Production and separation of new radioactive beams with MARS

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June 2009

REU group experiment – plan for the week

- June 22-29, 2009
  - Monday: general presentations, exp setup (day 1)
  - Tuesday: presentations and setup cont'd (day 2)
    - Finish exp setup. Close target detector chamber
    - Calibr of gamma-ray det: energy and efficiency
  - Wed-Thu-Fri: experiments
    - separation of ^{20}Na from ^{20}Ne primary beam on H_2 gas target at 3 energies (3 shifts separately)
    - stop ^{20}Na and study its beta-delayed alpha and gamma decay
  - Sat-Sunday: look for new reaction to produce ^{20}Mg from same beam on ^{3}He target (for experts and fans!)

Summary

1. Introduction, general presentation – LT
2. MARS – Momentum Achromat Recoil Spectrometer - use for RNB prod
   - Part 1 – dr. Brian Roeder
   - Part 2 – Alexandra Spiridon
3. Experiment outline, exp setup for ^{20}Na and its decay: Matthew McCleskey
4. Radiation detection: general and specific – Ellen Simmons
5. Gamma-ray det use and calibration – prof. Abeer Alharbi
6. Prod and sep of ^{20}Mg – Gopal Subedi (our group's REU student)

Monday:

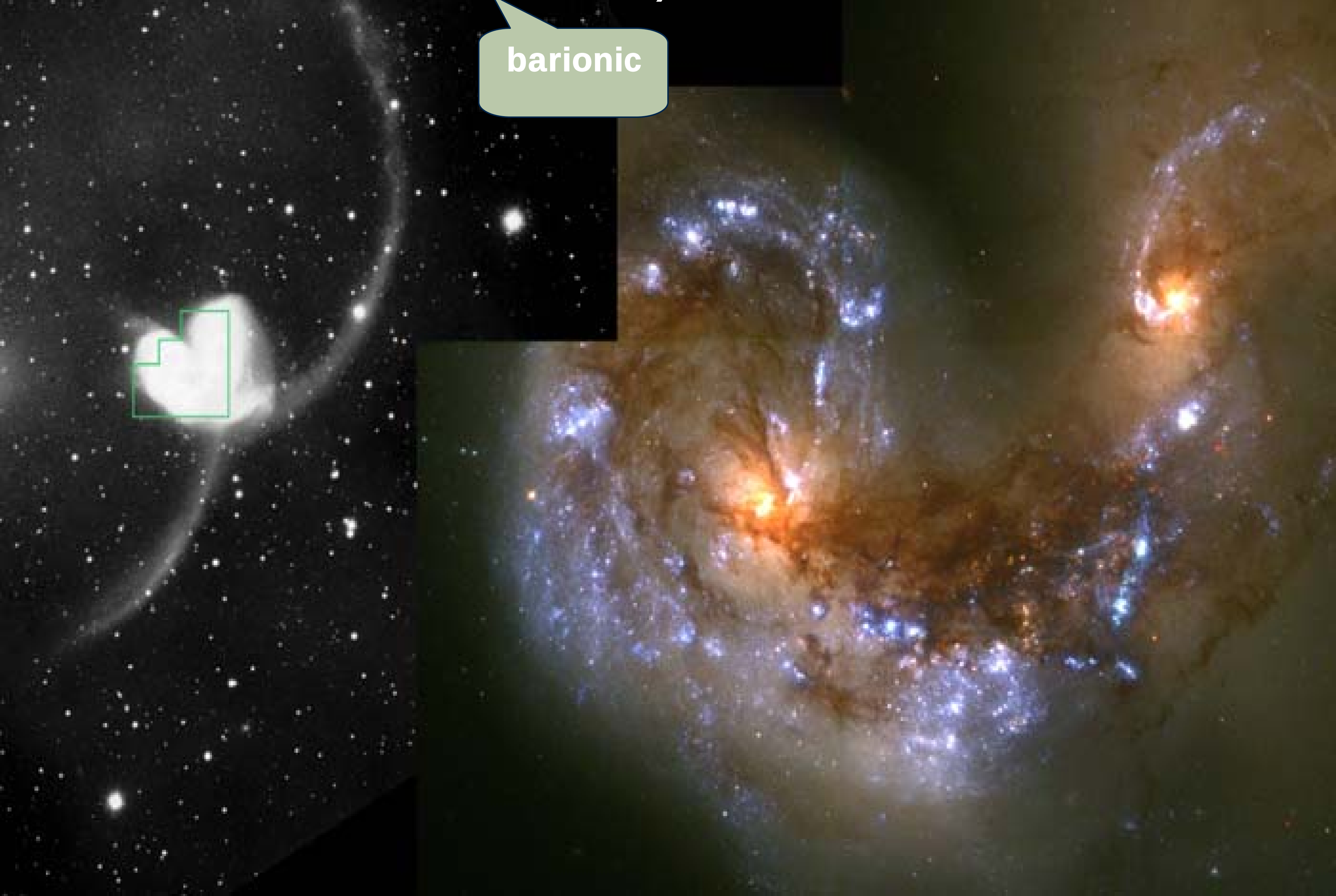
- set 3 shifts of 4 students each to work separately
- Visit MARS cave, present setup, start setting

Tuesday:

- Presentations (cont'd)
- Close target chamber, set gamma-ray (HPGe) det
- Calibrate HPGe detector

Nuclei: core of the matter, fuel of stars

barionic



Questions

Tools to seek answers

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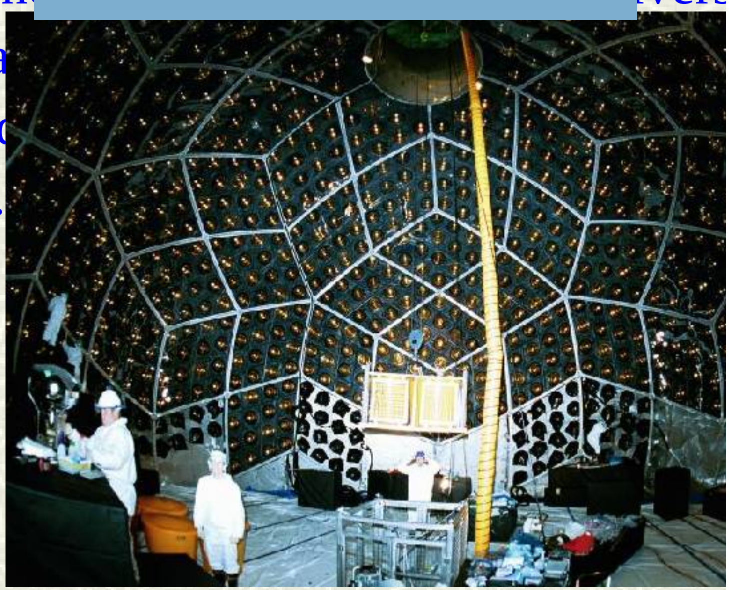
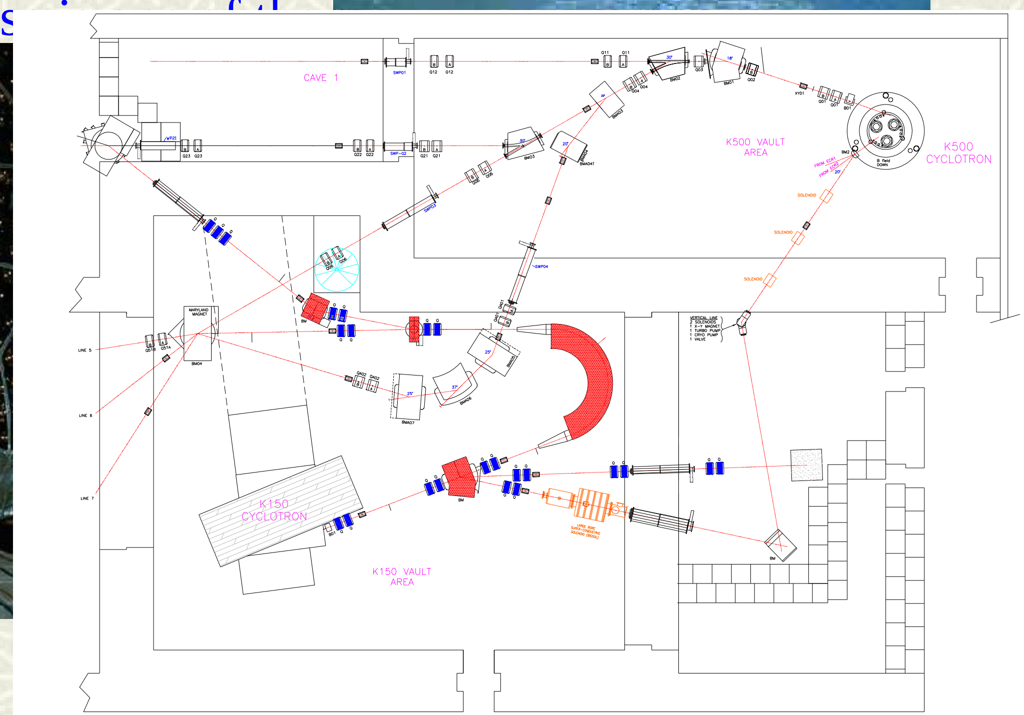




