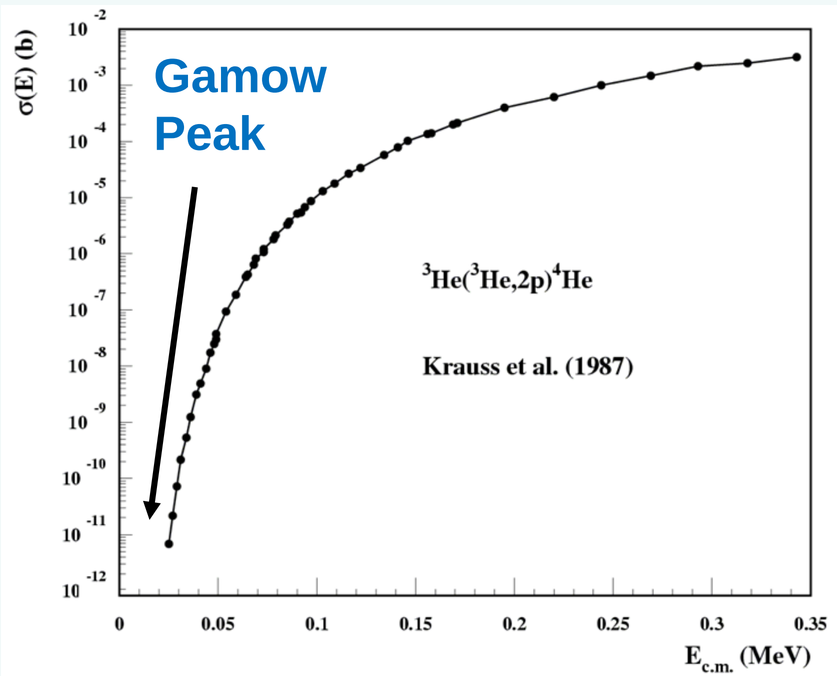
with E in keV

μ in u.m.a

Origin of the Sun's heat?

Two methods to determine σ(E) or S(E)

Direct Measurements



Indirect Measurements

Model Dependant

$$\sigma(E) = \pi \lambda\!\!\!^{-}{}^2 \quad \omega \quad \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + (\Gamma_{tot}/2)^2}$$

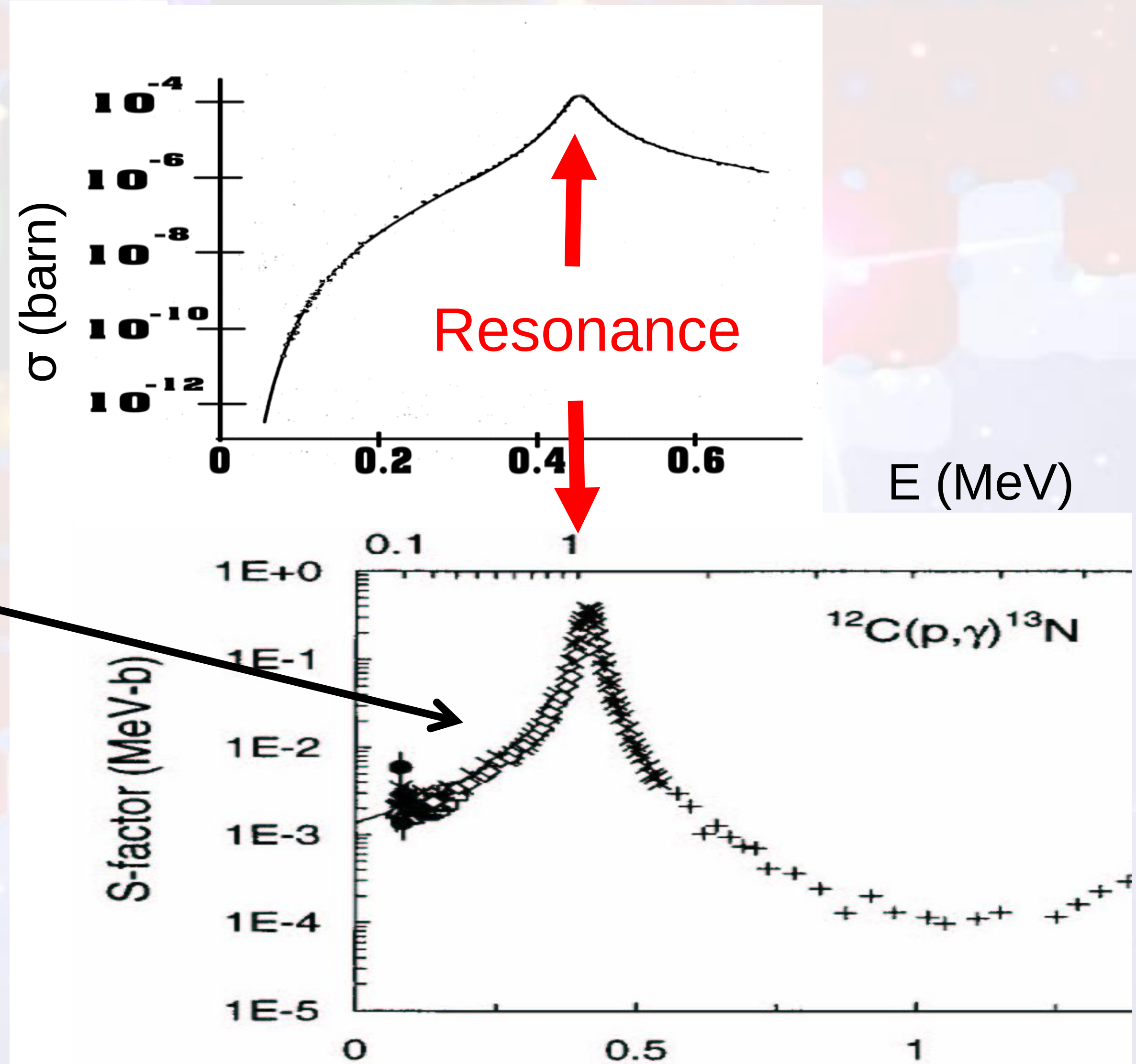
- Transfer Reaction
  - $^{12}C(^{7}Li,t)^{16}O$
- Resonant Elastic Scattering
  - $^{12}C(\alpha,\alpha)^{12}C$
- Coulomb Breakup
  - $^{16}O(\gamma,\alpha)^{12}C$
- Trojan Horse
  - $^{6}Li(^{12}C,\alpha\ ^{12}C)^{2}H$

Need experiments AND theory to determine stellar reaction rates

Example 1

A resonance in $^{12}C(p,\gamma)^{13}N$

$$^{12}C + p \Rightarrow \,^{13}N^* \Rightarrow \,^{13}N + \gamma$$



A model is needed to fit the shape of the resonance

Angulo et al. Nucl. Phys. A 656 (1999) 3

σ(E) for a resonance
Breit-Wigner Formula

X(p,γ)Y

$$\sigma(E) = \pi \lambda\!\!\!{}^{-}{}^2 \cdot \omega \cdot \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + (\Gamma_{tot}/2)^2}$$

$$\frac{656.6}{\mu}\frac{1}{E(\mathrm{keV})}\,\mathrm{barn}$$

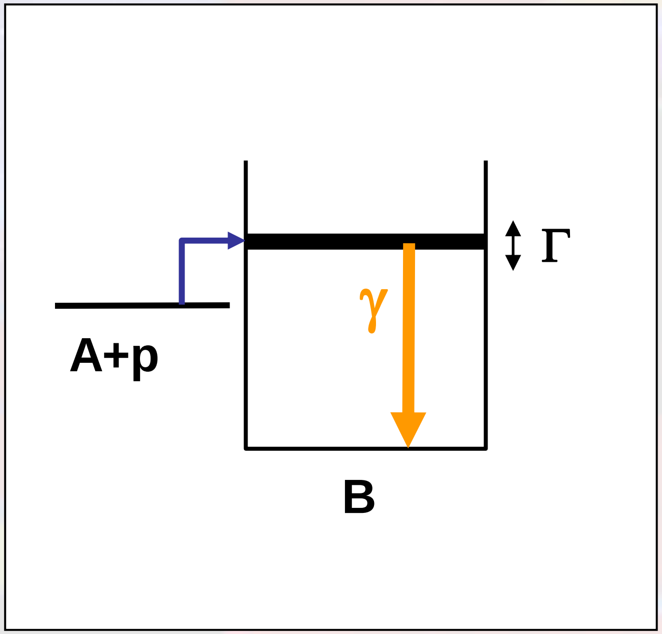
$$\omega = \frac{2J_Y + 1}{(2J_X + 1)(2J_p + 1)}$$

We need:

- Energy of excited states
- Spins
- Widths

$<\sigma v>$

Rate of a narrow resonance



Analytical formula

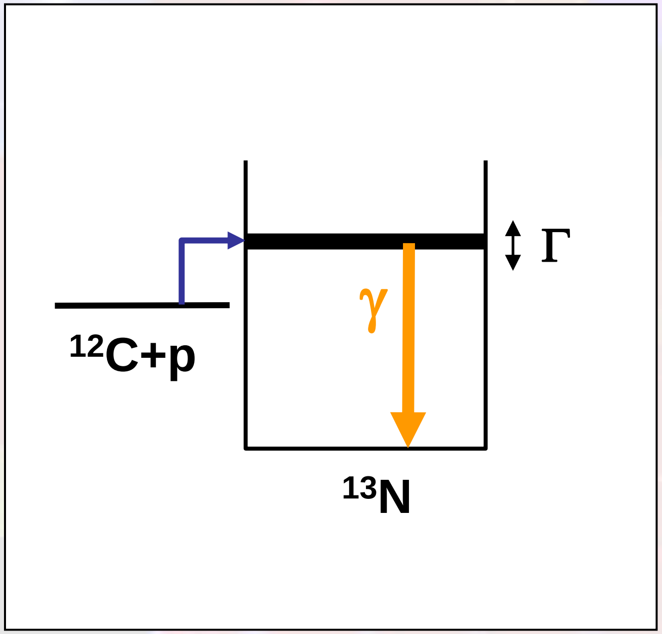
$$N_A <\sigma v> = C_8 (T_9)^{-\frac{3}{2}} \exp(-\frac{C_9}{T_9})$$

