Ph203: L15

Nuclear Astrophysics:
Invented @ Caltech in Kellogg Lab

Prior to 1950's Observed Chem. elements thought to be primordial (initial Soup)
but ... BBFH PIC

Key issues in Nucl. Astro.

1. Stellar Energy Production (via Nucl. Fusion)
2. Element/Isotope production (Nucleosynthesis)
   - a. BBN (Big Bang Nucleosyn.)
     ↳ developed in 80's & 90's
   - b. Fusion Burning in Stars (Medium Mass)
   - c. Heavy Element Production => Neutron Capture
3. Element Dissemination via Novae & Supernovae
4. Neutrino Production (Solar & Supernovae) → ν have mass!
5. Neutron Star Formation & Structure

Start with

Stellar Evolution & Nucleosyn.

Evolution summarized via 2D scatterplot of star observables based on Black Body Radiation Laws:

REVIEWS OF
MODERN PHYSICS

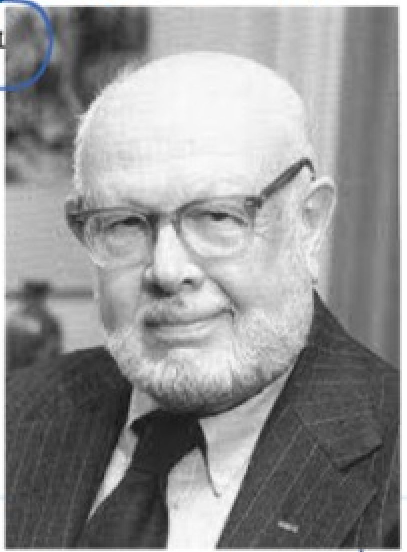
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

→B^{3}FH

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYL

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

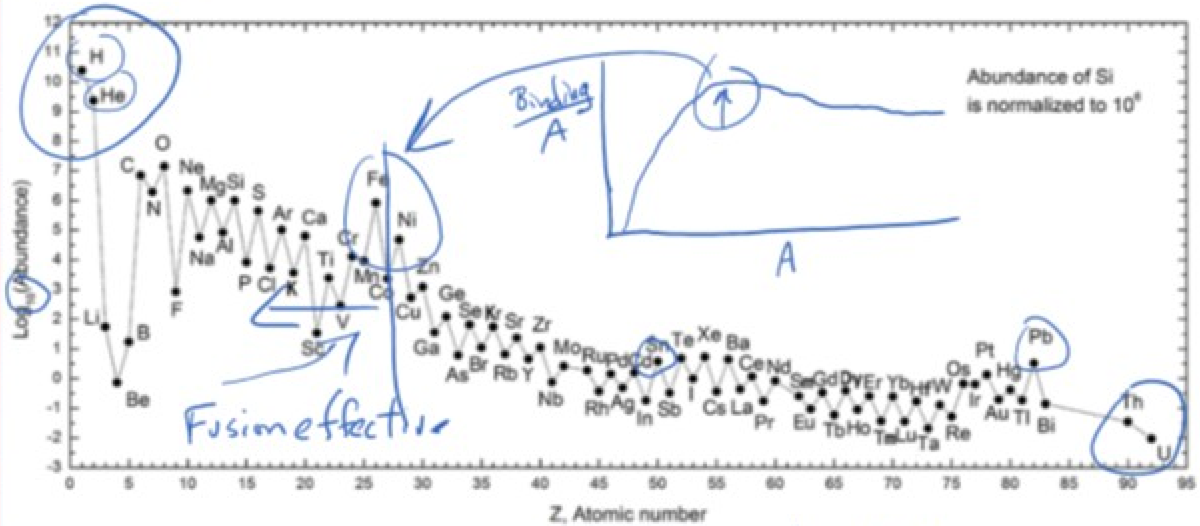


'83 Nobel

→

> "It is the stars, The stars above us, govern our conditions";
> (*King Lear*, Act IV, Scene 3)
>
> but perhaps
>
> →
>
> "The fault, dear Brutus, is not in our stars, But in ourselves,"
> (*Julius Caesar*, Act I, Scene 2)

Solar System abundances



↳ even proton #'s are more abundant ⇒ pairing!

Also magic #'s are more abundant

T_s = Surface Temp

y-axis
Stefan-Boltzmann Law

$$L_* = 4\pi R^2 \sigma T_s^4$$

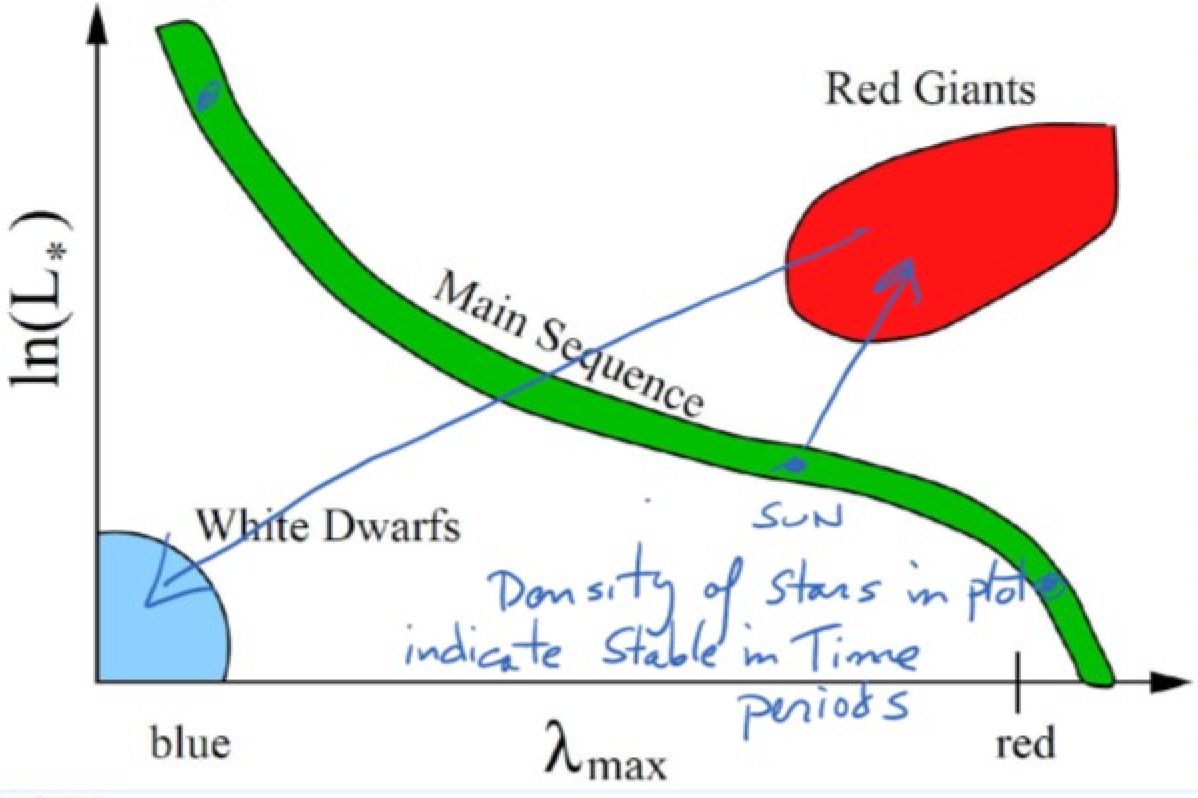
"Brightness"/Magnitude
(corrected for distance)

x-axis: Wien's Law: $\lambda_{max} \propto \frac{1}{T_s}$
"Color"