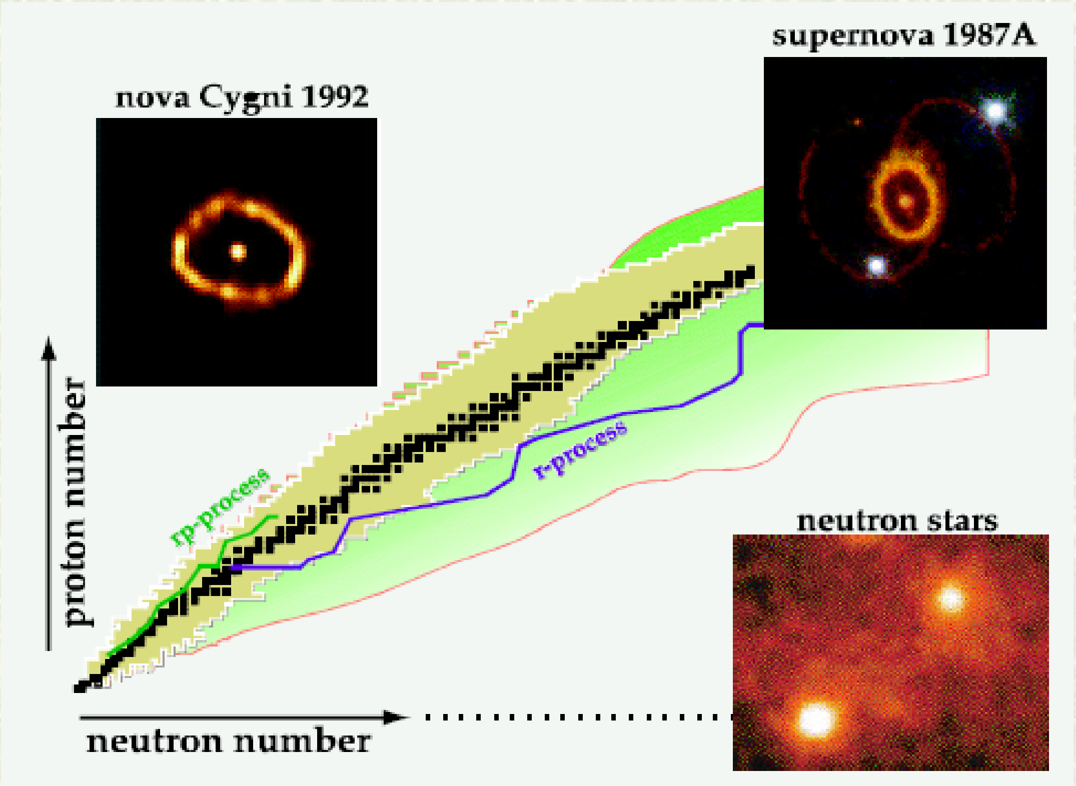
Nuclear Physics for Astrophysics

- Introduction
  - Questions on nucleosynthesis
  - Problems in Nuclear Physics for Astrophysics
  - Dictionary of terms
- Indirect methods in NPA with RNB (w. examples from TAMU)
  - A. Coulomb dissociation
  - B. Transfer reactions (ANC method)
  - C. Breakup of loosely bound nuclei
  - D. Variae – β-decay, resonant elastic scattering, etc
  - E. Trojan Horse Method (non-RNB so far!)

Introduction

- Q: origin of chemical elements?!
- A: nucleosynthesis: BBN, in stars
  - H-burning, He-burning
  - CNO cycle, HCNO …
  - s-process
  - r-process
  - rp-process
- Q: is nucleosynthesis finished or on-going?

  A: yes and yes!
- Q: Elemental/isotopic abundances?!
- A: Elemental/isotopic abundances are indelible, unique fingerprints of cosmic processes (comment, not answer!)
- Quantitative evaluation of models - need good NUCLEAR PHYSICS data – in laboratory for stars
- A: Fine, but is not trivial!



Dictionary of terms

- $X(p,\gamma)$, (n, γ), (α, γ) – radiative proton (n, α) capture reaction
- Cross section σ – related to probab to have a reaction
- Reaction rate $R=N_A\langle\sigma v\rangle$ - integrates over Maxwell distr
- $T_6=T/10^6$K; $T_9=T/10^9$ K (temp in million (billion K)
- Gamow peak – region of contrib to R
- Astrophysical S-factor: in charged particle reactions, takes out the Coulomb barrier penetrability factor:

  $\sigma(E)=1/E*\exp(-2\pi\eta)*S(E)$

  - Cross section varies exponentially with energy
  - S-factor varies slowly: $S(E)=S(0)+S'(0)*E+ \ldots$

Radiative capture reactions

* Radiative capture reactions A(p,γ)B, A(α,γ), A(n,γ)
* **Non-resonant or resonant** reactions.
* At low energy; the probability that the incoming **charged particle** penetrates the Coulomb barrier:

$$P = \exp(-2\pi\eta), where \quad \eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}$$

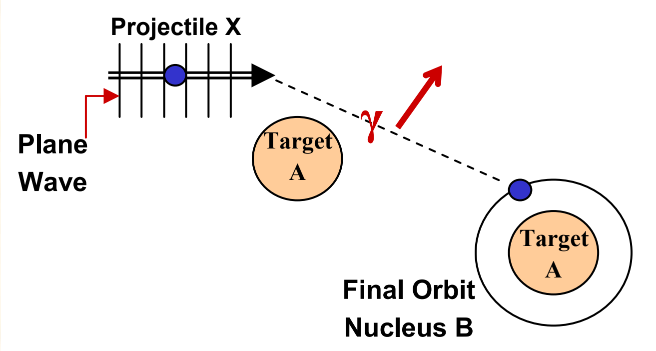
* The cross section – astrophysical S-factor:

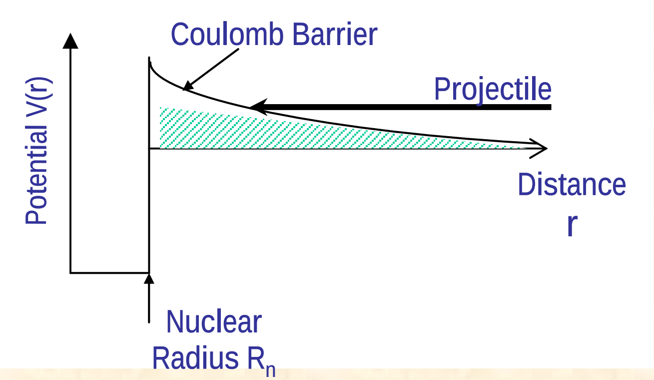
$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$$

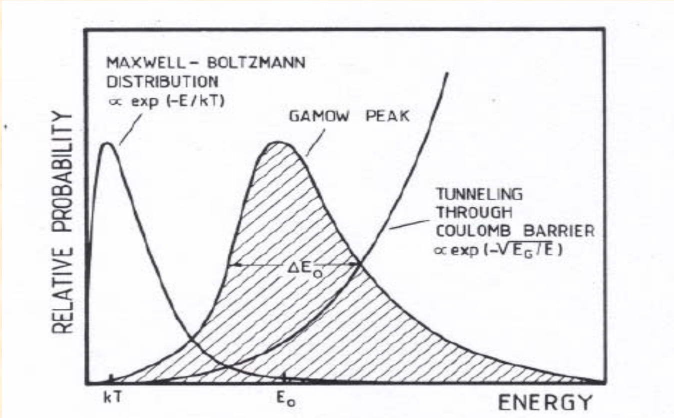
* Reaction rate per particle pair (integrate over E distr):

$$\langle\sigma\upsilon\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty S(E)\exp\left(-\frac{E}{kT}-\frac{b}{E^{1/2}}\right)dE$$

- Reactions (that matter) take place in the **Gamow** energy window.
- Direct, or non-resonant part







* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.