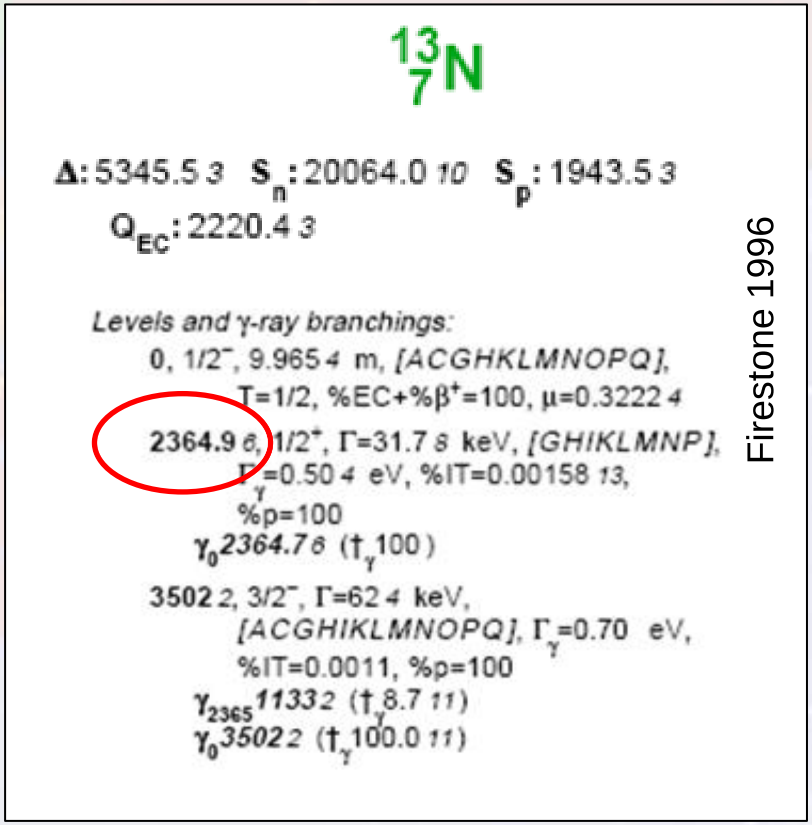
$$C_9 = 11.605\, E_R (\mathrm{MeV})$$

$$C_8 = 1.54x10^{11} \mu^{-3/2} \omega \gamma$$ $cm^3 mole^{-1} s^{-1}$

$$\gamma = \frac{\Gamma_\gamma \Gamma_p}{\Gamma_\gamma + \Gamma_p}$$ MeV

Exercise: Rate of $^{12}C(p,\gamma)^{13}N$?





$^{13}_{7}N$

Δ: 5345.5 3 S_n: 20064.0 10 S_p: 1943.5 3
Q_{EC}: 2220.4 3

Levels and γ-ray branchings:

0, 1/2⁻, 9.965 4 m, *[ACGHKLMNOPQ]*,
T=1/2, %EC+%β⁺=100, μ=0.3222 4

2364.9 6, 1/2⁺, Γ=31.7 8 keV, *[GHIKLMNP]*,
Γ_γ=0.50 4 eV, %IT=0.00158 13,
%p=100
γ_0 *2364.7* 6 (I_γ 100)

3502 2, 3/2⁻, Γ=62 4 keV,
[ACGHIKLMNOPQ], Γ_γ=0.70 eV,
%IT=0.0011, %p=100
γ_{2365} *1133* 2 (I_γ 8.7 11)
γ_0 *3502* 2 (I_γ 100.0 11)

Firestone 1996

Solution

Resonance energy

E_R = 2364.9-1943.5 = 421.4 keV

Γ = 31.7 keV $\Gamma\gamma$ = 0.5 eV

$$\omega = \frac{(2x0.5+1)}{(2x0+1)(2x0.5+1)} = 1$$

$$\gamma = \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{TOT}} \approx \Gamma_\gamma = 0.5\,x\,10^{-6}\ \mathrm{MeV}$$

→ **0.87e+05 /T932*exp(-4.890/T9)**

$^{12}\mathbf{C(p,\gamma)}^{13}\mathbf{N}$, $Q = 1.943$ MeV, (6%)

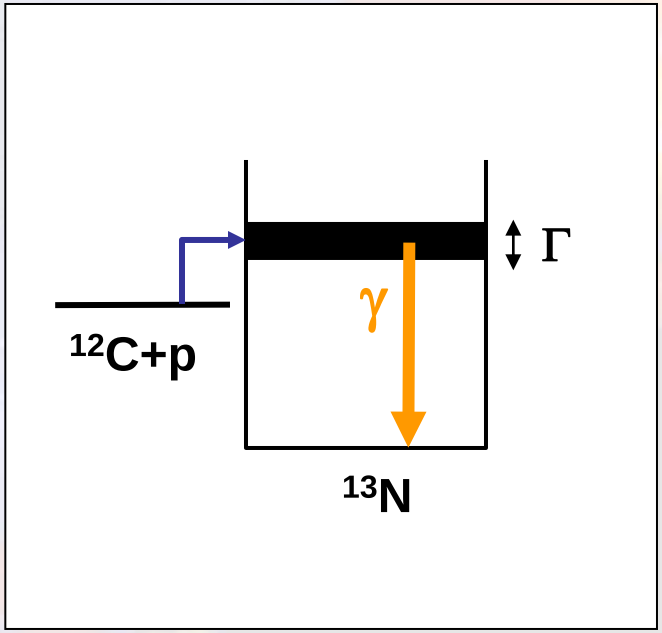
$$N_A\langle\sigma v\rangle_{gs} = 2.00\times10^{7}\,T_9^{-2/3}\exp(-13.692\,T_9^{-1/3} - (T_9/0.46)^2)\times(1 + 9.89\,T_9 - 59.8\,T_9^2 + 266\,T_9^3)$$
$$+1.00\times10^{5}\,T_9^{-3/2}\exp(-4.913/T_9) + 4.24\times10^{5}\,T_9^{-3/2}\exp(-21.62/T_9)$$

http://www.astro.ulb.ac.be/nacreii/

http://www.nuclear.csdb.cn/data/CF88/

http://starlib.physics.unc.edu/RateLib.php

Databases



In case of Broad resonances

The rate has to be calculated numerically

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \quad \cdot \quad \omega \quad \cdot \quad \frac{\Gamma_p(E)\Gamma_\gamma(E)}{(E - E_r)^2 + (\Gamma_{tot}(E)/2)^2}$$

$$\Gamma_p(E) = \Gamma_p(E_R)\ \frac{P(E)}{P(E_R)} = \mathrm{constant\ x}\ P(E)$$

or depending on the P(E) definition: $\Gamma_p(E) = \mathrm{constant}\sqrt{E}\,\mathrm{x}\,P(E)$

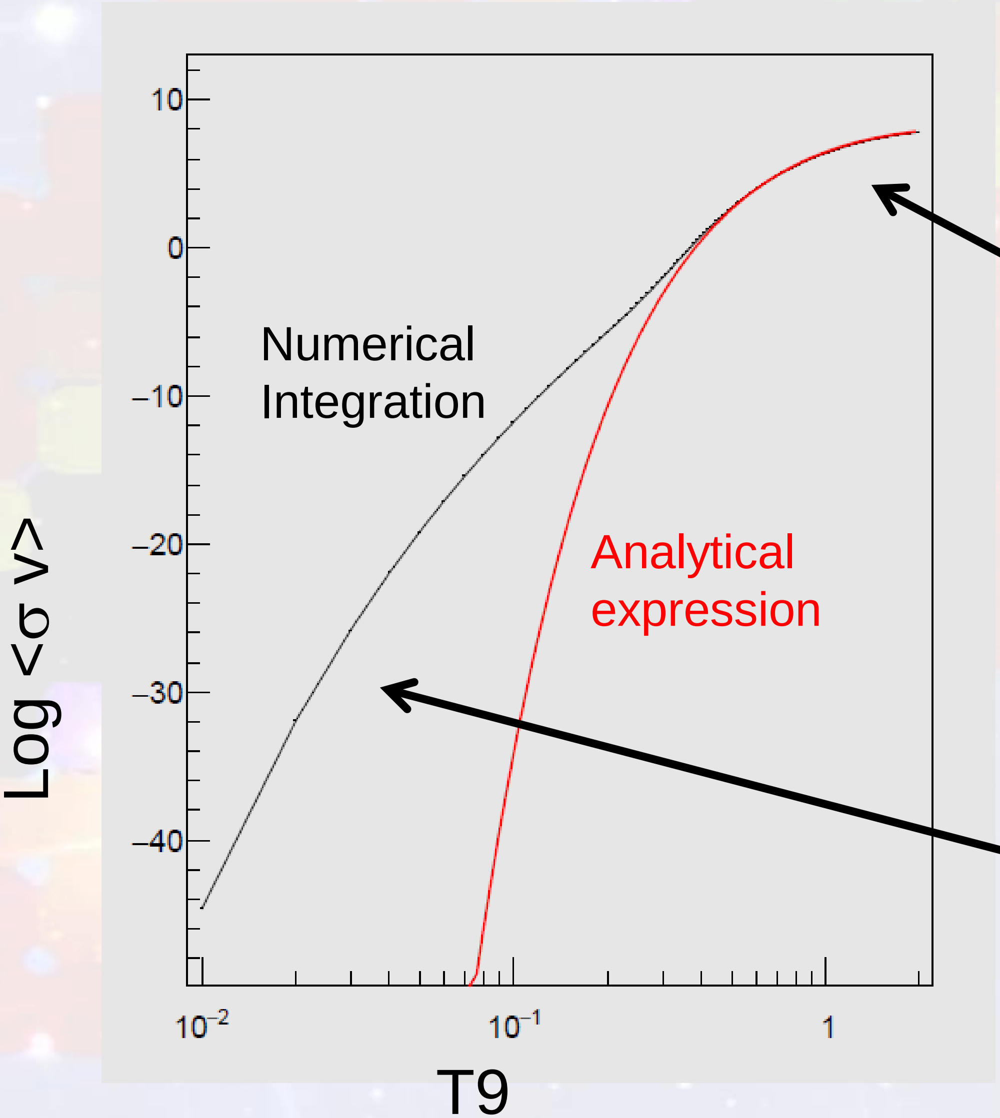
$$\Gamma(E_\gamma) = \alpha_L E_\gamma^{2L+1}$$

L = order of the γ-transition

Broad versus narrow resonance

$^{12}C(p,\gamma)^{13}N$

Γ = 31.7 keV, not very narrow



Very good approximation here.