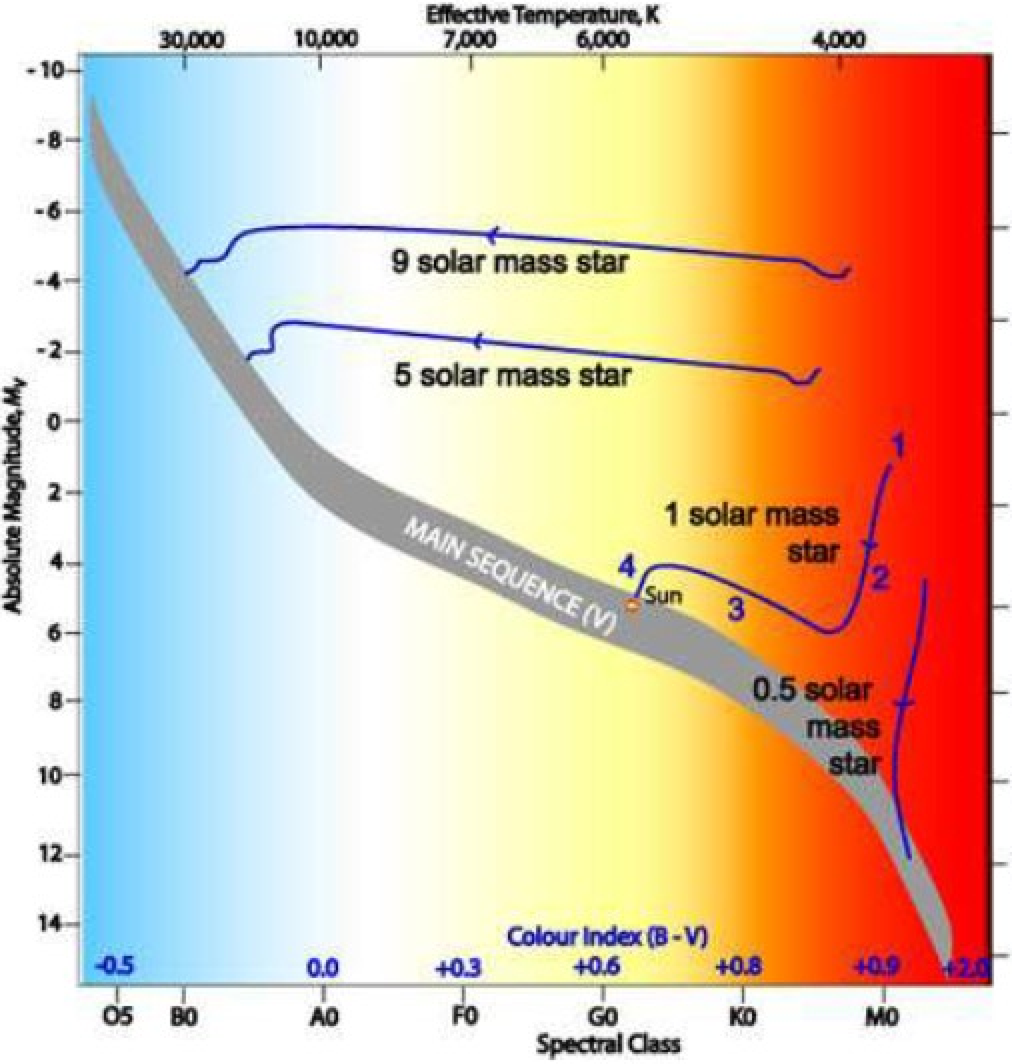
Start w Protostar Evolution

"Baby" → Middle Age → "Old Geezer"

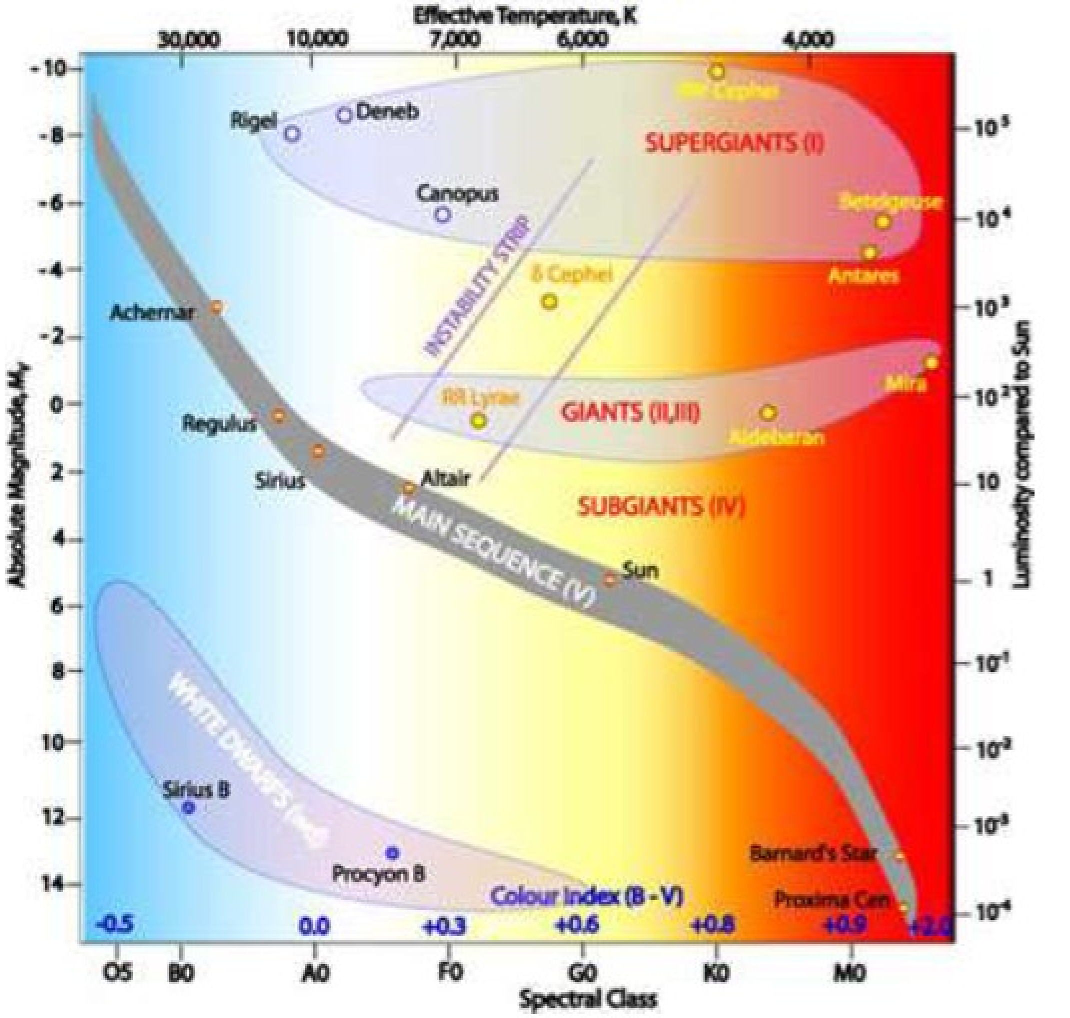
H-R Diagram:



Density of stars in plot indicate stable in time periods



Theoretical Hayashi Tracks of Protostars



Hertzsprung-Russell Diagram

Age Age Example Evolve: 1 $M_\odot$ Star aka SUN

$\tau_\odot$

($\times 10^9$ yrs)

1. Perturbation (Supernova, passing star) causes contraction of Molecular Cloud = 75% H, 25% ^{4}He by mass
↳ from BBN

2. Contraction converts Gravity Energy to PdV work, increasing T

3. Central Temp reaches $> 10^7$ K ($\equiv T_6 = 10$)
↳ fusion begins : H burning

0.05 4. @ $T_6 = 15$ Hydrostatic Equil. achieved. Gravity = Th
rad. pre
↳ called Zero-Age Main Sequence

10 5. Stable H-burning (see later) in core
Sun @ $\tau_\odot = 4.5 \cdot 10^9$ yrs

11 6. Core H fuel exhausted (via $4p \rightarrow {}^4He$)
Gravity contracts core $R_\odot \downarrow \therefore T_{core} \uparrow$
Shell H burns & radiation press > Gravity $\therefore R_\odot \uparrow$
& $T_S \downarrow$
∴ Red Gian

7. Core R ↓ until $T_6^{core} = 100-200$
then He burns ($3\,{}^4He \rightarrow {}^{12}C$, $4\,{}^4He \rightarrow {}^{16}$
outer R ↑↑ ⇒ Red Giant

12-13 8. He depleted & $R_\odot \downarrow\downarrow$ $T_S \uparrow$ e^- degeneracy stops the contraction
⟺ White Dwarf

15 Star cools to Brown Dwarf

Above combines Fluid Dynamics, Thermo/Stat. Mech, Radiative Transport (AMO) + Nuclear Reaction

Nuclear Reactions in a Thermal Environment

For astrophys., key reactions are:

1. Charged particle fusion reactions $\sigma(E)$
2. Neutron capture "

both @ "low" energy since for

$T_6 = 15$, $kT \simeq 1.3$ keV

$T_6 = 100$, $kT \simeq 9$ keV

Charged Part. Resonant vs. Non-Res.

Consider reaction $A + B \rightarrow X$:

Generally see 2 processes:

Compound Nucleus Reac.

$A + B \rightarrow C^* \rightarrow D + E$

$\uparrow$

short-lived intermediate state

"metastable"

$\tau_c >> V_A \times 2R_{(A+B)}$

Direct Reac.

$\left(\begin{smallmatrix}p\\n\end{smallmatrix}\right) + (A) \rightarrow (A+n) + (p)$

$d + A \rightarrow p + (A+n)$

↳ e.g. stripping reac.

$\tau \simeq V_d \times 2R_A$

If $E_{cm}^{A+B} \simeq$ excited state in C then can have resonant $\sigma(E)$ if WF of C (& J^{π}) overlaps w A+B:

see Pic

Nuclear Reaction Cross Sections for Astrophysics

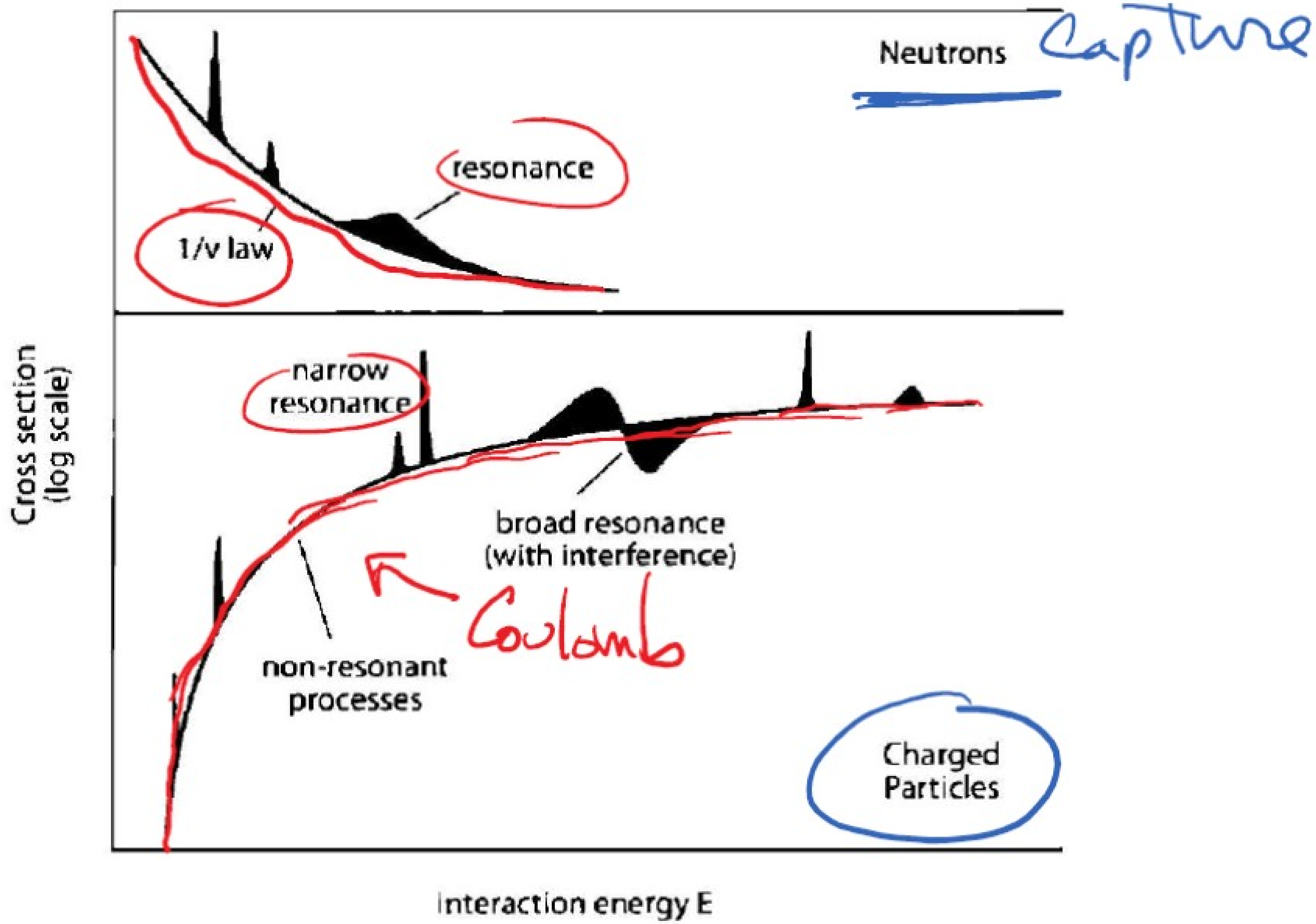
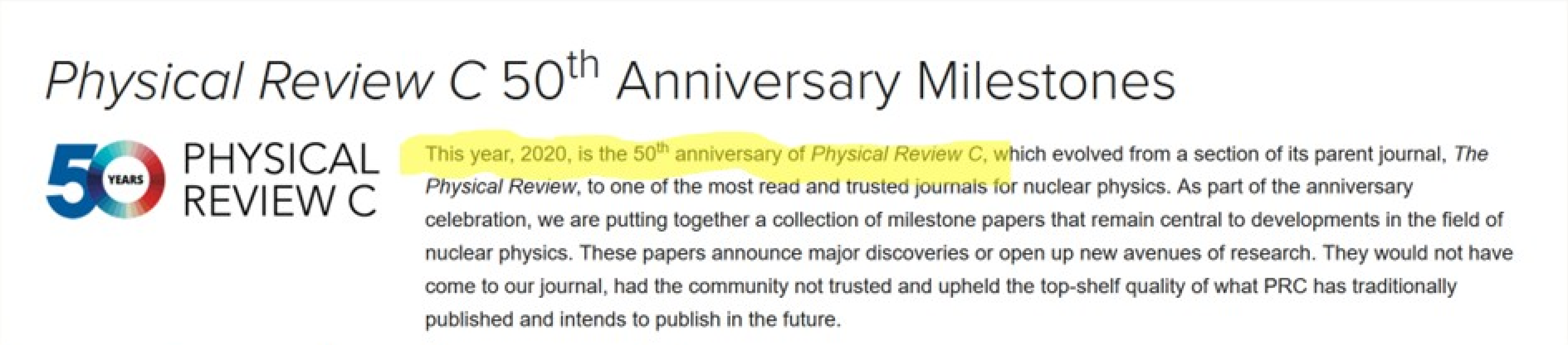
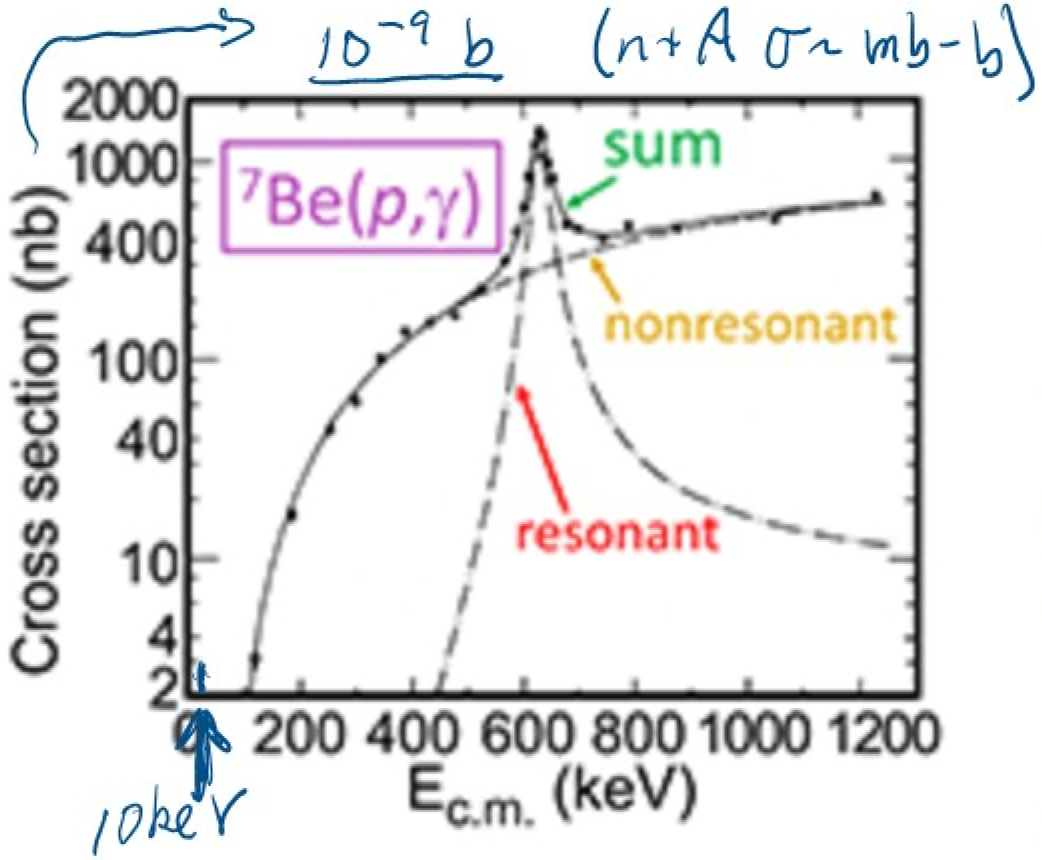


Figure 12.2 Dependence of total cross sections on the interaction energy for neutrons (top panel) and charged particles (bottom panel). Note the presence of resonances (narrow or broad) superimposed on a slowly varying nonresonant cross section.



Physical Review C 50th Anniversary Milestones

This year, 2020, is the 50th anniversary of *Physical Review C*, which evolved from a section of its parent journal, *The Physical Review*, to one of the most read and trusted journals for nuclear physics. As part of the anniversary celebration, we are putting together a collection of milestone papers that remain central to developments in the field of nuclear physics. These papers announce major discoveries or open up new avenues of research. They would not have come to our journal, had the community not trusted and upheld the top-shelf quality of what PRC has traditionally published and intends to publish in the future.



10^{-9} b (n+A $\sigma \sim$ mb-b)

10keV

ure cross section of ^{7}Be and the flux of ' solar neutrinos

or role in a variety of astrophysical phenomena, from stellar production of neutrinos and γ heaviest nuclear species. These papers used radioactive ^{7}Be, in one case as the target and o study two reactions of importance in astrophysics. These two reactions play a key role in ; in low-mass stars, such as the Sun, and in nucleosynthesis during the CNO-cycle in high- .