Resonant Reaction Rate

* **Resonant reactions are two-step processes.**

$$\sigma_\gamma \propto \left| \langle E_f | H_\gamma | E_r \rangle \right|^2 \left| \langle E_r | H_f | A + p \rangle \right|^2$$

* **The cross section (Breit-Wigner):**

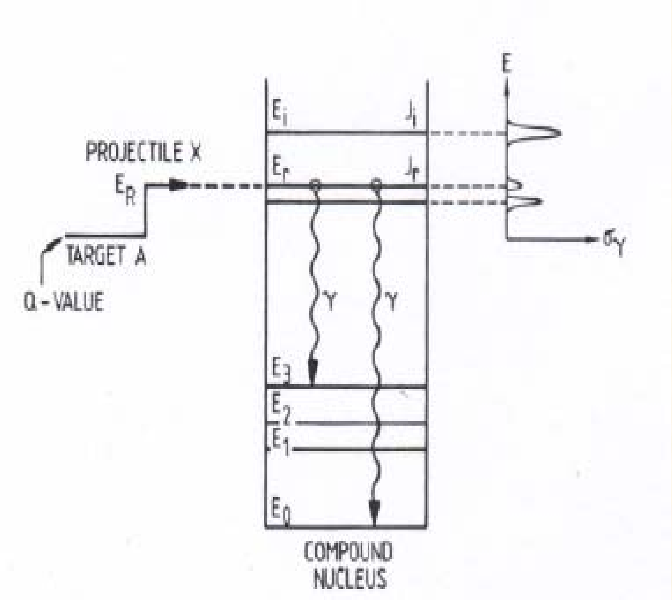
$$\sigma(E) = \frac{\lambda}{4\pi} \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{(E-E_r)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

* **The contribution to the reaction rate:**

$$\langle \sigma \upsilon \rangle_{res} = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT} \right)$$

where

$$\omega\gamma = \frac{2J_r+1}{(2J_p+1)(2J_t+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}$$



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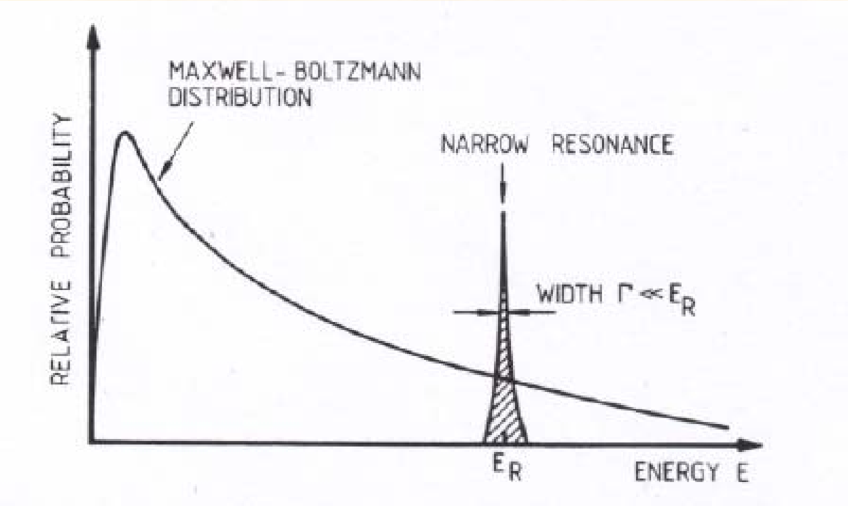


Direct vs. indirect measurements

- Direct: involve measurements at low energies (very low cross sections – nb, pb, fb), typically way above the Gamow region,

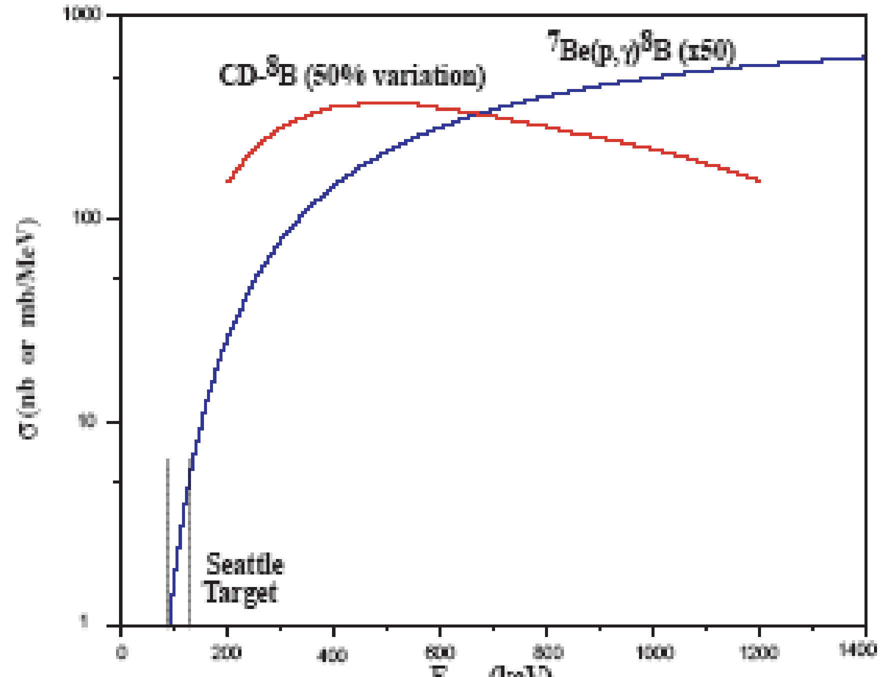


Fig. 1. The cross section of the Coulomb dissociation of ^8B as cross section of the $^7Be(p,\gamma)^8B$ direct reaction.

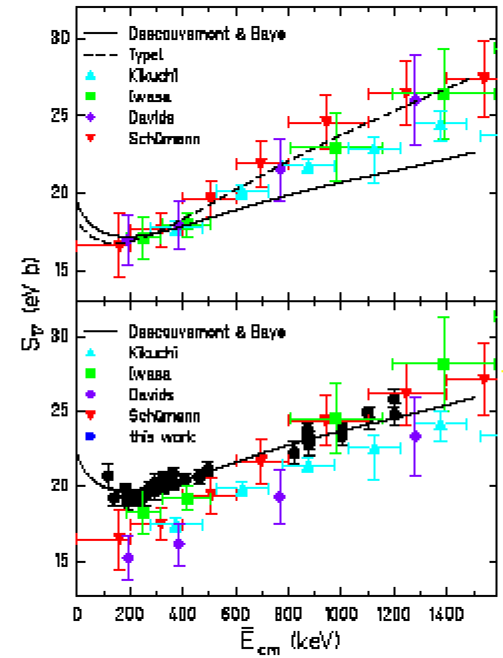
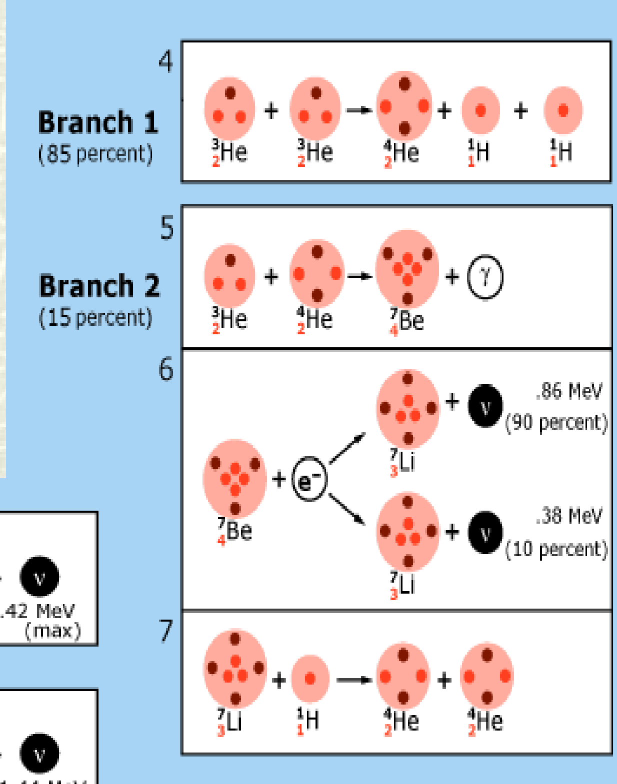


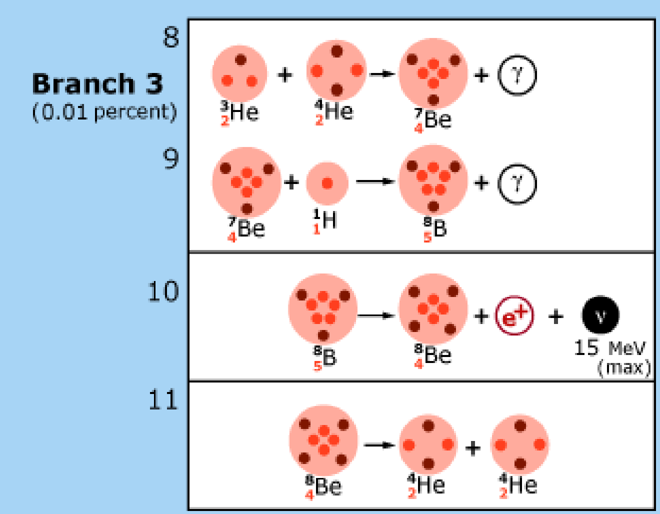
FIG. 19: E1 ^{7}Be(p,γ)^{8}B S-factors inferred from Coulomb dissociation (CD) experiments. Bottom panel: absolute CD S-factors, together with our direct results (with the 1^+ resonance subtracted) and the best-fit DB curve to our direct low-energy data. Top panel: CD data plotted with a common normalization based on the mean value of 19.3 eV b for $S_{17}(0)$ determined by fitting each data set to the DB theory below 400 keV. Solid curve: DB calculation; dashed curve: Typel calculation. The experimental error bars shown in all cases are relative, and do not include scale-factor uncertainties.