Effect of the tail of the resonance seen at low temperature

Example 2

Direct measurement of $^3He(^3He,2p)^4He$

Important in the Sun

Table 2.3 *Classification of the main reactions involved in nuclear astrophysics.*

Process			Examples	$S(0)$ (MeV-b)
Nuclear	Non – resonant		$^6Li(p,\alpha)^3He$	≈ 3
	Resonant	$\ell_R = \ell_{min}$	$^3He(d,p)\alpha$	≈ 6
		$\ell_R > \ell_{min}$	$^{11}B(p,\alpha)^8Be$	≈ 300
		multiresonance	$^{22}Ne(\alpha,n)^{25}Mg$	$\approx 10^8$
	Subthreshold state		$^{13}C(\alpha,n)^{16}O$	$\approx 10^7$

$E_0 = 1.22\,(Z_1^2 Z_2^2\, \mu\, T_6^2)^{\frac{1}{3}}$ keV $T_6=15$ $\sigma(E) = \frac{S}{E}\exp(-2\pi\eta)$

$E_0 = 21$ keV
$S \sim 3$ MeV b
→ $\sigma(50 \text{ keV}) = 5.5 \times 10^{-11}$ b

Beam 350 µA = 2×10^{15} pps
(gas) Target ~ 10^{16} atm/cm2

→ dN=4 counts/hour

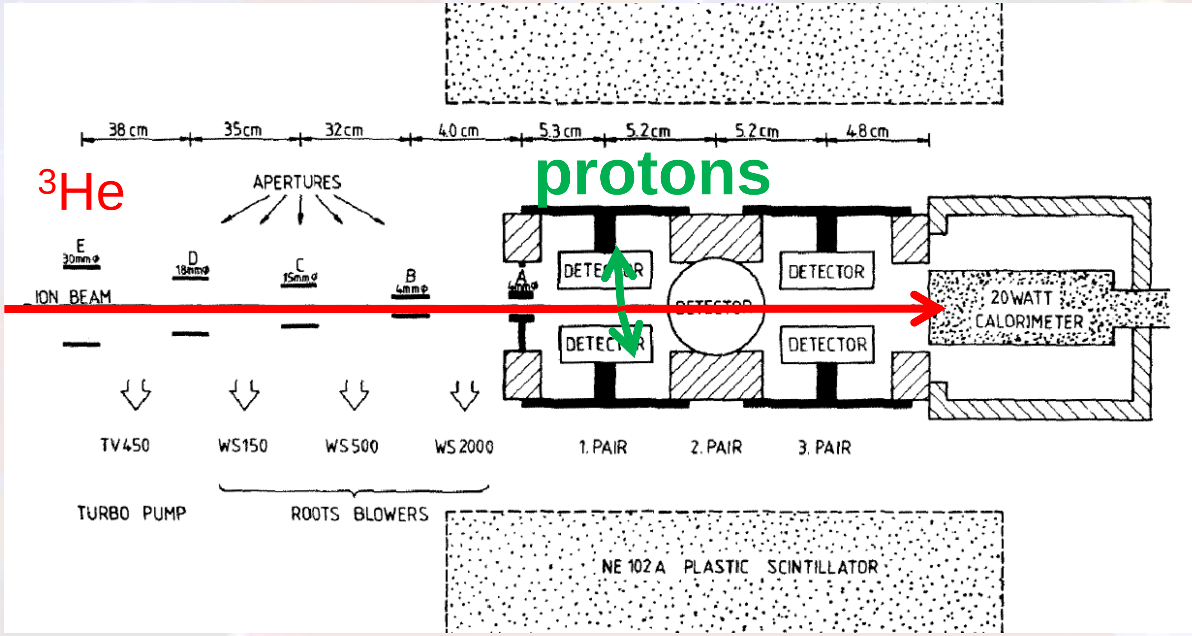
It is possible to measure it directly!

Direct measurement of $^3He(^3He,2p)^4He$

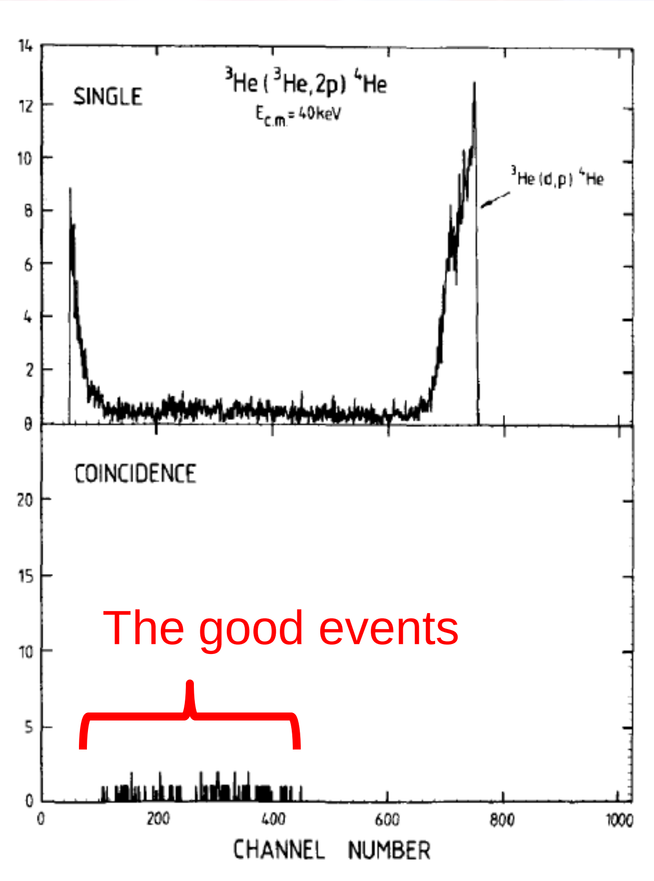
Bochum - Dynamitron Tandem

350 µA = 2×10^{15} pps

10^{16} atm/cm2



+ Windowless gas target
+ 6 Silicon detectors to measure the protons



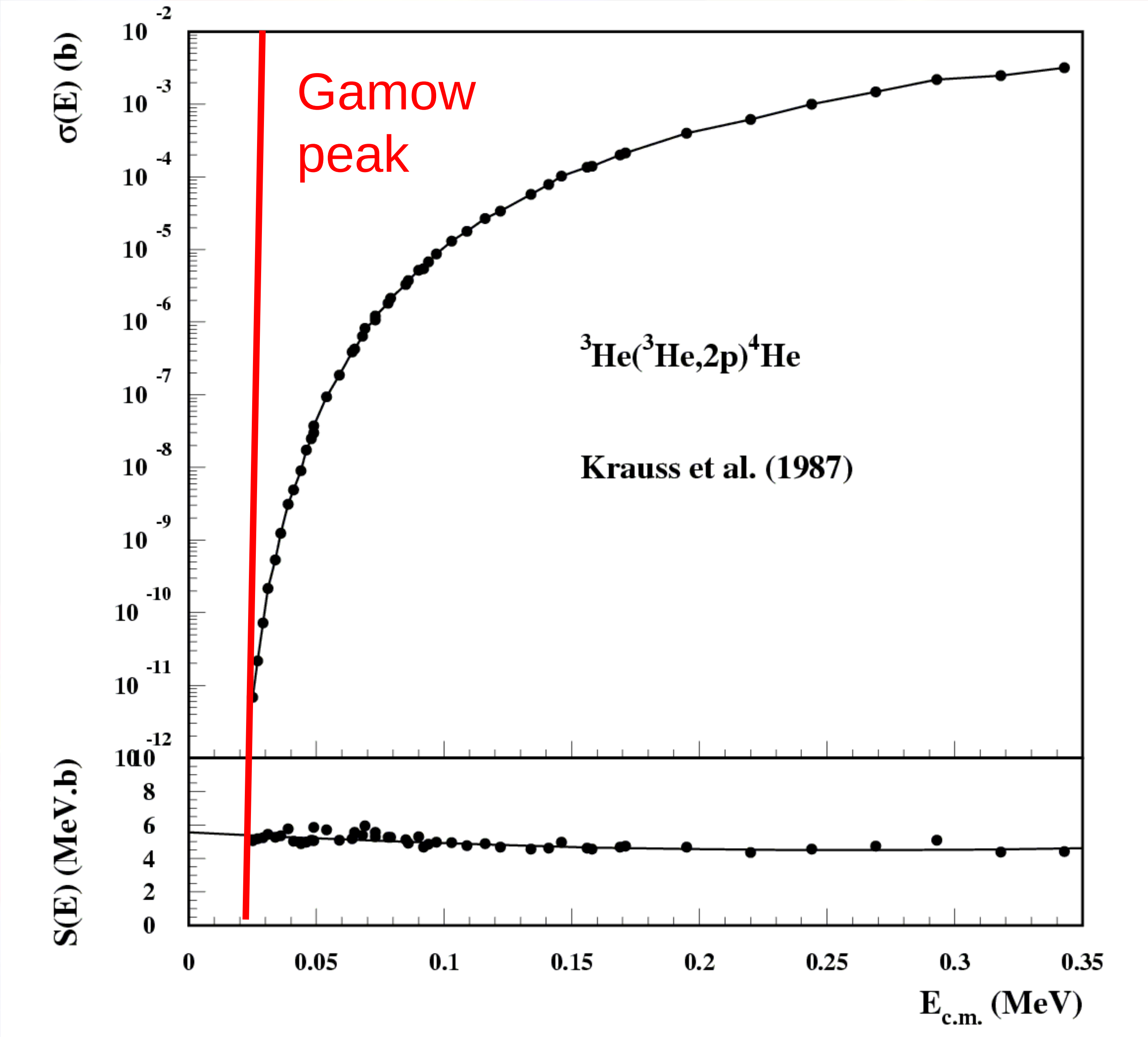
$$N(E) = 2N_p N_t \, d\Omega_{max} l_{eff} \sigma(E).$$

$$d\Omega_{max} l_{eff} = 0.25 \text{ sr} \cdot \text{cm}$$

l_{eff} = effective target thickness

Krauss et al. Nuclear Physics A467 (1987) 273-290

Results



Gamow
peak
$^{3}He(^{3}He,2p)^{4}He$
Krauss et al. (1987)
σ(E) (b)
S(E) (MeV.b)
$E_{c.m.}$ (MeV)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

Mechanism of $^3He(^3He,2p)^4He$ reaction?

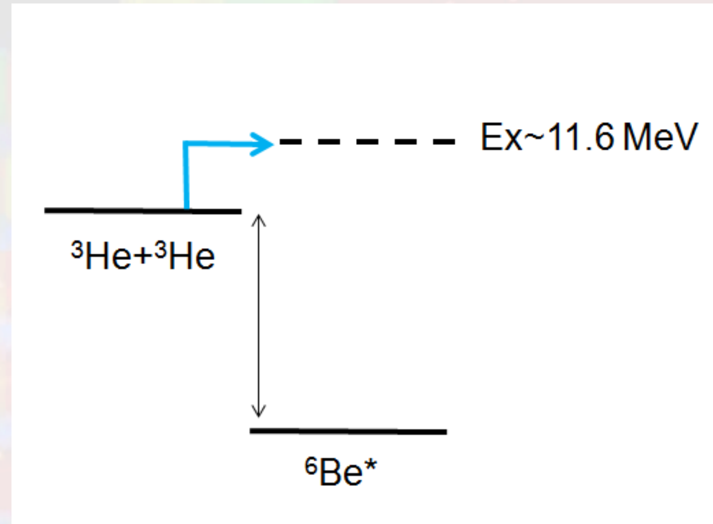
3 reaction mechanisms possible to explain the cross section

- Formation of a compound nucleus

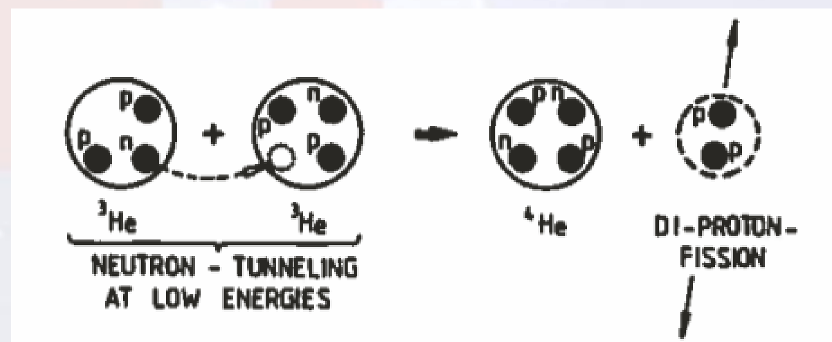
  $^3He + ^3He \rightarrow ^6Be^* \rightarrow ^4He + 2p$

  No resonance known in 6Be

  $\Rightarrow$ No cross section!