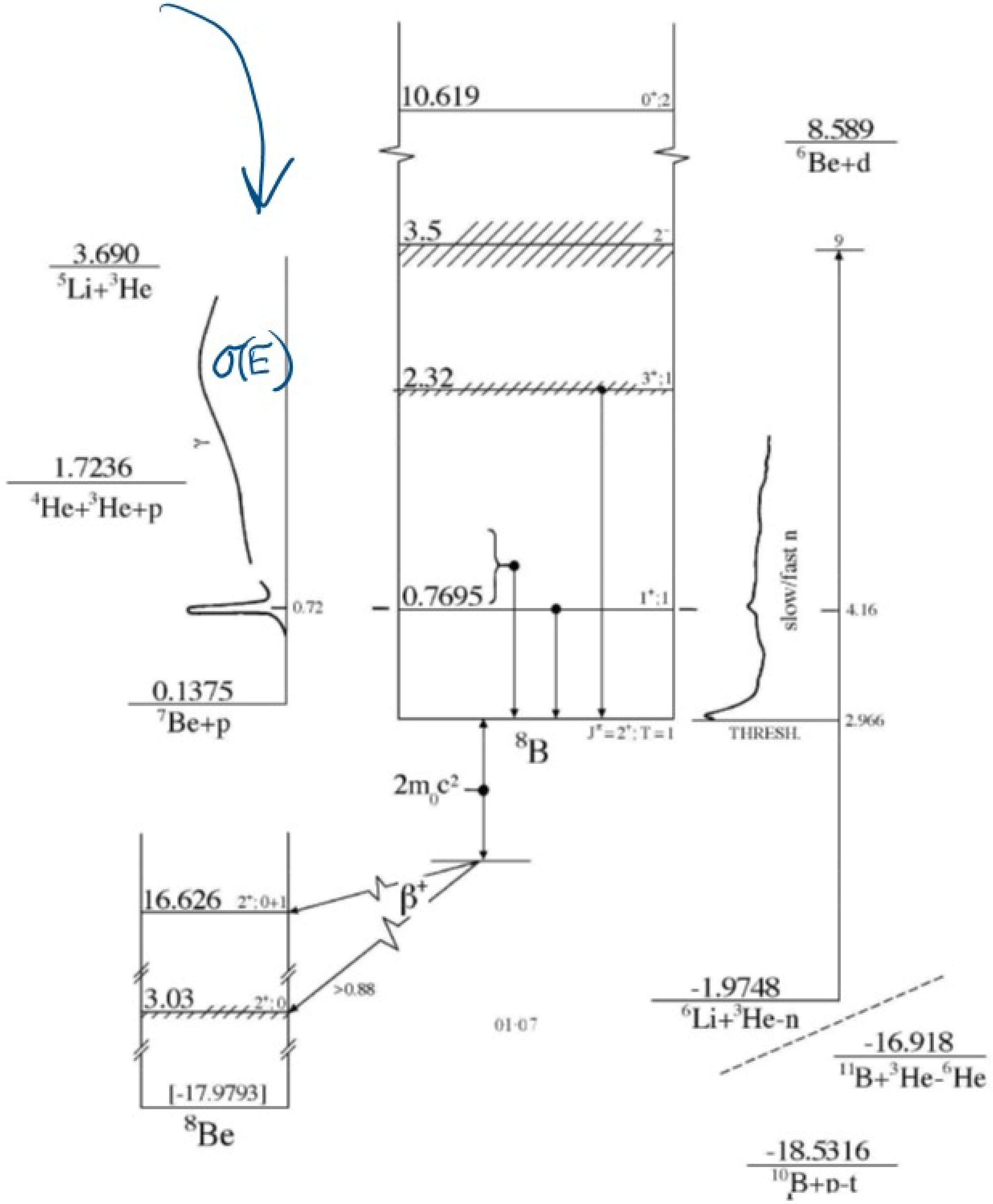
ction of ^{7}Be and the flux of high energy solar neutrinos
wyn, C. N. Davids, and D. D. Koetke
1983)

e structure in ^{11}C studied via resonant f ^{7}Be + α and with the ^{7}Be(α, p) reaction

Unstable nuclei play a major role in a variety of astrophysical phenomena, from stellar production of neutrinos and γ rays to the creation of the heaviest nuclear species. These papers used radioactive ^{7}Be, in one case as the target and in the other as the beam, to study two reactions of importance in astrophysics. These two reactions play a key role in the production of neutrinos in low-mass stars, such as the Sun, and in nucleosynthesis during the CNO-cycle in high-temperature environments.

α-resonance structure in ^{11}C studied via resonant scattering of ^{7}Be + α and with the ^{7}Be(α, p) reaction
H. Yamaguchi (山口英斉), D. Kahl, Y. Wakabayashi (若林 泰生), S. Kubono (久保野 茂), T. Hashimoto (橋本 尚志), S. Hayakawa (早川 勢也), T. Kawabata (川畑 貴裕), N. Iwasa (岩佐 直仁), T. Teranishi (寺西 高), Y. K. Kwon (권영관), D. N. Binh, L. H. Khiem, and N. N. Duy
Phys. Rev. C **87**, 034303 (2013)

$$P + {}^{7}Be \rightarrow {}^{8}B + \gamma$$



5/21/24
⑥

$\sigma_{Res}(E)$ is Breit-Wigner form:

$$\sigma(E) = \pi \lambda^2 \frac{\Gamma_\alpha \Gamma_\beta}{(E-E_R)^2 + \left(\frac{\Gamma_{tot}}{2}\right)^2}$$