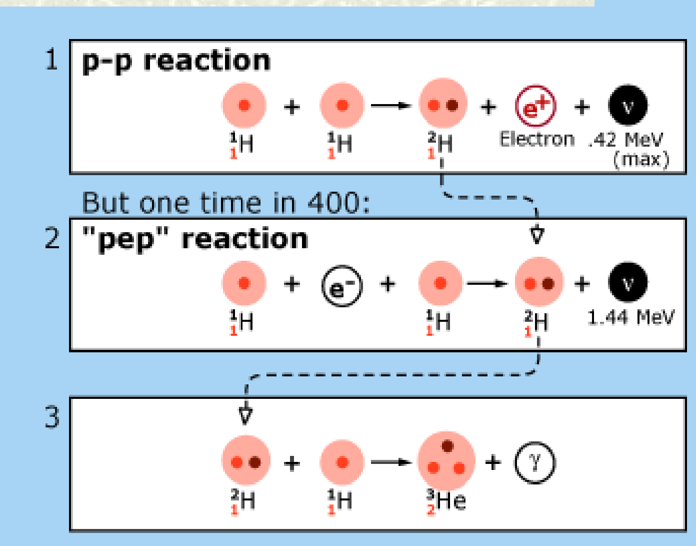
Example: $^{7}Be(p,\gamma)^{8}B$
Solar neutrino problem

$$4\,^{1}H \rightarrow \,^{4}He + 2e^{+} + 2\nu$$

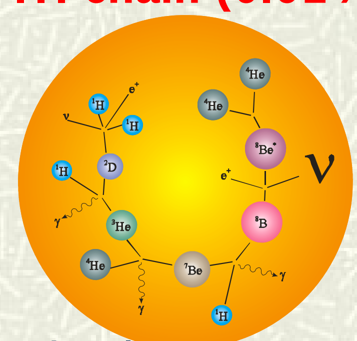
p-p chain reaction





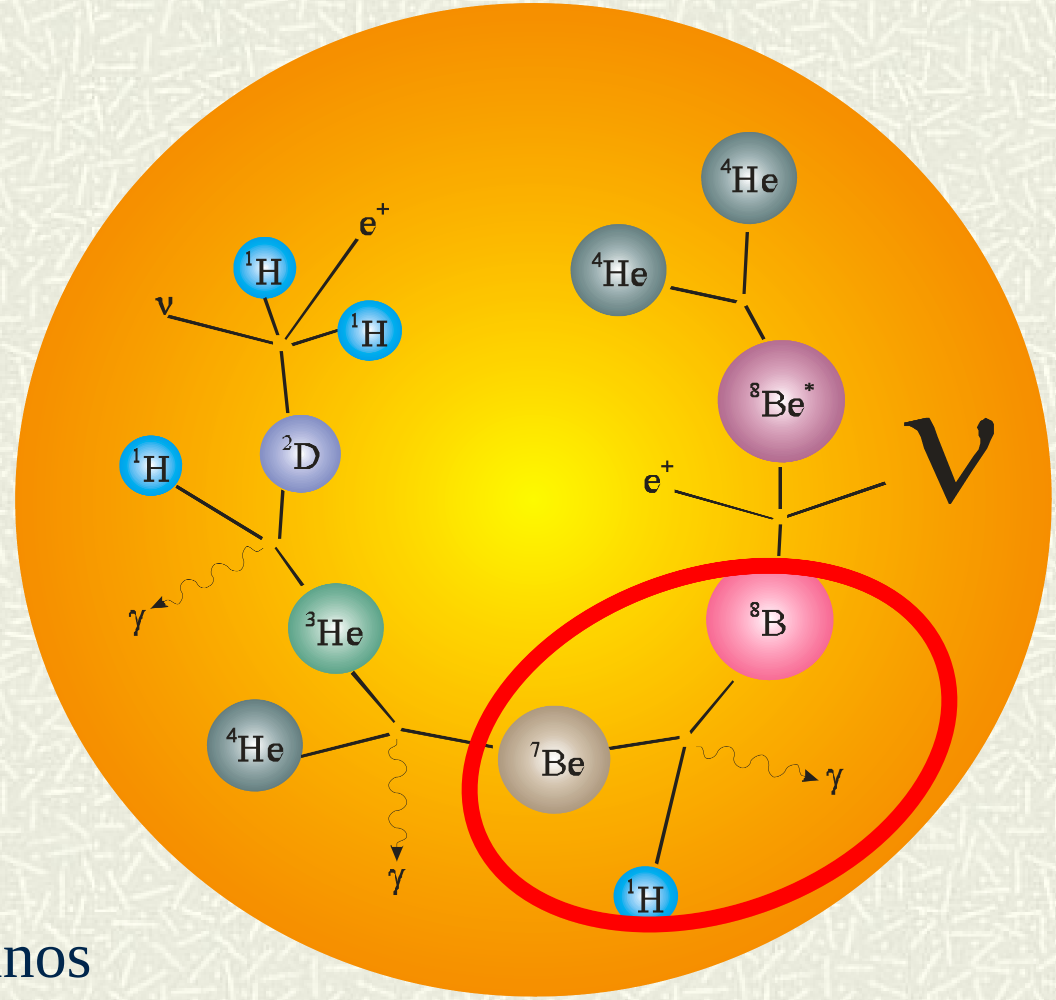


pp III chain (0.01%)



The figures are adapted from J. N. Bahcall, *Neutrinos from the Sun*

Solar neutrinos

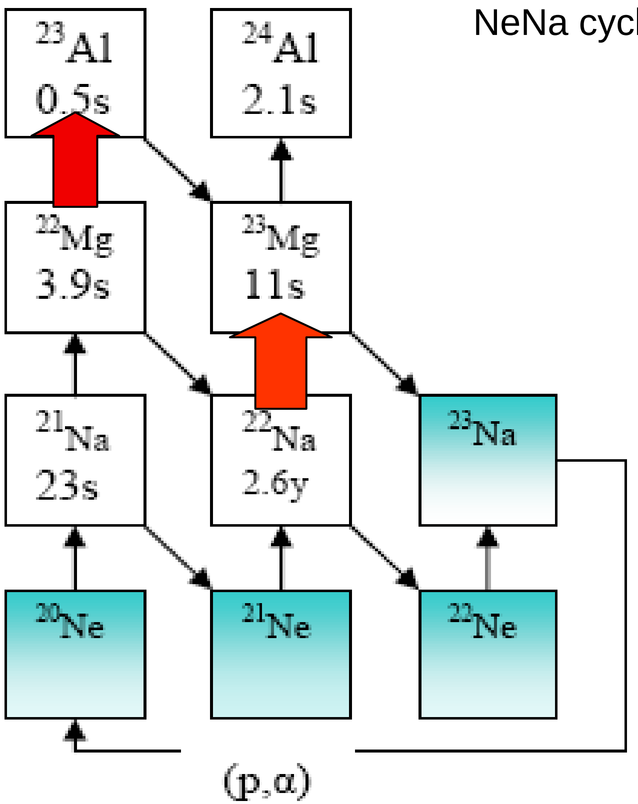


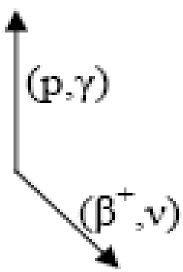
^{8}B neutrinos
pp III chain (0.01%)

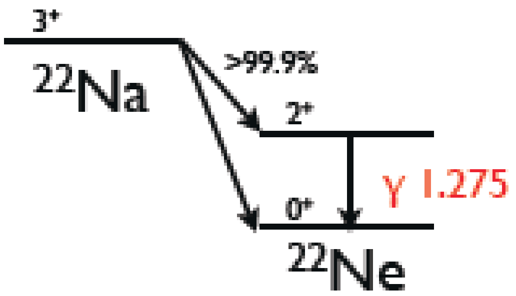
Another example: "^{22}Na puzzle"

- γ rays from the decay of long-lived isotopes ^{26}Al, ^{60}Fe have been detected
- E=1.275 MeV γ ray following the decay of ^{22}Na predicted, but not observed by space gamma-ray telescopes

NeNa cycle







Q: **^{22}Na depletion in novae: how does it happen?**

NeNa cycle: ^{20}Ne(p,γ)^{21}Na(p,γ)^{22}Mg(β,ν)^{22}Na

Depleted via?
- ^{22}Mg(p,γ)^{23}Al ↔ direct & res. capture
- ^{22}Na(p,γ)^{23}Mg ↔ resonant capture

- what are the stellar reaction rates for the **^{22}Mg(p,γ)^{23}Al** and **^{22}Na(p,γ)^{23}Mg**?