- Direct process neutron tunneling

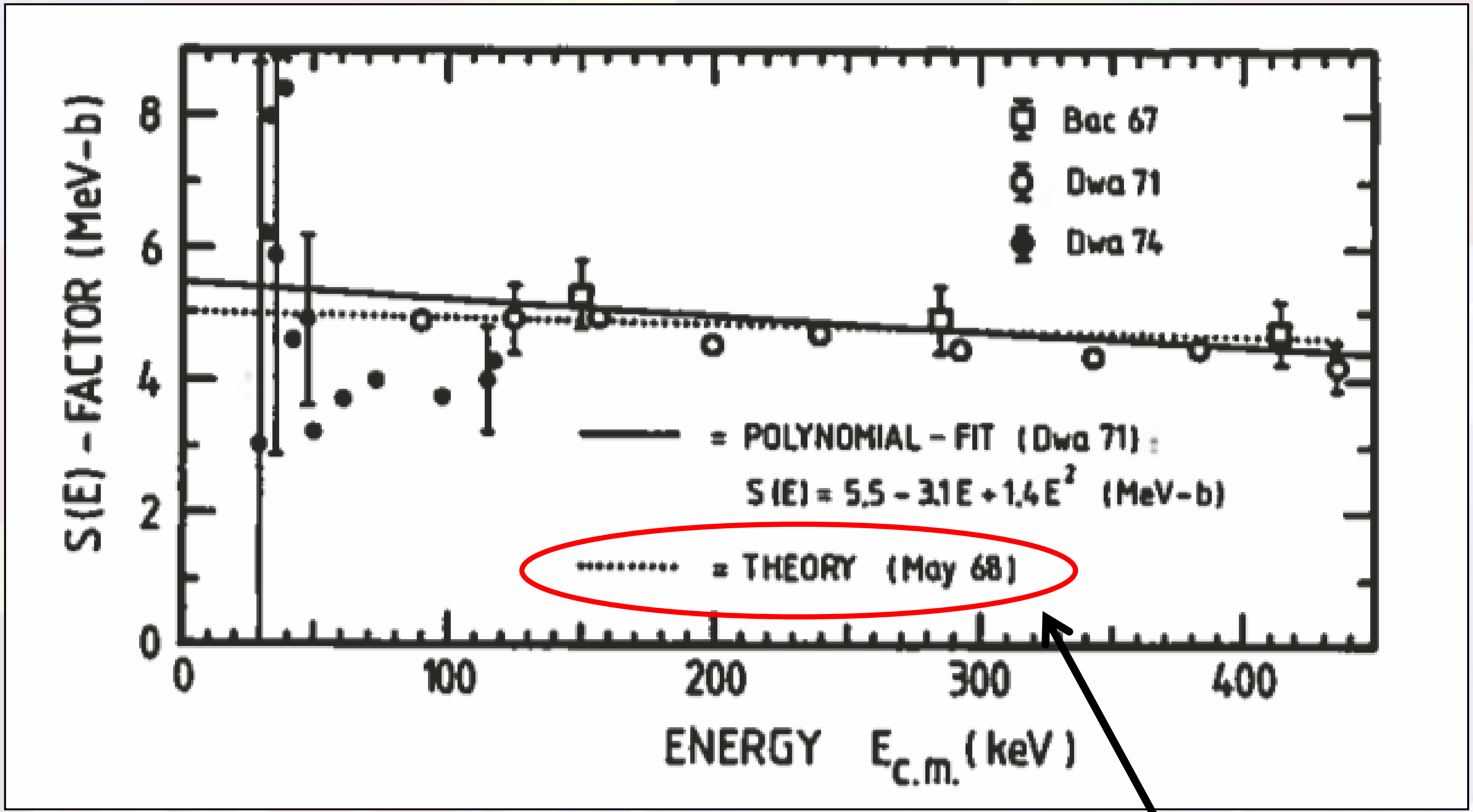


- Sequential process d tunneling

$$^3He + ^3He \rightarrow p + ^5Li(gs) \rightarrow p + p + ^4He$$

Cauldrons in the Cosmos C. Rolfs & W. Rodney

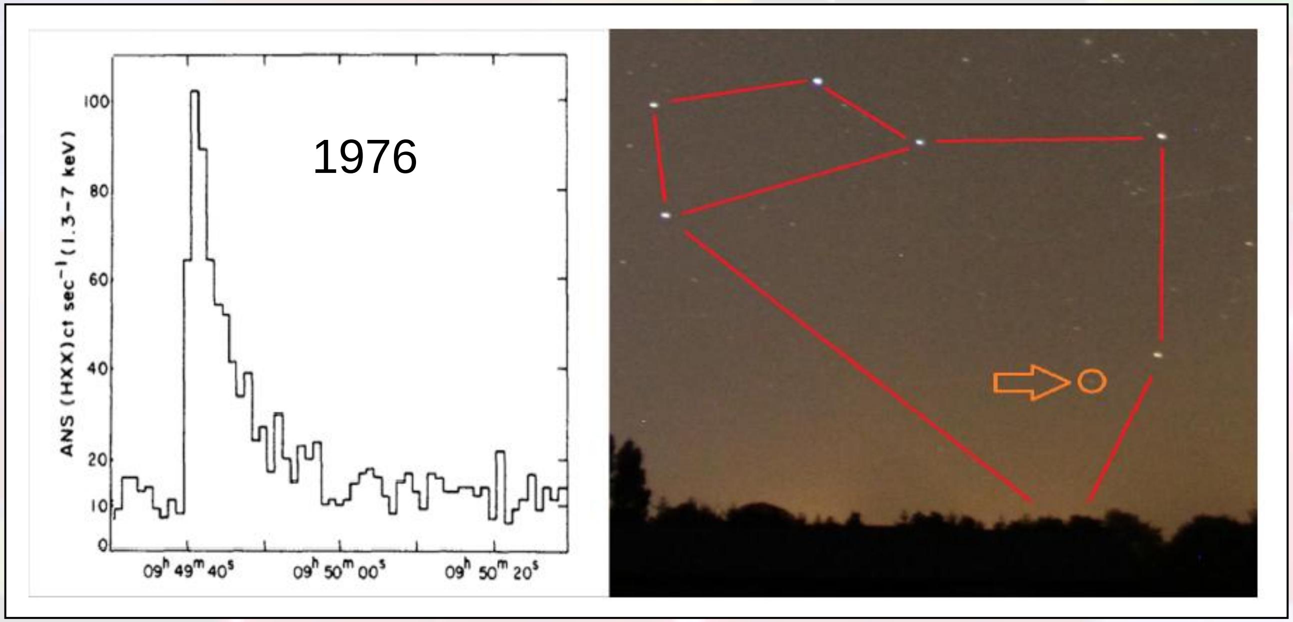
Mechanism of $^3He(^3He,2p)^4He$ reaction?



Neutron tunneling model agrees with experiment at low energy

Example 3

The rate of $^{15}O(\alpha,\gamma)^{19}Ne$



Observation of X-ray Bursts

10 s

Sagittarius

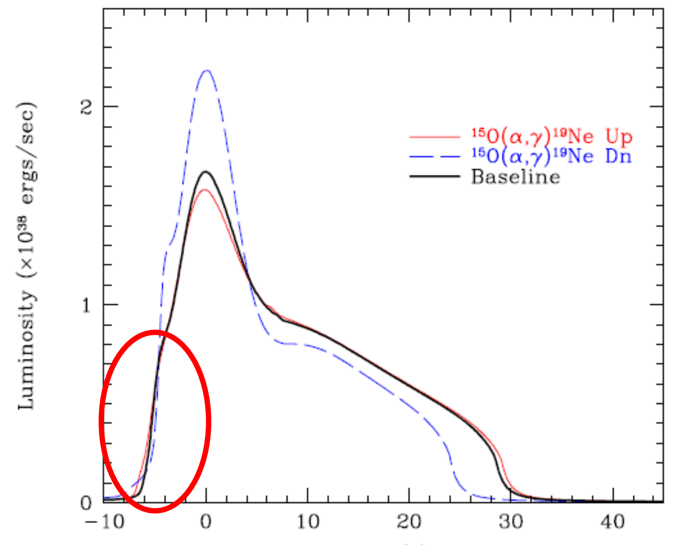
Typical X-ray bursts:

- 10^{38} erg
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

→ Novae are ~ 1 million times more intense, and type I supernovae are ~1 million times more intense than novae