reaction channels: $\alpha \Rightarrow A+B$, $\beta = D+E$

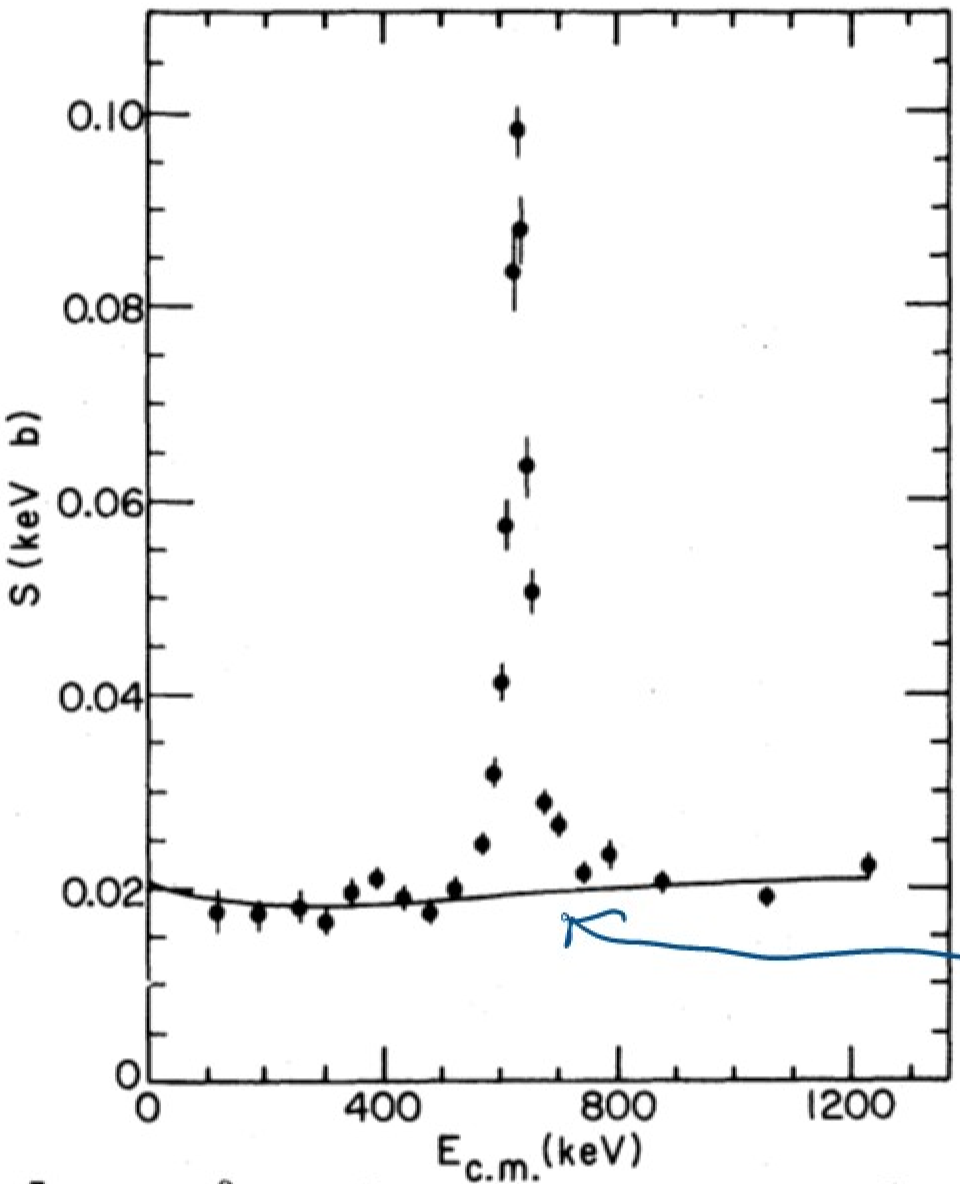
Γ_α = rate to produce C from A+B

Γ_β = " " " D+E " C

↳ if only 2 channels then $\Gamma_{tot} = \Gamma_\alpha + \Gamma_\beta$

& $\sigma(E_R)$ is large if Γ_{tot} is small

also get σ_R for neutron capture



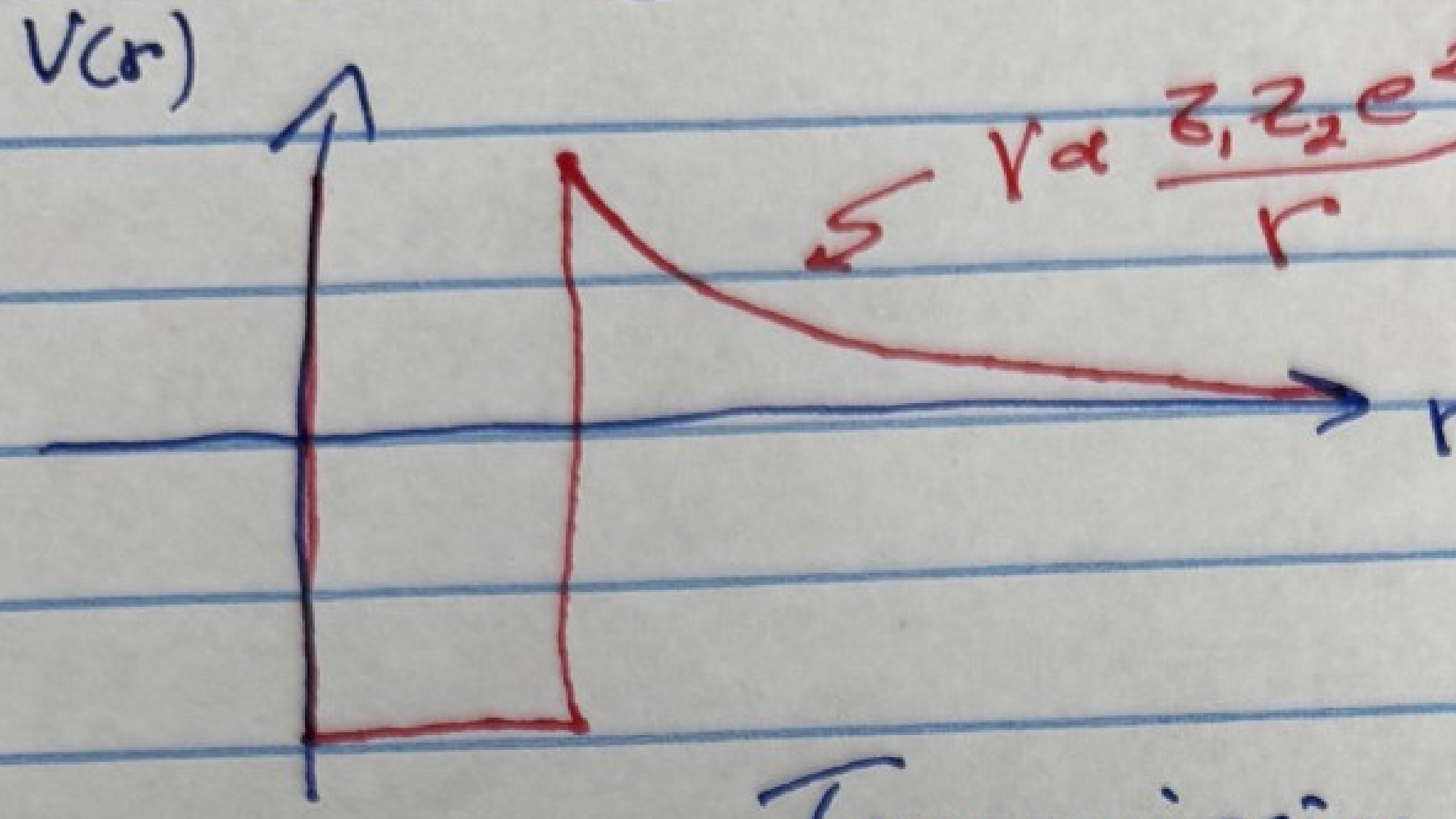
Theory Calc,

FIG. 8. ^{7}Be(p,γ)^{8}B S factor versus center of mass energy. The solid curve is a least-squares normalization of the calculation of Ref. 6 to the off-resonance data.

For non-res. $\sigma(E)$:

Charged Particle:

$\sigma(E)$ @ low E dominated by Coulomb Barrier:



Transmission thru barrier (WKB) gives

$$\sigma \propto T \propto e^{-(E_G/E_{cm})^{1/2}}$$

see H.W. Bert. 12.10

$$E_G = (2\pi\alpha_{Em} Z_1 Z_2)^2 \frac{\mu c^2}{2}$$

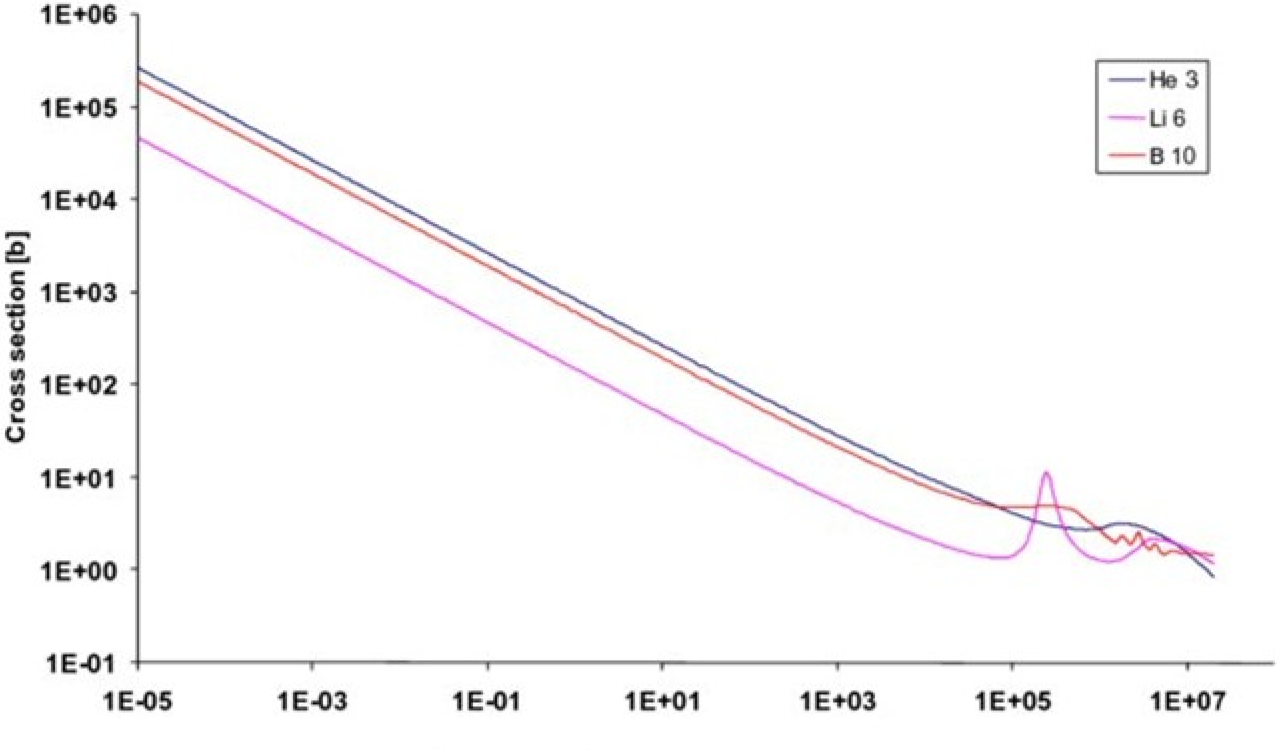
μ = reduced mass of A + B $= \frac{m_A m_B}{m_A + m_B}$

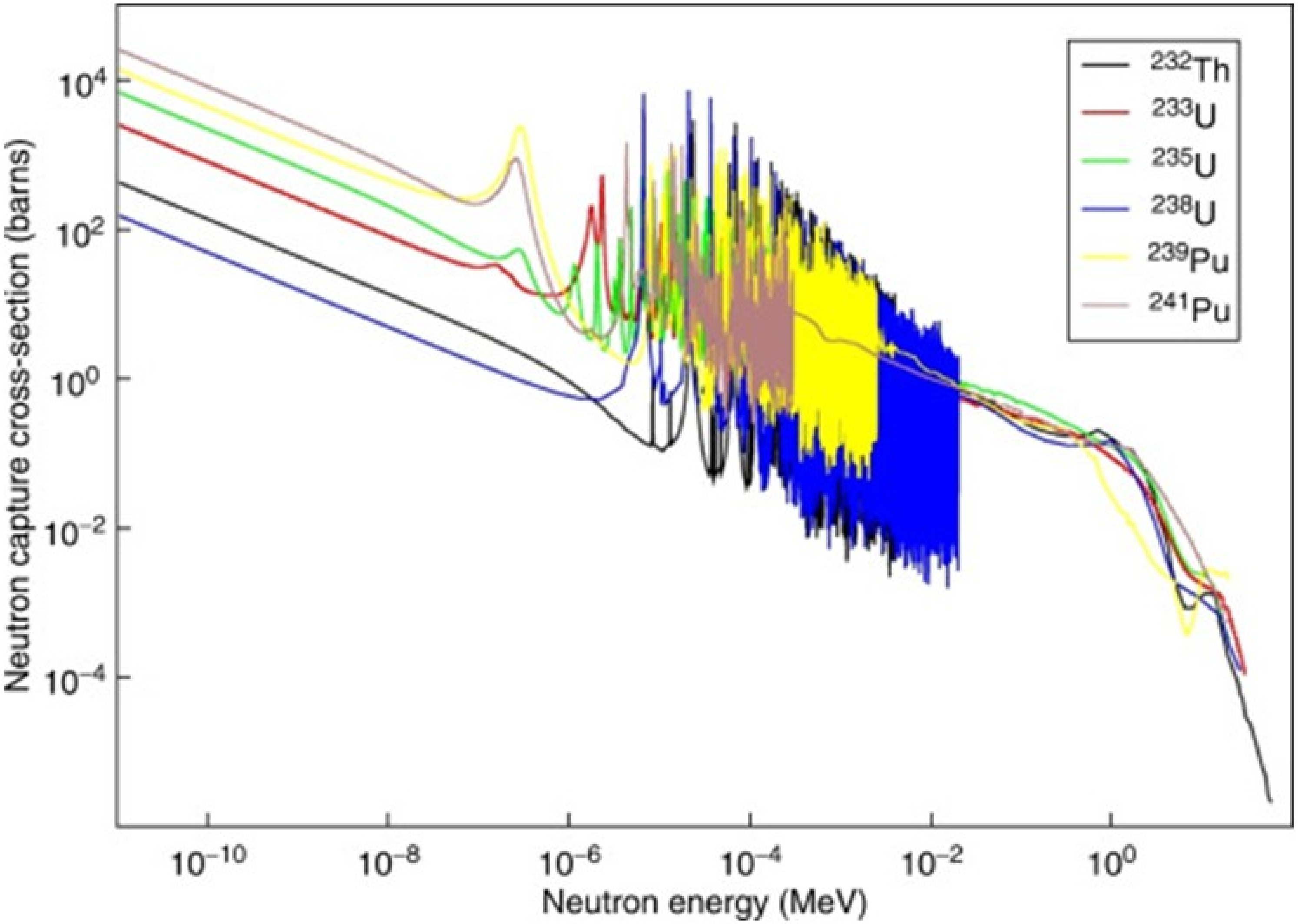
Now including $\pi \lambda^2$ term ($\propto \frac{1}{E_{cm}}$)