$^{23}Al \rightarrow \beta^+ \; ^{23}Mg^* \rightarrow \; ^{22}Na+p$ inverse of $^{22}Na(p,\gamma)^{23}Mg$

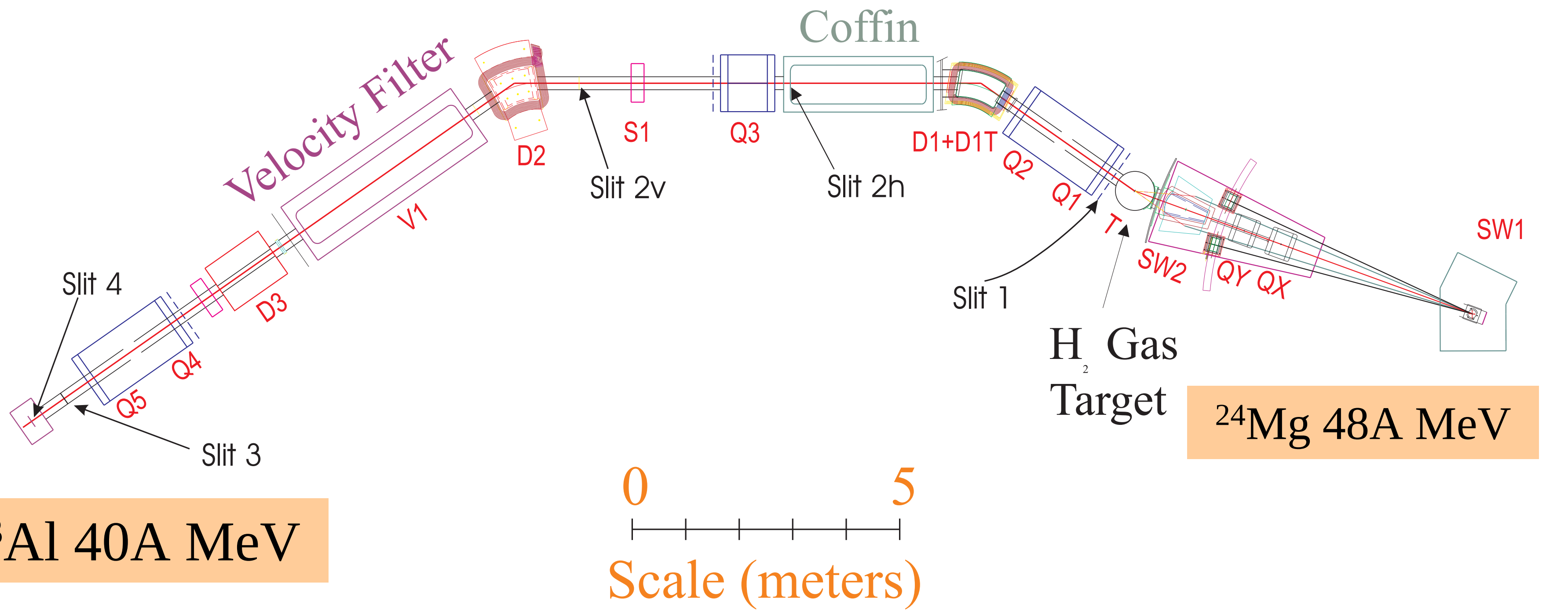
- Study β-delayed p-decay and γ-decay to find resonances in $^{22}Na(p,\gamma)^{23}Mg$
- Need to produce and separate ^{23}Al
- Study decays: $\beta\gamma$ and βp

Producing ^{23}Al w/ MARS

Momentum Achromat Recoil Separator

R.E. Tribble et al., NIM **A285**, 441 (1989)

In-flight RB production



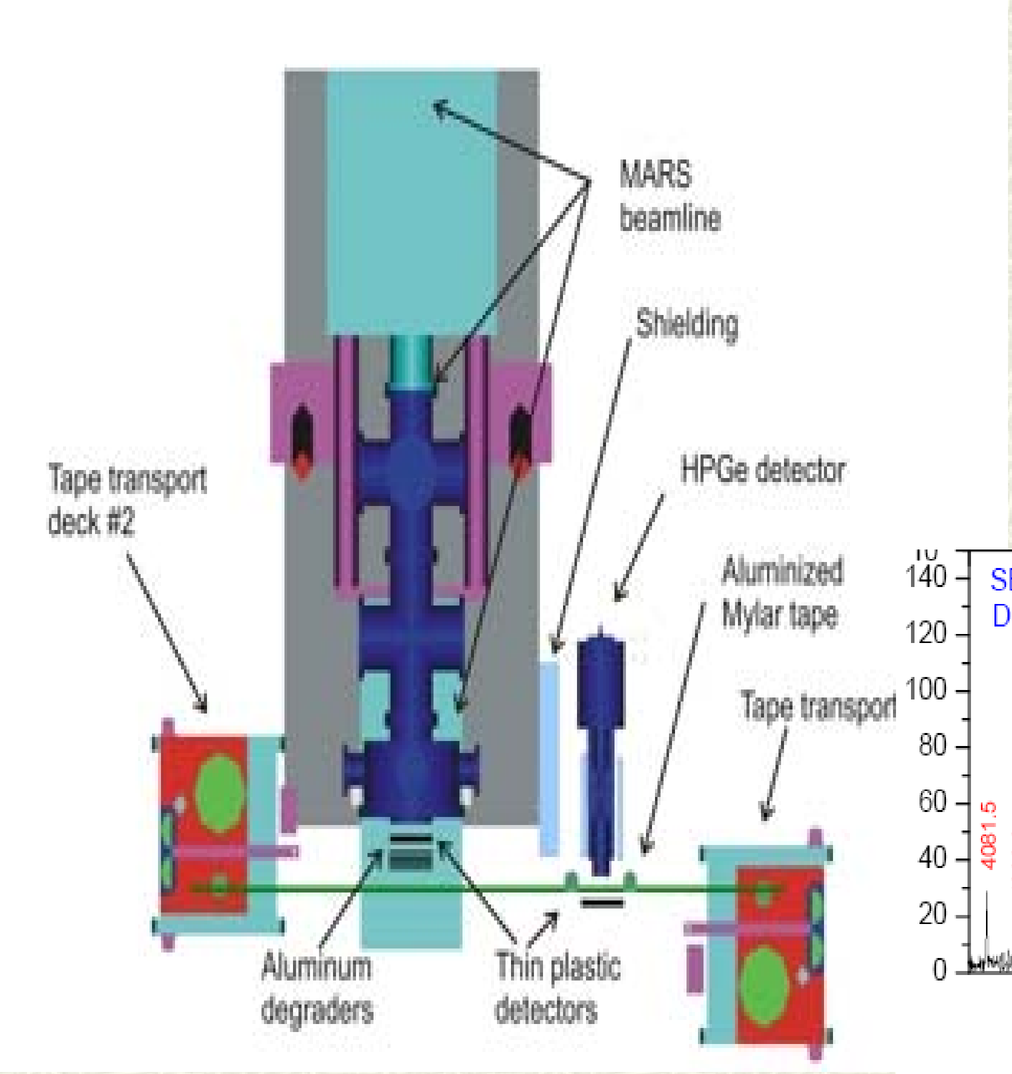
Purity: 90%
Intensity: ~ 4000 pps
First time - intense and pure ^{23}Al

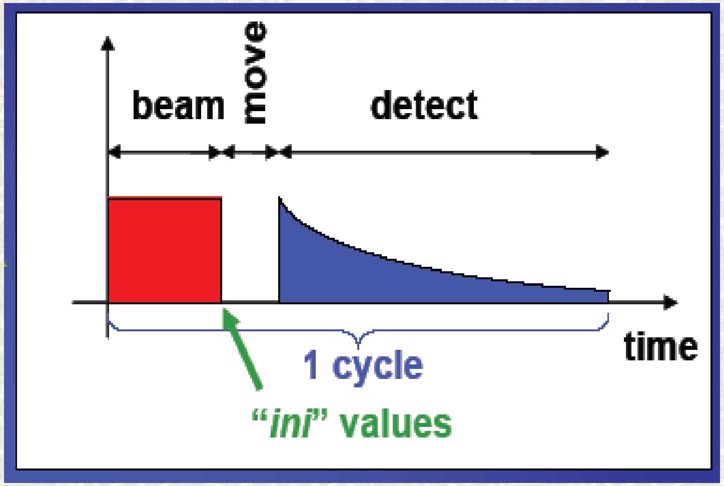
Primary beam ^{24}Mg @ 48A MeV – K500 Cycl
Primary target LN$_2$ cooled H_2 gas p=1.6 atm
Secondary beam ^{23}Al @ 40.2A MeV