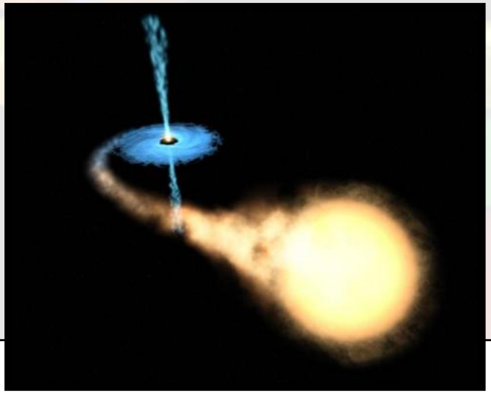
1 erg = 624.15 GeV

Astrophysical model

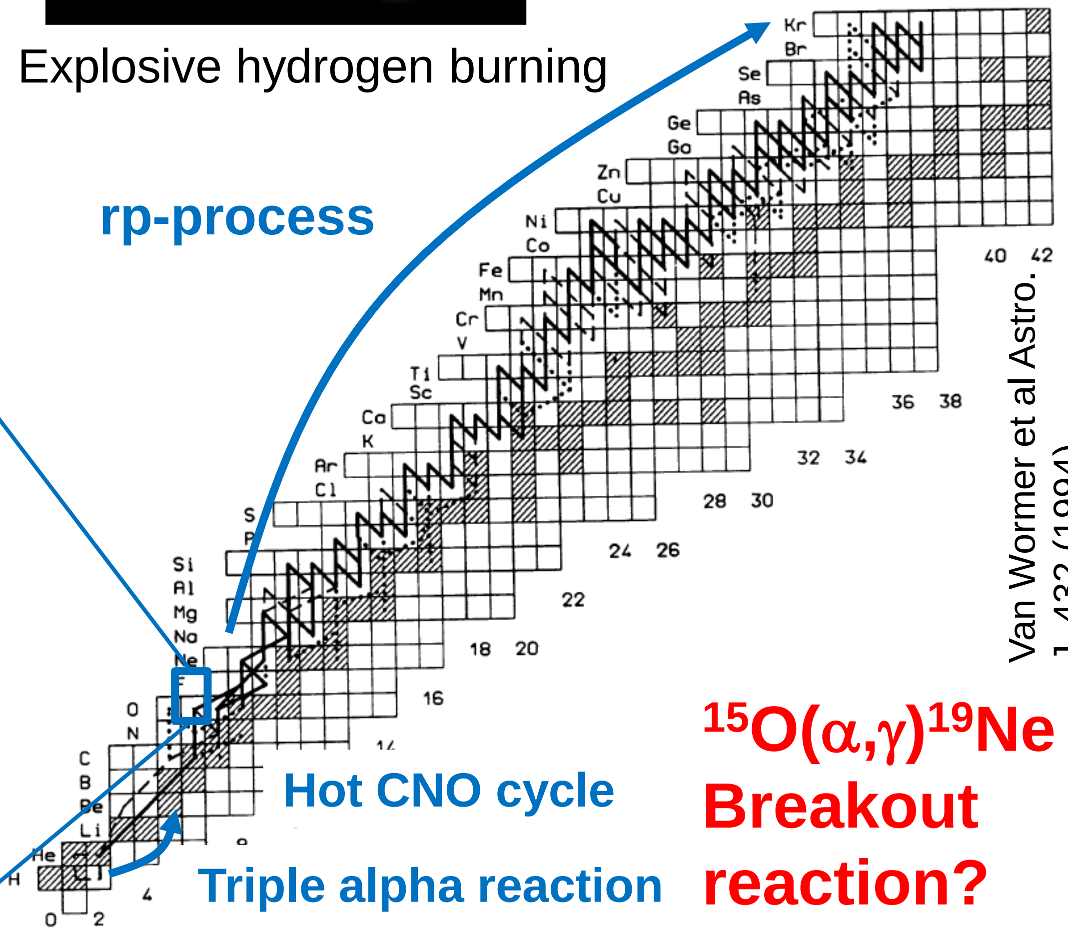


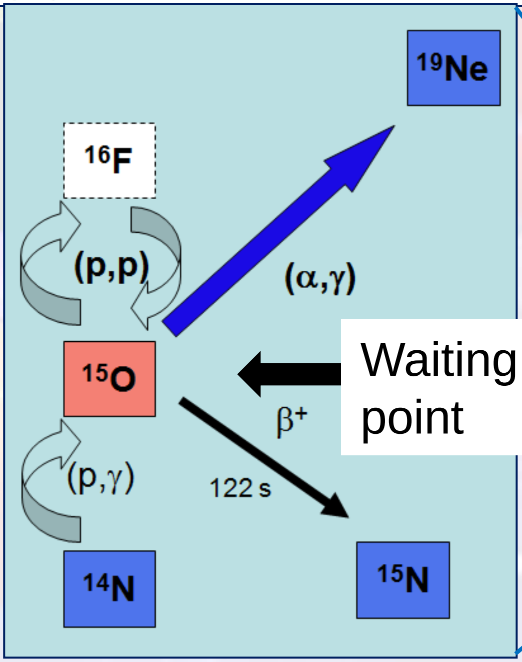
Not changed : triple alpha

...urst light curves induced by variation of the ... reaction up (Up) and down (Dn).



Explosive hydrogen burning





$^{15}O(\alpha,\gamma)^{19}Ne$ Breakout reaction?

Cyburt et al. (2016). *The Astrophysical Journal, 830*(2), 55.

Van Wormer et al Astro. J. 432 (1994)

Direct measurement of $^{15}O(\alpha,\gamma)^{19}Ne$?

Electromagnetic	Non − resonant	$^{6}Li(p,\gamma)^{7}Be$	$\approx 10^{-4}$
	Resonant: $\ell_R = \ell_{min}$	$^{12}C(p,\gamma)^{13}N$	$\approx 10^{-3}$
	Resonant: $\ell_R > \ell_{min}$	$^{7}Be(p,\gamma)^{8}B$	$\approx 2 \times 10^{-5}$
	Resonant: multiresonance	$^{22}Ne(\alpha,\gamma)^{26}Mg$	$\approx 2 \times 10^{3}$
	Subthreshold state	$^{12}C(\alpha,\gamma)^{16}O$	≈ 0.5

T9~1
S=constant=2×10^{3} MeV.b

E0 = 931 keV
σ(E0) = 4.7×10^{-10} b

But ^{15}O is radioactive
GANIL beam intensity ~ 1.7×10^{7} pps

dN ~ 2.5 counts / century

Not possible to measure directly

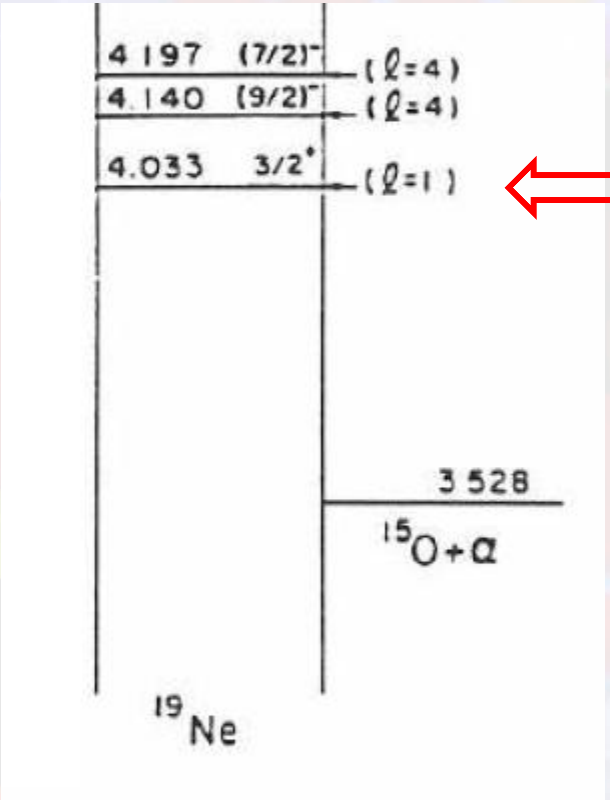
$\Rightarrow$ Indirect measurements

Direct measurement possible only to….

dN ~ 100 counts / hour
(efficiency ~ 1% => 1/h) $\Rightarrow$ E minimum (CM) = 8.67 MeV

Far from E0 = 931 keV

Indirect determination of $^{15}O(\alpha,\gamma)^{19}Ne$



Resonance!

Parameters for the BW formula

J^π 3/2+ ℓ=1 $J^\pi(^{15}O)$=1/2-

Γ_α extremely low, not measurable

$B_\alpha = \Gamma_\alpha / \Gamma_\gamma = (2.9 \pm 2.1)\ 10^{-4}$

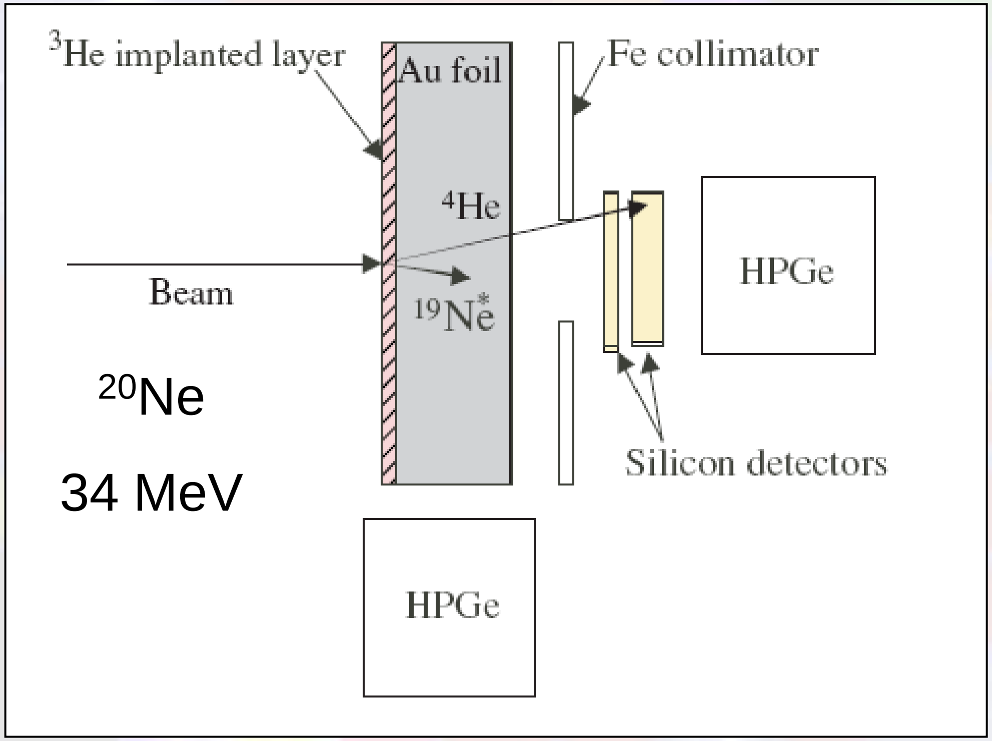
Γ_γ ???

DSAM (Doppler Shift Attenuation Method)

Experiment performed at TRIUMF

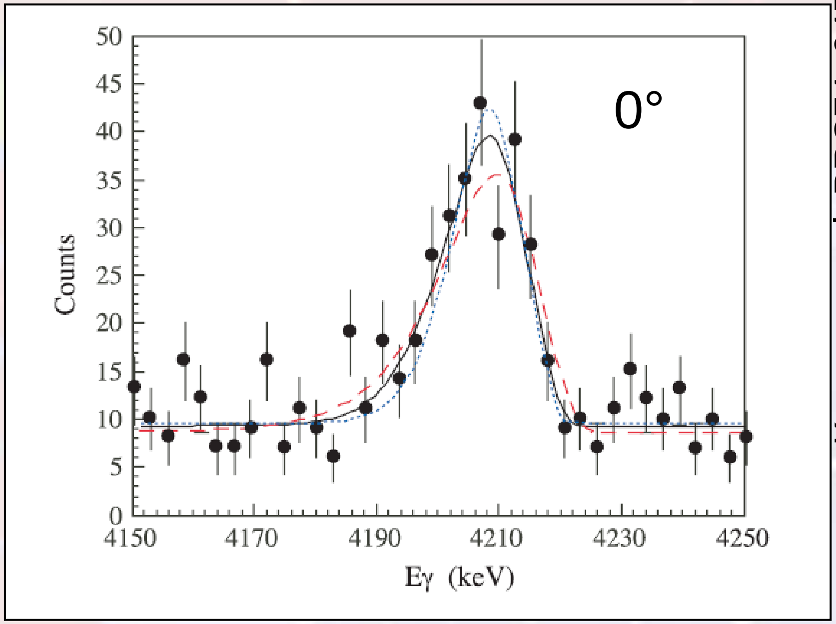
$^{3}He(^{20}Ne,^{4}He)^{19}Ne^{*}$

$E_x = 4.03$ MeV



^{20}Ne

34 MeV



Kanungo et al, PRC74, 045803 (2006)

Best fit of the line shape (solid line)

De-excitation γ *rays were detected in coincidence with α particles.*

$\Rightarrow \quad \tau = 11^{+4}_{-3}\ \text{fs} \qquad \Gamma_\gamma = \frac{\hbar}{\tau} = 0.06\ \text{eV}$

$\Rightarrow \quad \Gamma_\alpha = 17\ \mu\text{eV}$

Doppler effect

$E_{\gamma,lab} = E_{\gamma,cm}\ (1 + (v_{rec}/c)\ .\ \cos\theta_\gamma)$

$$N_A < \sigma v > = 0.93\,(T_9)^{-\frac{3}{2}} \exp(-\frac{5.86}{T_9})$$

Example 4

Which nuclear reaction is at the origin of the Sun's heat?