$$\sigma_{NR}(E_{cm}) = \frac{S(E_{cm})}{E_{cm}} e^{-(E_G/E_{cm})^{1/2}}$$

w $S(E_{cm}) \simeq$ constant => see Pic

Neutron Capture Cross Section Examples



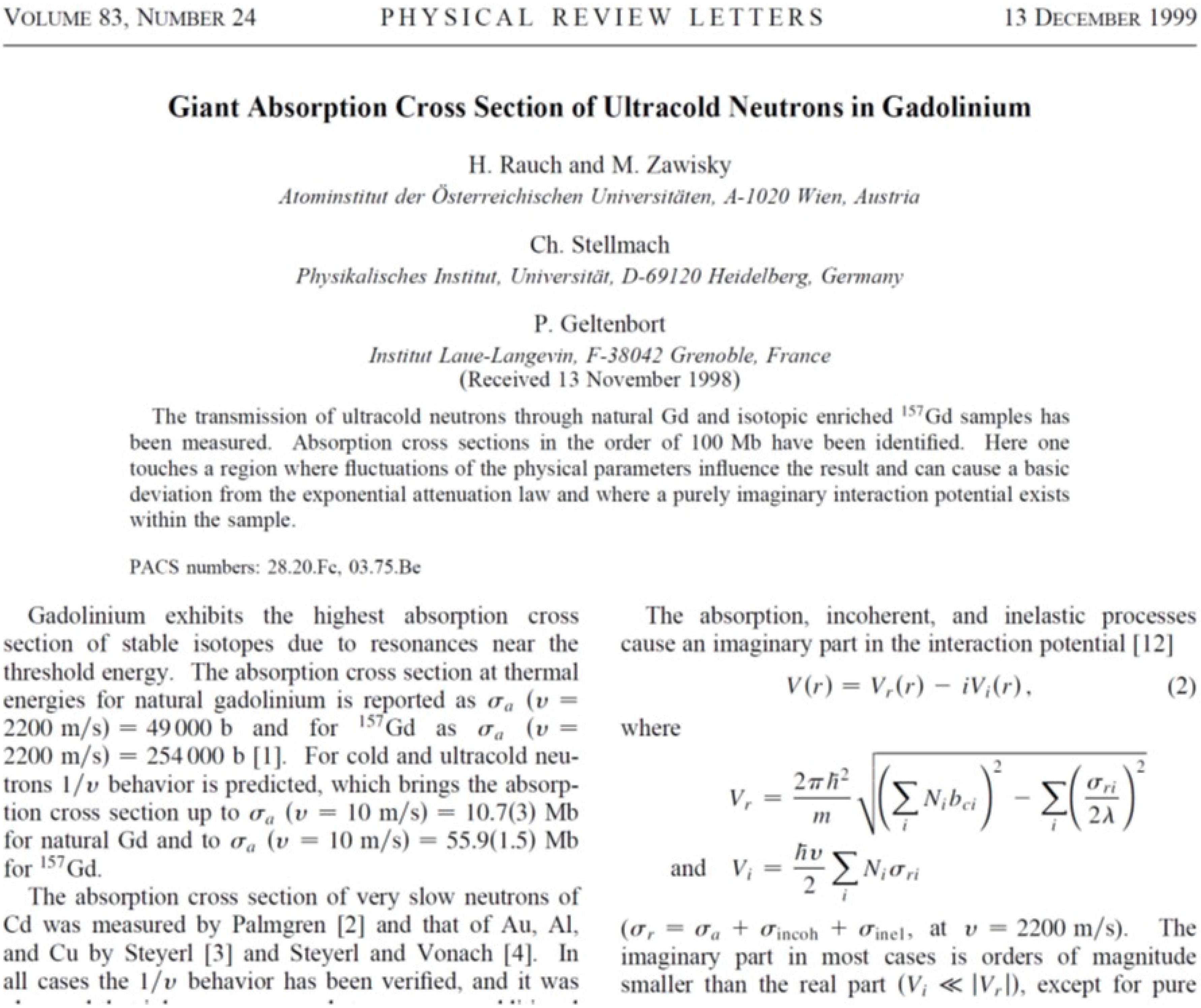


NNDC shows LARGE variation of neutron capture cross sections at “thermal” energies

Note: @ T = 300K, E = 25 meV, Corresponds to neutrons with v = 2200 m/s

Capture cross section at v = 2200 m/s in 157Gd = 254,000 b

→ How low can you go??



VOLUME 83, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1999

Giant Absorption Cross Section of Ultracold Neutrons in Gadolinium

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(Received 13 November 1998)

The transmission of ultracold neutrons through natural Gd and isotopic enriched ^{157}Gd samples has been measured. Absorption cross sections in the order of 100 Mb have been identified. Here one touches a region where fluctuations of the physical parameters influence the result and can cause a basic deviation from the exponential attenuation law and where a purely imaginary interaction potential exists within the sample.

PACS numbers: 28.20.Fc, 03.75.Be

Gadolinium exhibits the highest absorption cross section of stable isotopes due to resonances near the threshold energy. The absorption cross section at thermal energies for natural gadolinium is reported as σ_a ($v = 2200$ m/s) = 49 000 b and for ^{157}Gd as σ_a ($v = 2200$ m/s) = 254 000 b [1]. For cold and ultracold neutrons $1/v$ behavior is predicted, which brings the absorption cross section up to σ_a ($v = 10$ m/s) = 10.7(3) Mb for natural Gd and to σ_a ($v = 10$ m/s) = 55.9(1.5) Mb for ^{157}Gd.

The absorption cross section of very slow neutrons of Cd was measured by Palmgren [2] and that of Au, Al, and Cu by Steyerl [3] and Steyerl and Vonach [4]. In all cases the $1/v$ behavior has been verified, and it was

The absorption, incoherent, and inelastic processes cause an imaginary part in the interaction potential [12]

$$V(r) = V_r(r) - iV_i(r), \qquad (2)$$

where

$$V_r = \frac{2\pi\hbar^2}{m}\sqrt{\left(\sum_i N_i b_{ci}\right)^2 - \sum_i\left(\frac{\sigma_{ri}}{2\lambda}\right)^2}$$

$$\text{and} \quad V_i = \frac{\hbar v}{2}\sum_i N_i \sigma_{ri}$$

($\sigma_r = \sigma_a + \sigma_{\text{incoh}} + \sigma_{\text{inel}}$, at $v = 2200$ m/s). The imaginary part in most cases is orders of magnitude smaller than the real part ($V_i \ll |V_r|$), except for pure

Reactions (cont.)

Neutron Capture $\sigma(E)$

Recall Week 1 Scattering:

S-Matrix

$$\sigma_{sc} = \frac{\pi}{k^2}\sum_l (2l+1)\,|1 - S_l|^2, \quad S_l = e^{2i\delta_l}$$

consider low E ($l=0$) & $\delta = \text{complex} = \delta_0 + i\epsilon_0$

$\epsilon_0 > 0$

then

S_l not unitary &

$$\sigma_{cap} = \frac{\pi}{k^2}\left(1 - |S_0|^2\right)$$

$$\text{w } |S_0|^2 = \left(e^{2i\delta_0}e^{-2\epsilon_0}\right)\left(e^{-2i\delta_0}e^{-2}\right.$$

$$= e^{-4\epsilon_0}$$

$$\therefore \sigma_{cap} = \frac{\pi}{k^2}\left(1 - e^{-4\epsilon_0}\right) \simeq \frac{4\pi\epsilon_0}{k^2} \;;\text{if } \epsilon_0 \ll 1$$

see pics of n-capture (next page)

$\left[\sigma \propto \frac{1}{v} \text{ @ low E}\right]$

$\frac{\epsilon_0}{k} = \text{const.}$

$\propto R_A$

$\epsilon_0 \lambda = \text{const.}$