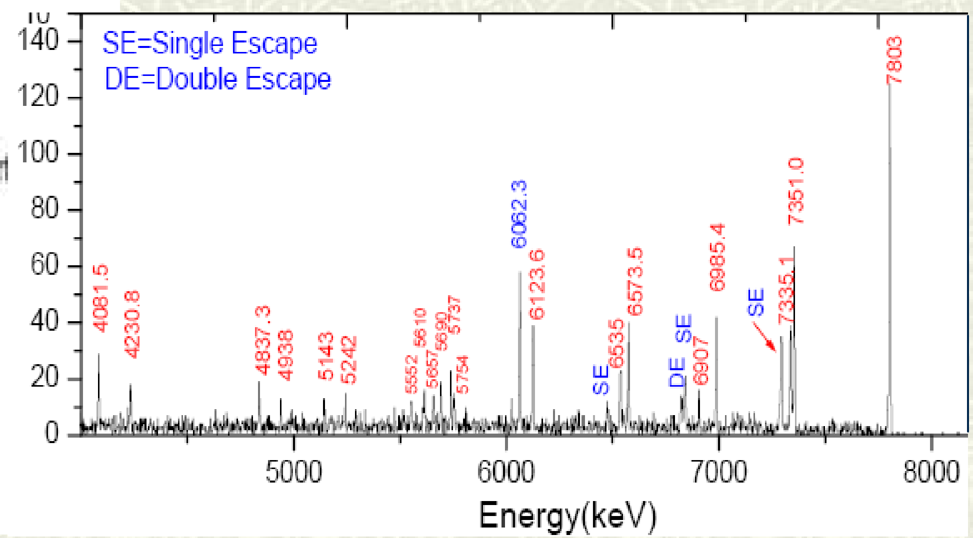
(p,2n) reaction

CYCLOTRON INSTITUTE
Texas A&M University

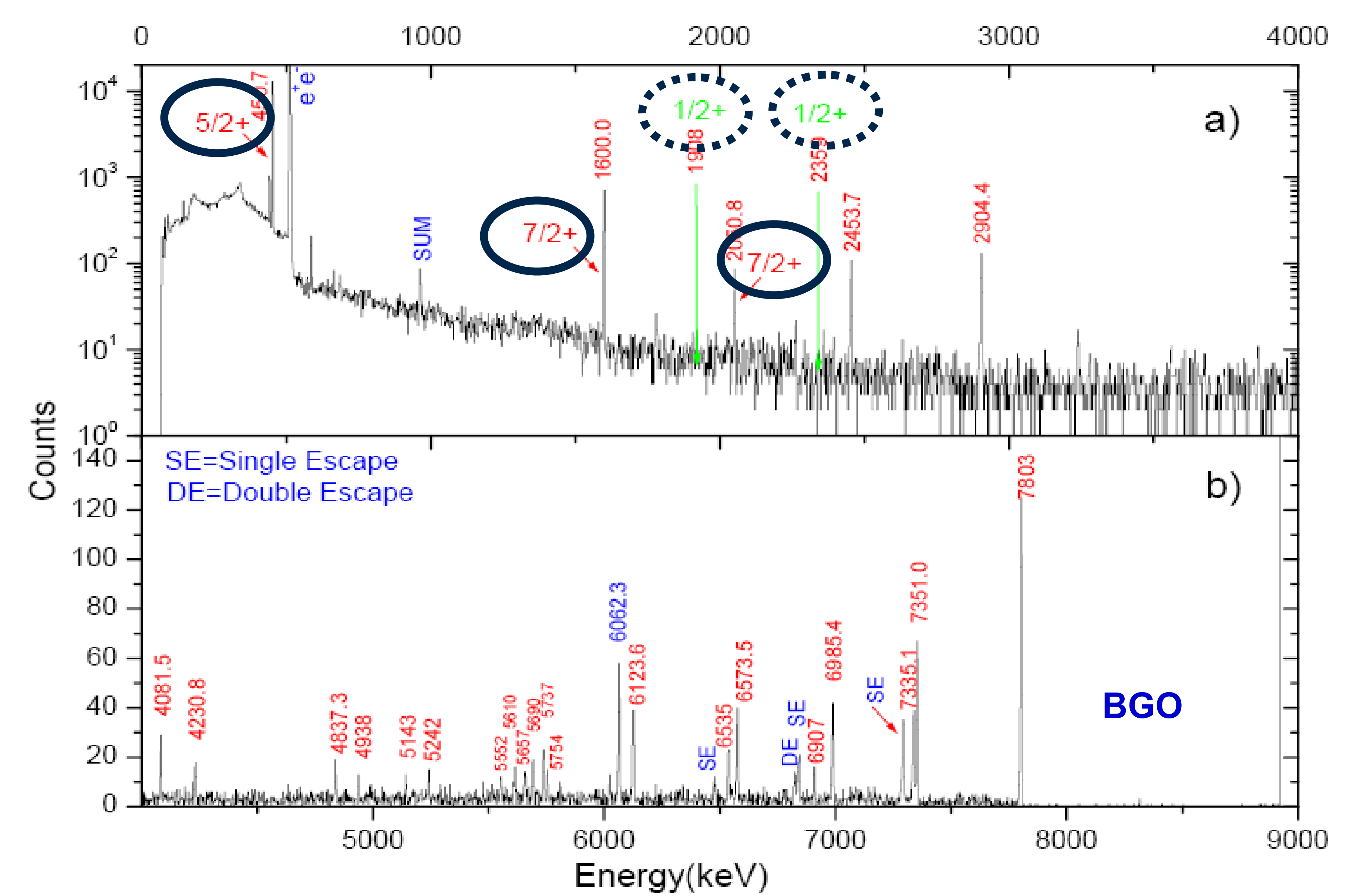
β decay study of pure RB samples



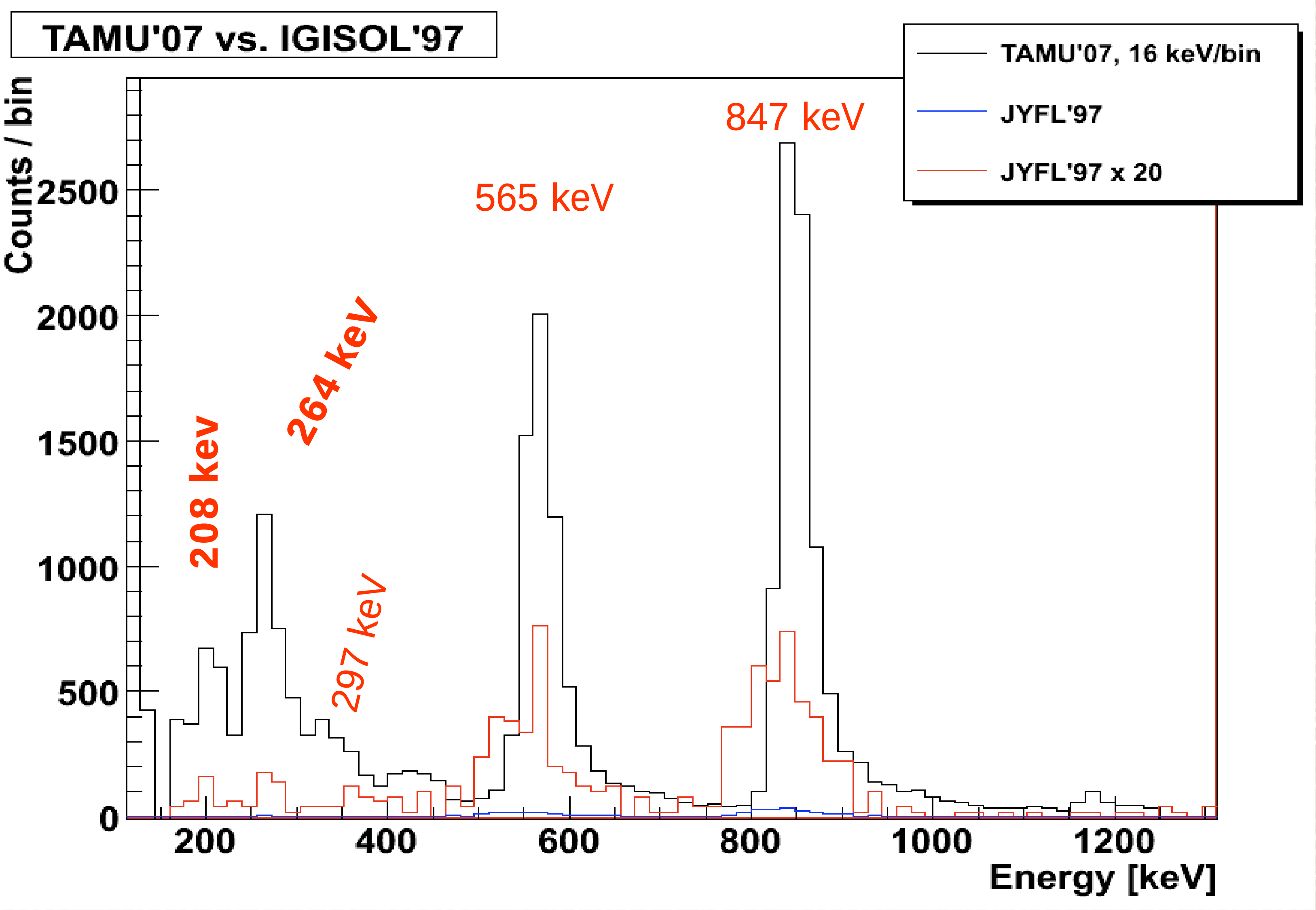




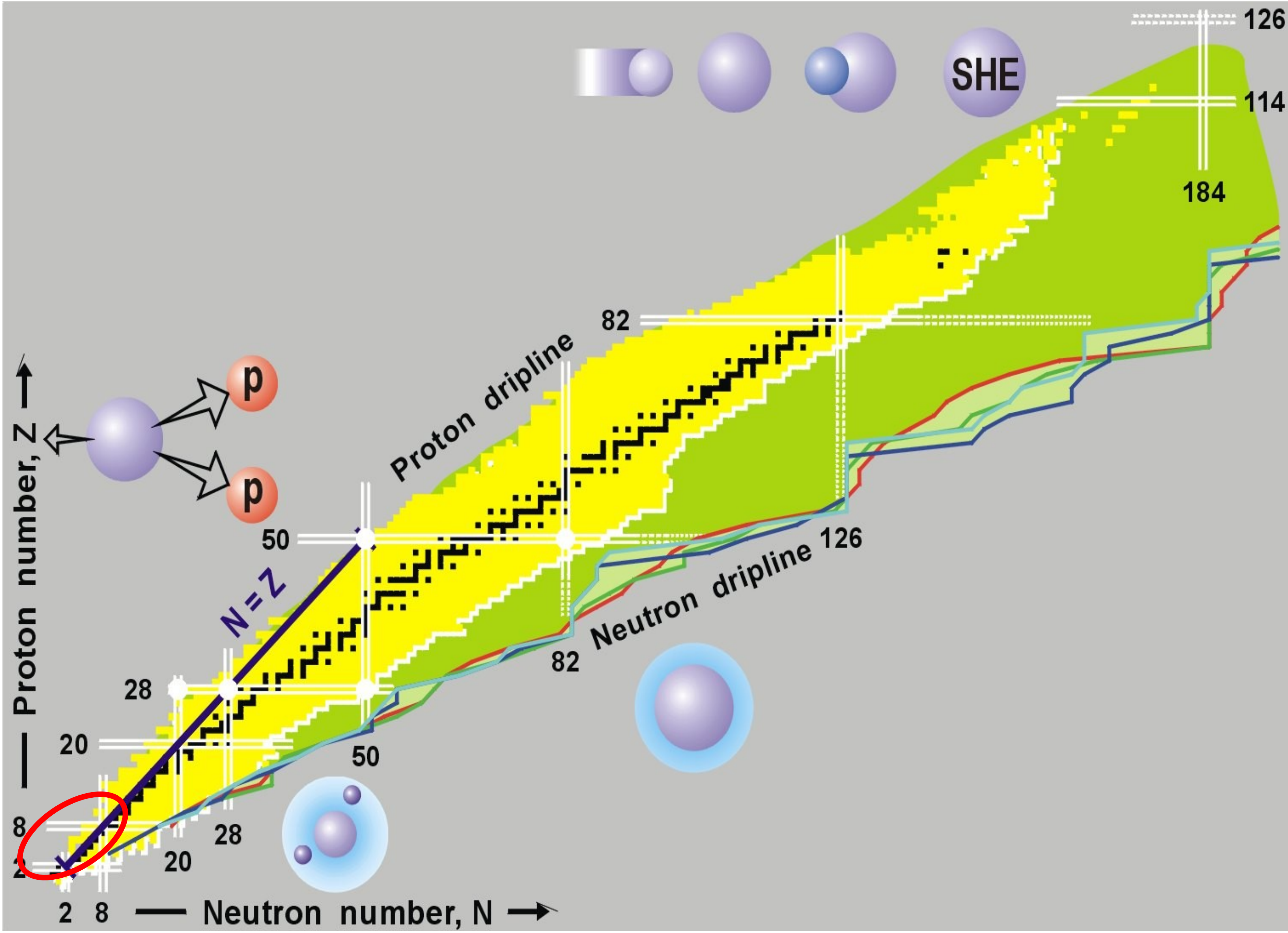
^{23}Al β-γ coincidence measured spectrum