$p + p \Rightarrow {}^{2}He \Rightarrow p + p$

$p + {}^{4}He \Rightarrow {}^{5}Li \Rightarrow p + {}^{4}He$

${}^{4}He + {}^{4}He \Rightarrow {}^{8}Be \Rightarrow {}^{4}He + {}^{4}He$

What else???

$p + {}^{16}O \Rightarrow \gamma + {}^{17}F$???

1929

Zur Frage der Aufbaumöglichkeit der Elemente in Sternen.

Von **R. d'E. Atkinson** und **F. G. Houtermans** in Berlin-Charlottenburg.

(Eingegangen am 19. März 1929.)

The first ones to apply quantum mechanics to astrophysics

Only the light nuclei can be at the origin of the Sun's heat?

Tabelle 1.

Element	Eindringungswahrscheinlichkeit $\bar{W}_1$ pro Stoß	Lebensdauer bezüglich Protoneneindringung τ
2 He 4	$2{,}7 \cdot 10^{-8}$	8 sec
3 Li 6	$9{,}7 \cdot 10^{-11}$	37 min
3 Li 7	$10{,}6 \cdot 10^{-11}$	34 min
(4 Be 6	$4{,}1 \cdot 10^{-13}$	6,3 Tage)
(4 Be 7	$5{,}1 \cdot 10^{-13}$	4,9 „)
(4 Be 8	$5{,}8 \cdot 10^{-13}$	4,3 „)
4 Be 9	$6{,}5 \cdot 10^{-13}$	3,9 „
(4 Be 10	$7{,}1 \cdot 10^{-13}$	3,6 „)
(4 Be 11	$7{,}6 \cdot 10^{-13}$	3,5 „)
5 B 10	$5{,}0 \cdot 10^{-15}$	1,4 Jahre
5 B 11	$5{,}4 \cdot 10^{-15}$	1,3 „
6 C 12	$6{,}2 \cdot 10^{-17}$	110 „
7 N 14	$8{,}4 \cdot 10^{-19}$	8 200 „
8 O 16	$1{,}5 \cdot 10^{-20}$	470 000 „
9 F 19	$3{,}1 \cdot 10^{-22}$	$2{,}3 \cdot 10^{7}$ „
10 Ne 20	$6{,}7 \cdot 10^{-24}$	$1{,}0 \cdot 10^{9}$ „

~Penetrability

~Effective lifetime

Zeitschrift für Physik A 54(9), 656-665 (1929)

1932

Possible Existence of a Neutron

It has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons

CHADWICK. *Nature*, 1932, vol. 129, no 3252, p. 312.

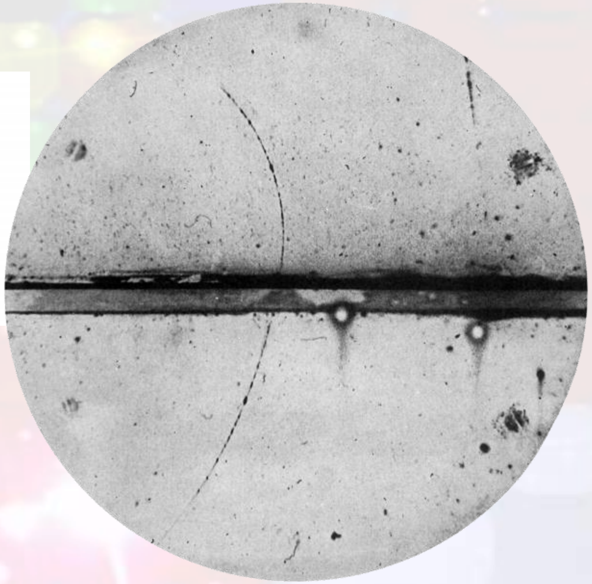
James Chadwick

1933 Discovery of the **positron**

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)



Existence of **neutrino** suggested by Pauli

In June 1931, on the occasion of a conference at Pasadena, I proposed the following interpretation: The laws of conservation remain valid/recognized, the emission of the particles β being accompanied by a very penetrating radiation of neutral particles, which has not been observed until now. The total energy of particle β and of the neutral particle (or the neutral particles, since we do not know whether there is only one or there are a lot) emitted by the nucleus during a single process, would be equal to the energy which corresponds to the upper boundary of spectrum β. Needless to say we not only keep the conservation of energy, but also of momentum, of angular momentum and of the nature of the statistics in all the basic processes.

Pauli. October 1933 at the Solvay Congress in Brussels.

1934

First time named

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota [1] di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del «neutrino» e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

Fermi, E. (1934). *Il Nuovo Cimento 11*(1), 1.

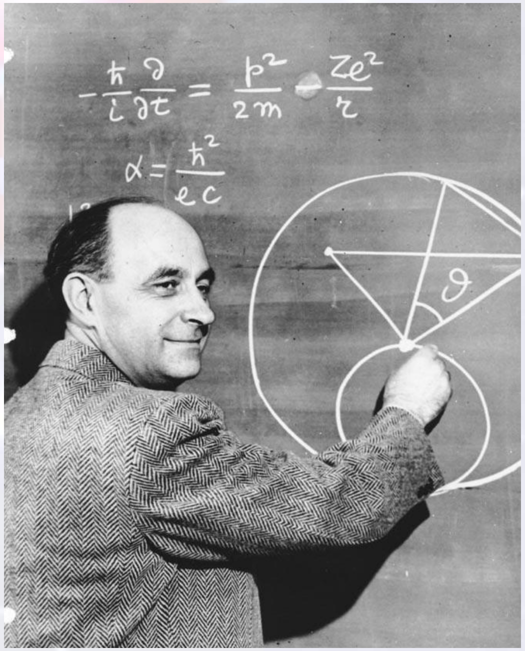
L'inversa della vita media si ottiene integrando (44) da $\eta = 0$ fino a $\eta = \eta_0$; si trova

$$\frac{1}{\tau} = 1{,}75 \cdot 10^{95} g^2 \left| \int v_m^* u_n d\tau \right|^2 F(\eta_0) \qquad (45)$$

dove si è posto

$$F(\eta_0) = \frac{2}{3}\sqrt{1+\eta_0^2} - \frac{2}{3} + \frac{\eta_0^4}{12} - \frac{\eta_0^2}{3} + 0{,}355\left[-\frac{\eta_0}{4} - \frac{\eta_0^3}{12} + \frac{\eta_0^5}{30} + \frac{\sqrt{1+\eta_0^2}}{4}\log\left(\eta_0 + \sqrt{1+\eta_0^2}\right)\right]. \qquad (46)$$

dove η_0 rappresenta l'impulso massimo dei raggi β emessi, misurato in unità mc.



Beta decay probability

Nuclear

Fermi function

1938

No neutrino

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

The Formation of Deuterons by Proton Combination

H. A. BETHE, *Cornell University, Ithaca, N. Y.*

AND

C. L. CRITCHFIELD, *George Washington University, Washington, D. C.*

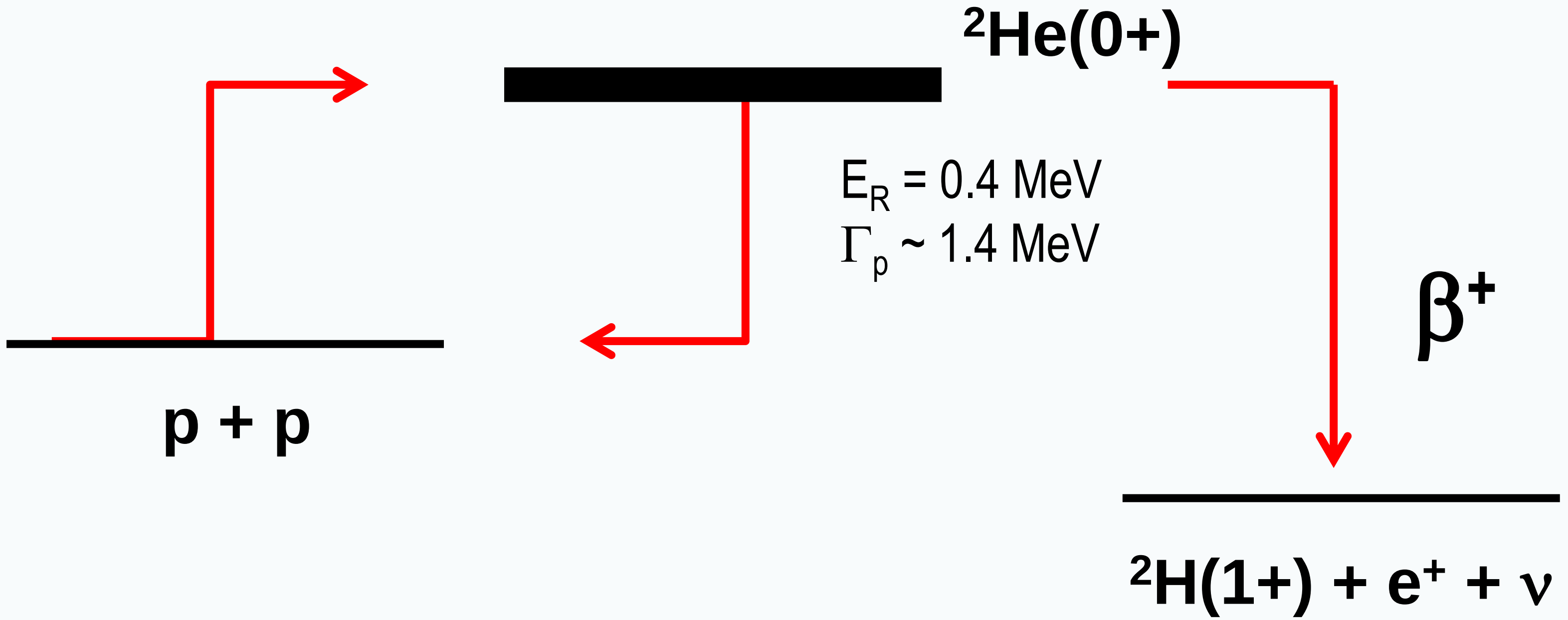
(Received June 23, 1938)

The probability of the astrophysically important reaction $H+H=D+\epsilon^+$ is calculated. For the probability of positron emission, Fermi's theory is used. The penetration of the protons through their mutual potential barrier, and the transition probability to the deuteron state, can be calculated exactly, using the known interaction between two protons. The energy evolution due to the reaction is about 2 ergs per gram per second under the conditions prevailing at the center of the sun (density 80, hydrogen content 35 percent by weight, temperature $2\cdot10^7$ degrees). This is almost but not quite sufficient to explain the observed average energy evolution of the sun (2 ergs/g sec.) because only a small part of the sun has high temperature and density. The reaction rate depends on the temperature approximately as $T^{3.5}$ for temperatures around $2\cdot10^7$ degrees.