^{23}Al β-delayed p-decay



Antti Saastamoinen et al., to be published


126
SHE
114
184
82
Proton dripline
p
p
Proton number, Z
50
N=Z
28
20
8
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Neutron dripline 126
82
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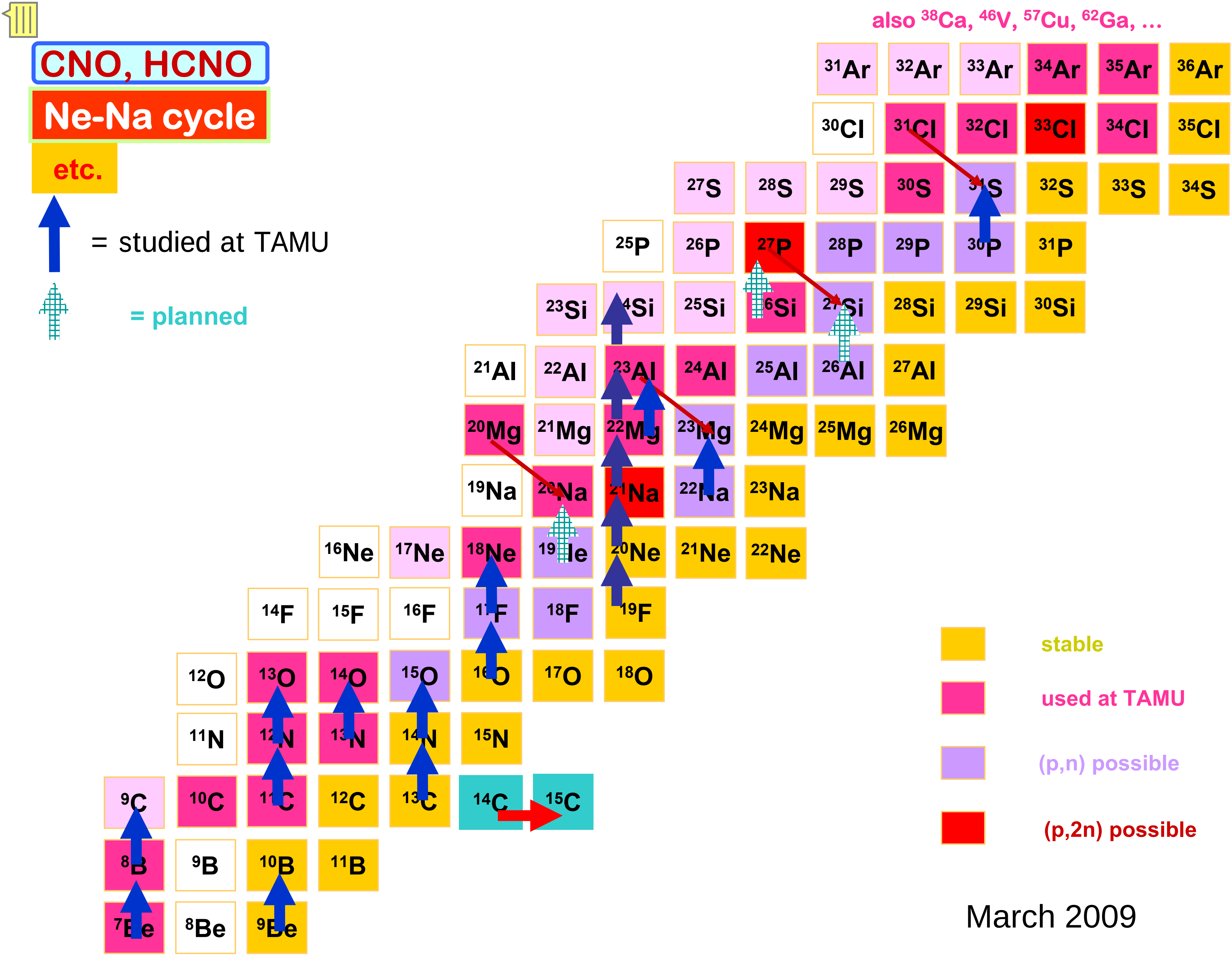
Neutron number, N