Fermi's theory

Gamow theory

Exercise: Let's calculate the p(p,d) reaction



1) σ(E=0.4 MeV) ?
2) Rate of the reaction (function of Temperature)?
3) What % of the Sun's mass is burning?
4) Lifetime of the Sun?

A few clues

$$\sigma(E)_{pp} = \pi\lambda\!\!\!^{-2}\omega \frac{\Gamma_p \Gamma_p}{(E - E_R)^2 + (\frac{\Gamma_{total}}{2})^2}$$

$$\sigma(E)_{p,\beta^+} = \sigma(E)_{pp}\; BR_{\beta^+}$$

$$BR_{\beta^+} = \frac{\Gamma_{\beta+}}{\Gamma_{total}} \approx \frac{\Gamma_{\beta+}}{\Gamma_p}$$

$$\Gamma_{\beta^+}(E) = \frac{\hbar}{2\, t_{\beta^+}(E)}$$

§2. The Probability of Positron Emission

According to Fermi's theory, the probability of β-emission (per second) is

$$\beta = gf(W)|G|^2. \qquad (6)$$

Here G is the matrix element of the nuclear transition,

$$G = \int \psi_i \psi_f d\tau, \qquad (7)$$

ψ_i and ψ_f the initial and final state of the nucleus, except for the substitution of one neutron by a proton. f is a function of the energy W of the emitted β-particle,

$$f(W) = (W^2-1)^{\frac{1}{2}}\left(\frac{1}{30}W^4 - \frac{3}{20}W^2 - \frac{2}{15}\right)$$

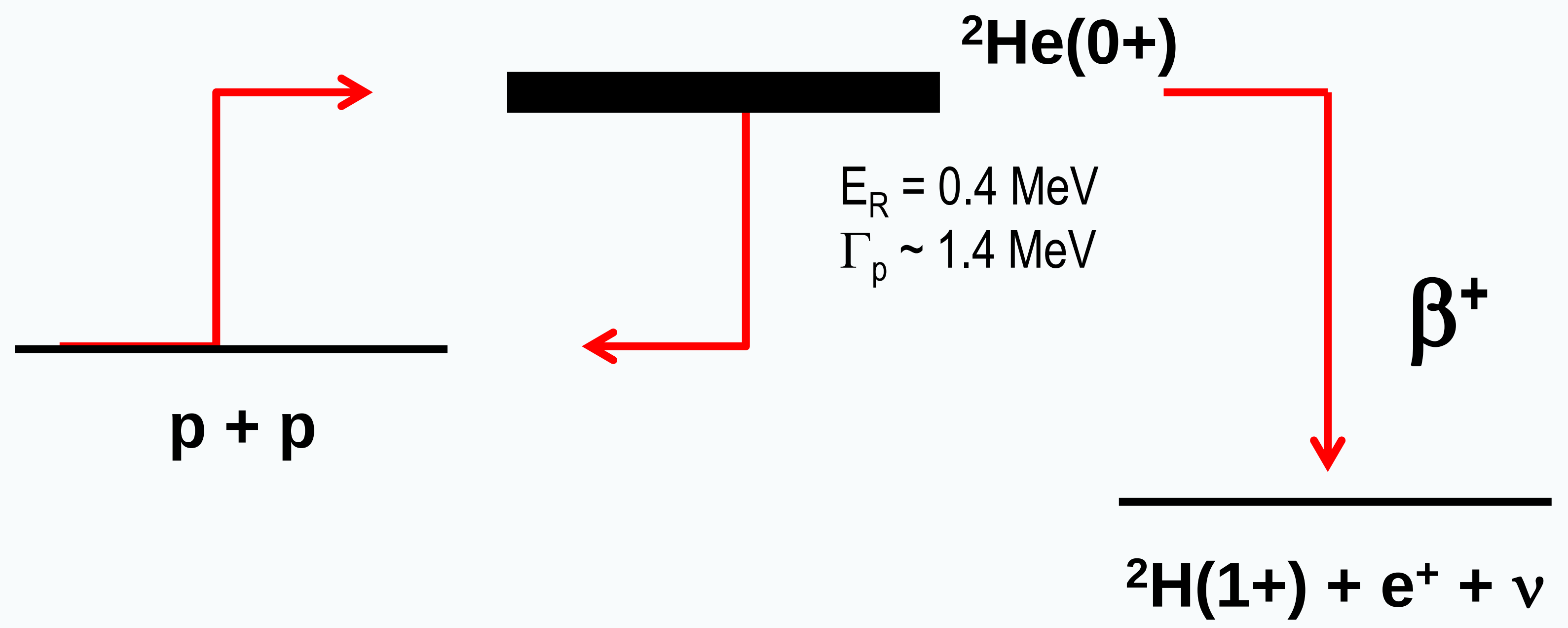
$$+\frac{1}{4}W \log\left[W + (W^2-1)^{\frac{1}{2}}\right], \qquad (8)$$

$$\beta = \lambda = \frac{\ln 2}{t_{\beta+}}$$

$$W = \frac{E(keV)}{511} + 1$$

(n => p) Log f $t_{\beta+}$ = 3.0

Solution



(n => p) Log ft = 3.0

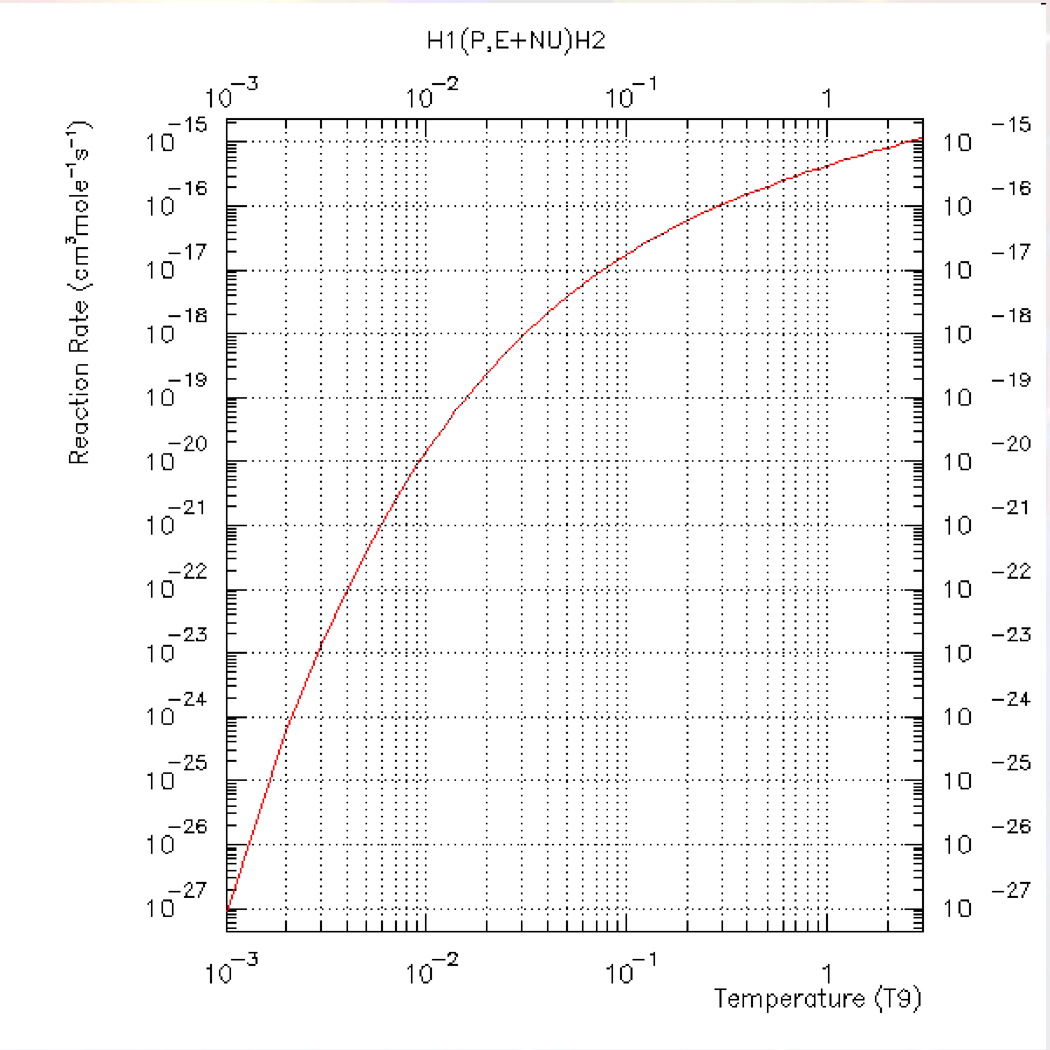
$T_{1/2}(\beta^+) \sim 530$ s (at E_R) $\Rightarrow$ $\Gamma_\beta \sim 10^{-26}$ MeV

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \quad \omega \frac{\Gamma_p \Gamma_\beta}{(E - E_r)^2 + (\Gamma_{tot}/2)^2}$$

➡ Answer 1)

$\sigma(0.4 \text{ MeV}) \sim 10^{-24}$ b

Solution



Answer 2)

Analytical expression (CF88)

rate = 4.01e-15/T923*exp(-3.380/T913)*   (1.0+0.123*T913+1.09*T923 +0.938*T9)

Solution

Rate (T6=15) $<\sigma v> \sim 8 \times 10^{-20}$ cm^{3}mole^{-1}s^{-1}

$$dN_{reactions} = - N_p^2 < \sigma v > dt$$

Energy production rate:

$$P(W\,cm^{-3}) = Q\,N_A \frac{dN_{reactions}}{dt}$$

4p => 4He Q=26 MeV/ reaction
Avogadro number $N_A = 6.02 \times 10^{23}$
$N_p = 150$ g/cm^3 x 74 % = 111 moles cm^{-3}

→ P = 2.5 mW cm^{-3}

Answer 3)

Power of Sun P = 4x10^{26} Watts => Volume involved = 1.6 x 10^{29} cm^3
Mass involved = 2.4 x 10^{28} kg
Mass of the Sun = 2x10^{30} kg

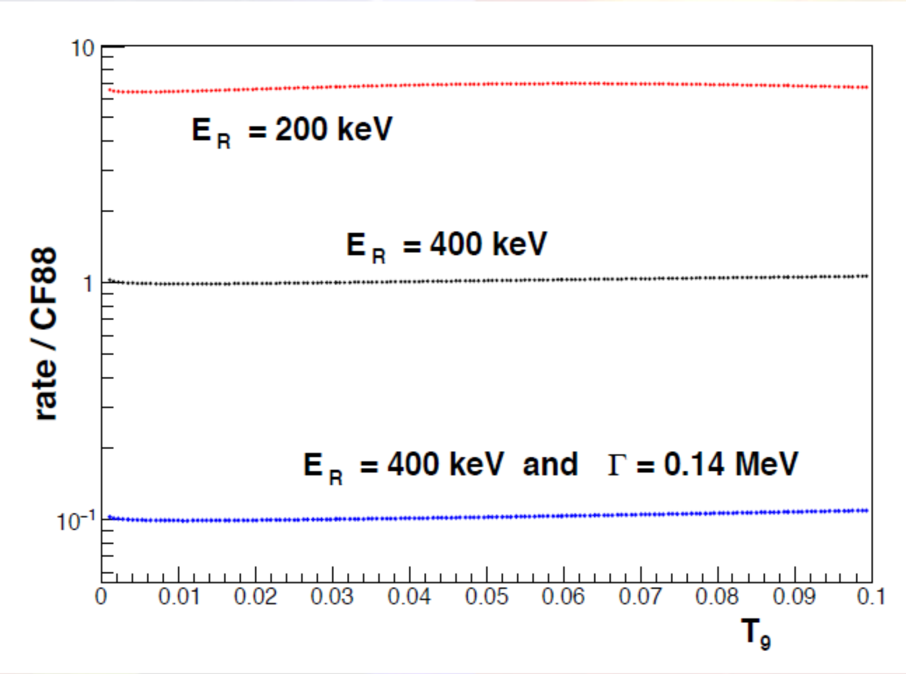
→ 1% of the Sun's mass

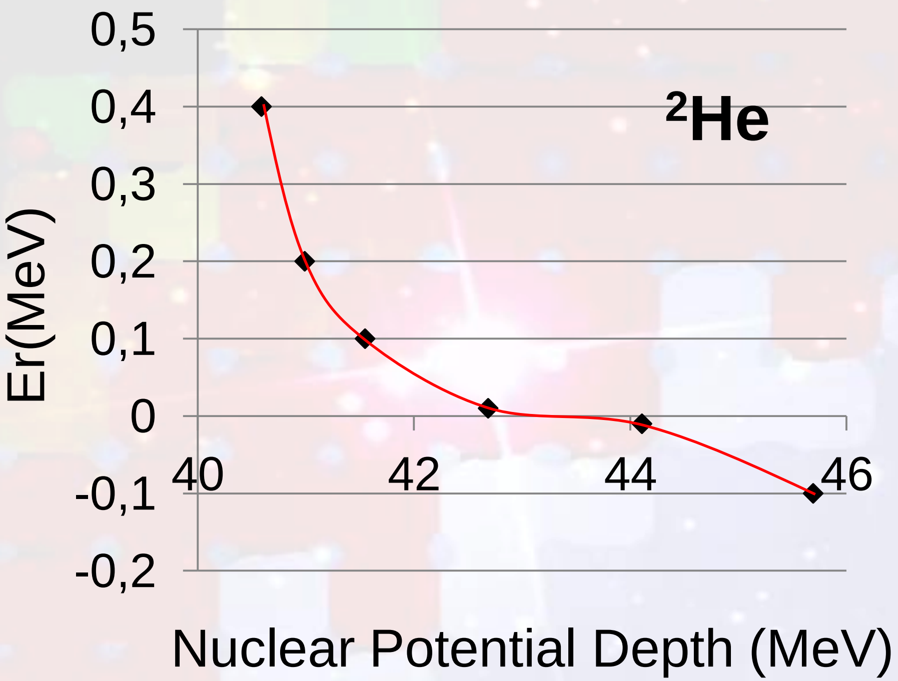
Answer 4)

Lifetime $$\tau = \frac{1}{N_p < \sigma v >}$$

$\tau \sim 3.6 \times 10^9$ years

If nuclear force was changed?





Calculated with program “dwu”

```
0SINGLE PARTICLE WIDTH =.10736E-02  MEV
  V=  42.686   DET= 0.0   NODES= 0.0   RM=  1.300   E= 0.010   ITER.= 6.0
```

^{2}He would be bound if the nuclear force was increased by 6.9%

1939

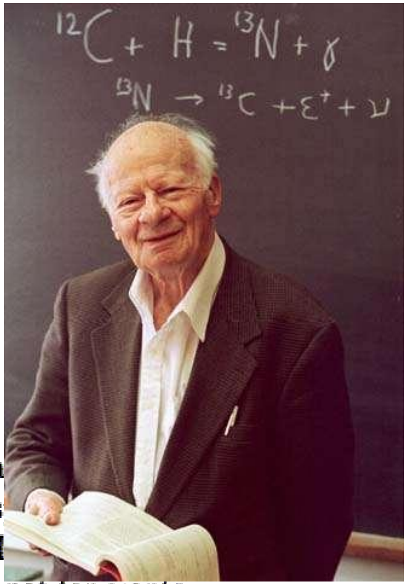
MARCH 1, 1939 PHYSICAL REVIEW

CNO Cycle
Bethe-Weizsäcker cycle

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)



It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^{+}$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^{+}$, $N^{15}+H=C^{12}+He^{4}$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

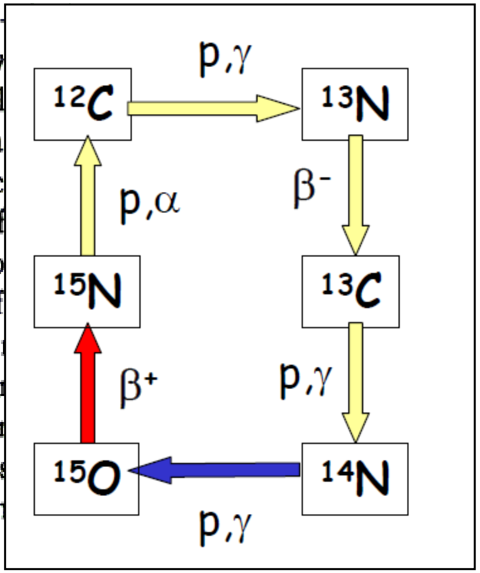
The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equa brilliant star Y Cygni the corres and 32. This good agreement hold the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^{+}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5 He^{4} *can be built up in ordi* mentioned above, that all tegrated by proton bomba built up (by radiative c reduces the formation of The production of neutro The heavier elements f have existed already whe

Finally, the suggested is used to draw conclusio such as the mass-luminos against temperature char (§12).



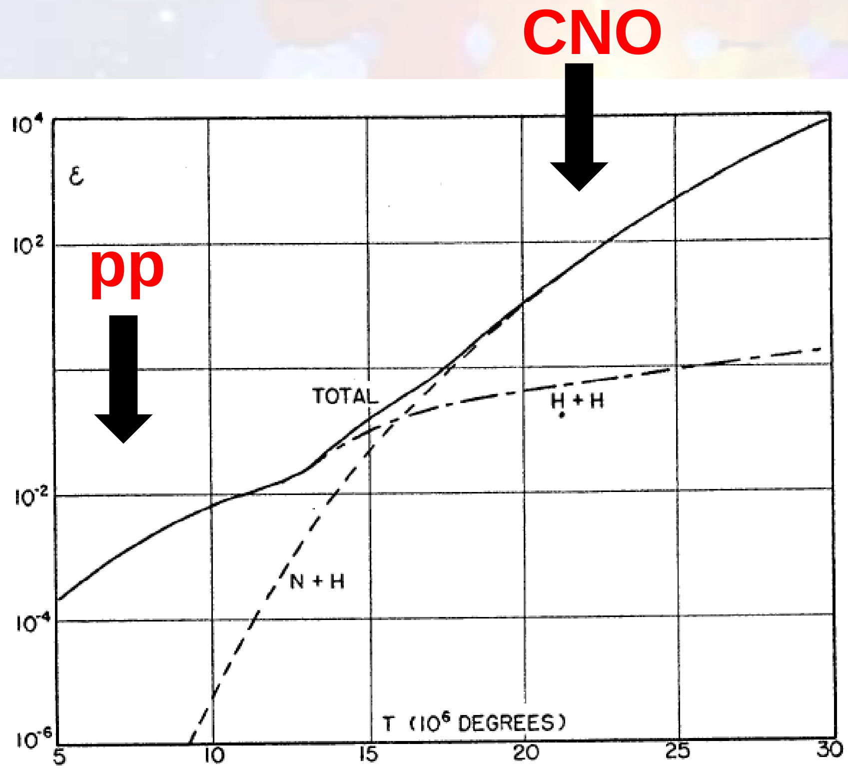
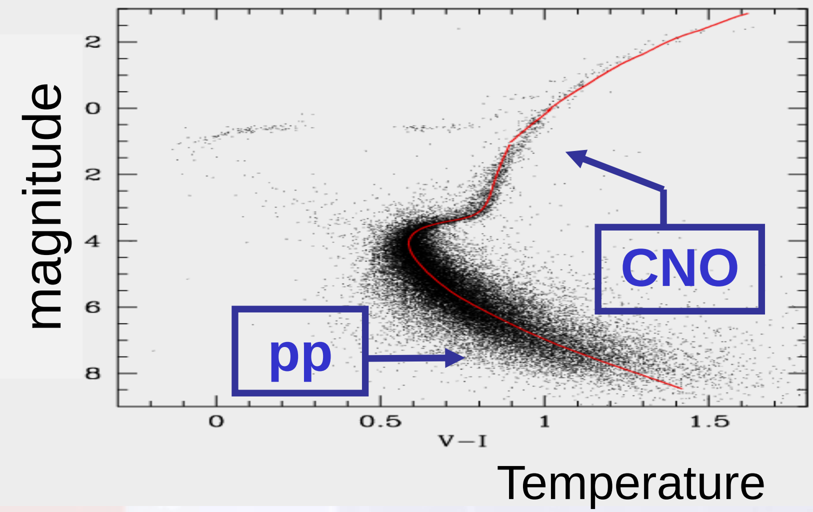


FIG. 1. The energy production in ergs/g sec. due to the proton-proton combination (curve H+H) and the carbon-nitrogen cycle (N+H), as a function of the central temperature of the star. Solid curve: total energy production caused by both reactions. The following assumptions were made: central density = 100, hydrogen concentration 35 percent, nitrogen 10 percent; average energy production 1/5 of central production for H+H, 1/10 for N+H.

Diagram Hertzsprung Russell

Globular Cluster of stars

All these stars were
formed at the same time



The exact shape is a function of the age of the cluster

Age Univers = (14 ± 1) 10^9 ans

Imbriani *et al.* , Astronomy & Astrophysics, 420, 2004

The end