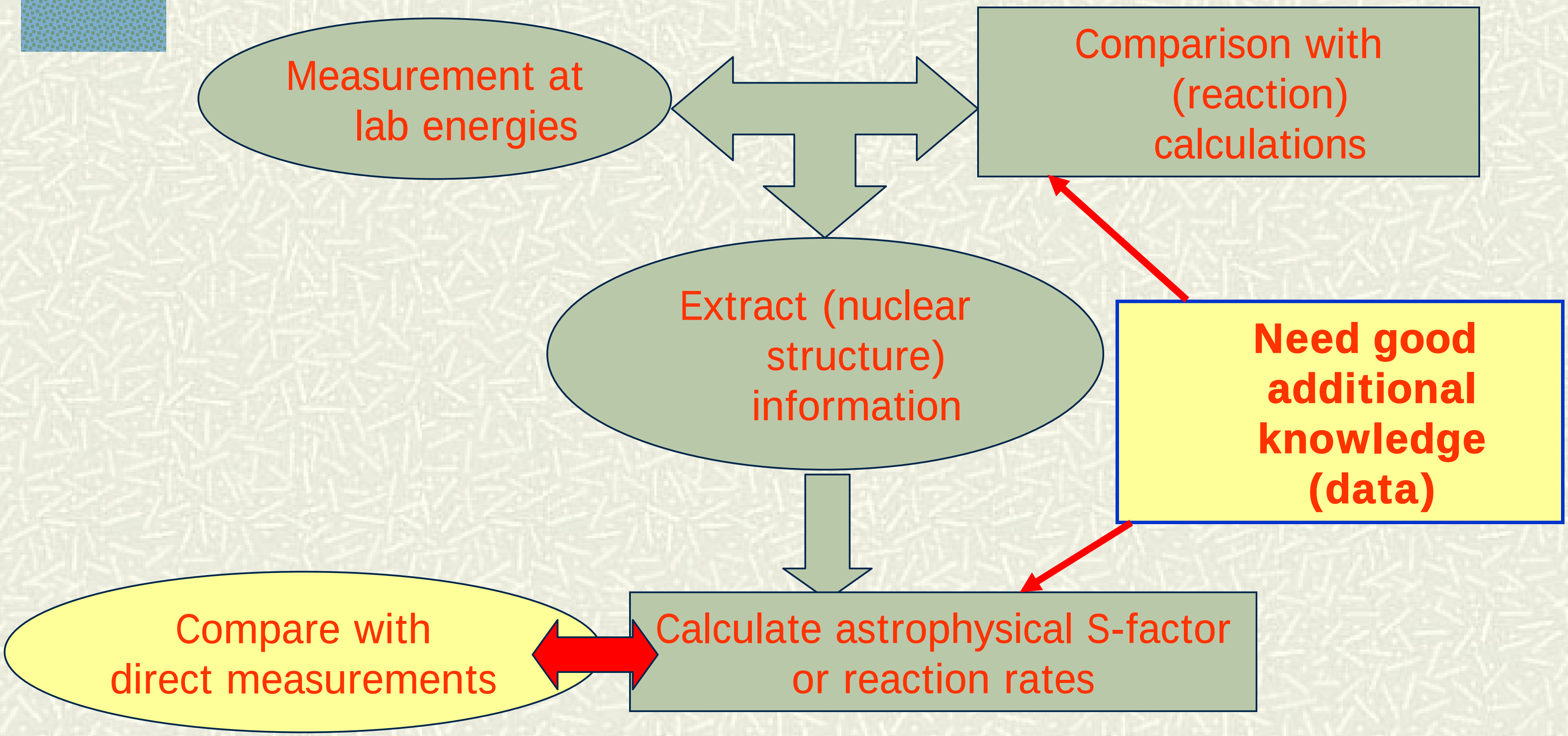
CNO, HCNO
Ne-Na cycle
etc.
= studied at TAMU
= planned
also ^{38}Ca, ^{46}V, ^{57}Cu, ^{62}Ga, …
^{31}Ar ^{32}Ar ^{33}Ar ^{34}Ar ^{35}Ar ^{36}Ar
^{30}Cl ^{31}Cl ^{32}Cl ^{33}Cl ^{34}Cl ^{35}Cl
^{27}S ^{28}S ^{29}S ^{30}S ^{31}S ^{32}S ^{33}S ^{34}S
^{25}P ^{26}P ^{27}P ^{28}P ^{29}P ^{30}P ^{31}P
^{23}Si ^{24}Si ^{25}Si ^{26}Si ^{27}Si ^{28}Si ^{29}Si ^{30}Si
^{21}Al ^{22}Al ^{23}Al ^{24}Al ^{25}Al ^{26}Al ^{27}Al
^{20}Mg ^{21}Mg ^{22}Mg ^{23}Mg ^{24}Mg ^{25}Mg ^{26}Mg
^{19}Na ^{20}Na ^{21}Na ^{22}Na ^{23}Na
^{16}Ne ^{17}Ne ^{18}Ne ^{19}Ne ^{20}Ne ^{21}Ne ^{22}Ne
^{14}F ^{15}F ^{16}F ^{17}F ^{18}F ^{19}F
^{12}O ^{13}O ^{14}O ^{15}O ^{16}O ^{17}O ^{18}O
^{11}N ^{12}N ^{13}N ^{14}N ^{15}N
^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C
^{8}B ^{9}B ^{10}B ^{11}B
^{7}Be ^{8}Be ^{9}Be
stable
used at TAMU
(p,n) possible
(p,2n) possible
March 2009

Remember

- Nuclear physics for astrophysics
- Use indirect methods (only)
- We use RNB:
  - Have to produce them
  - MARS used for RNB prod and separation
  - We use various exp methods – good to know and understand them!

Part 2

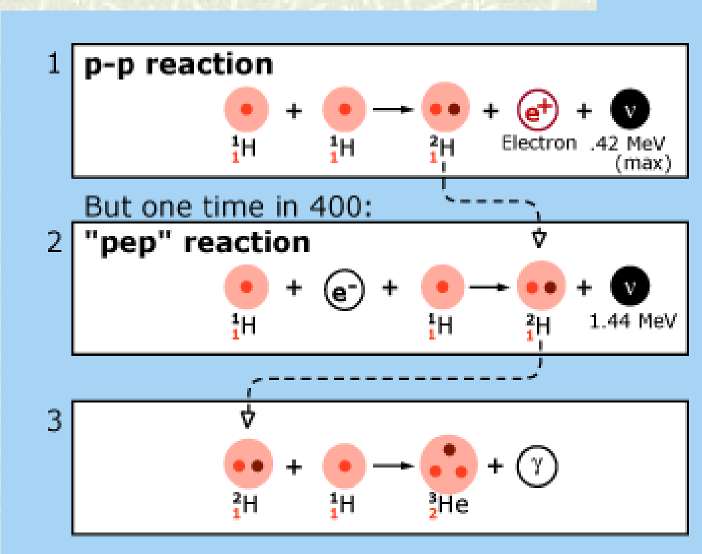
Indirect methods for nuclear astrophysics

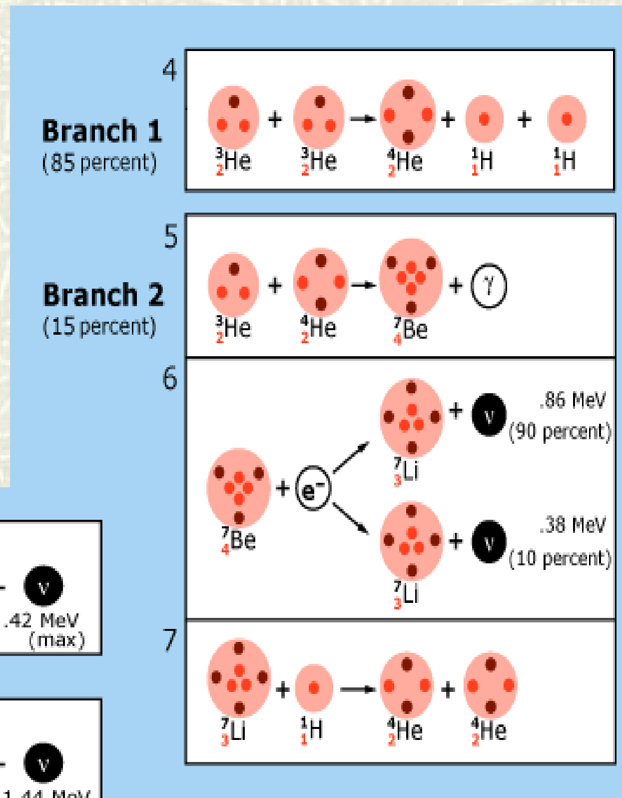


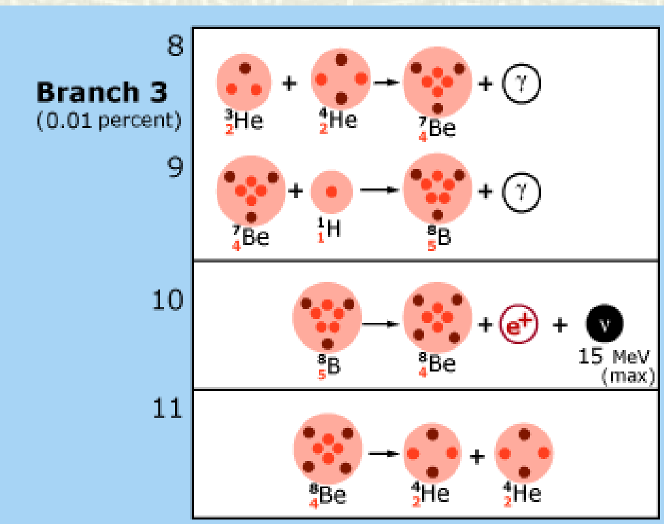
Example: $^7Be(p,\gamma)^8B$
Solar neutrino problem

$4\,^1H \rightarrow \,^4He + 2e^+ + 2\nu$

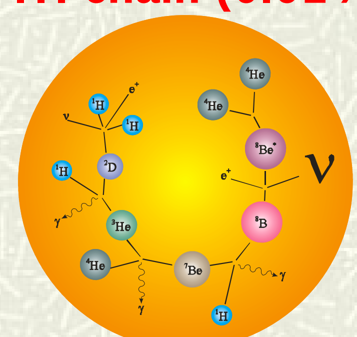
p-p chain reaction





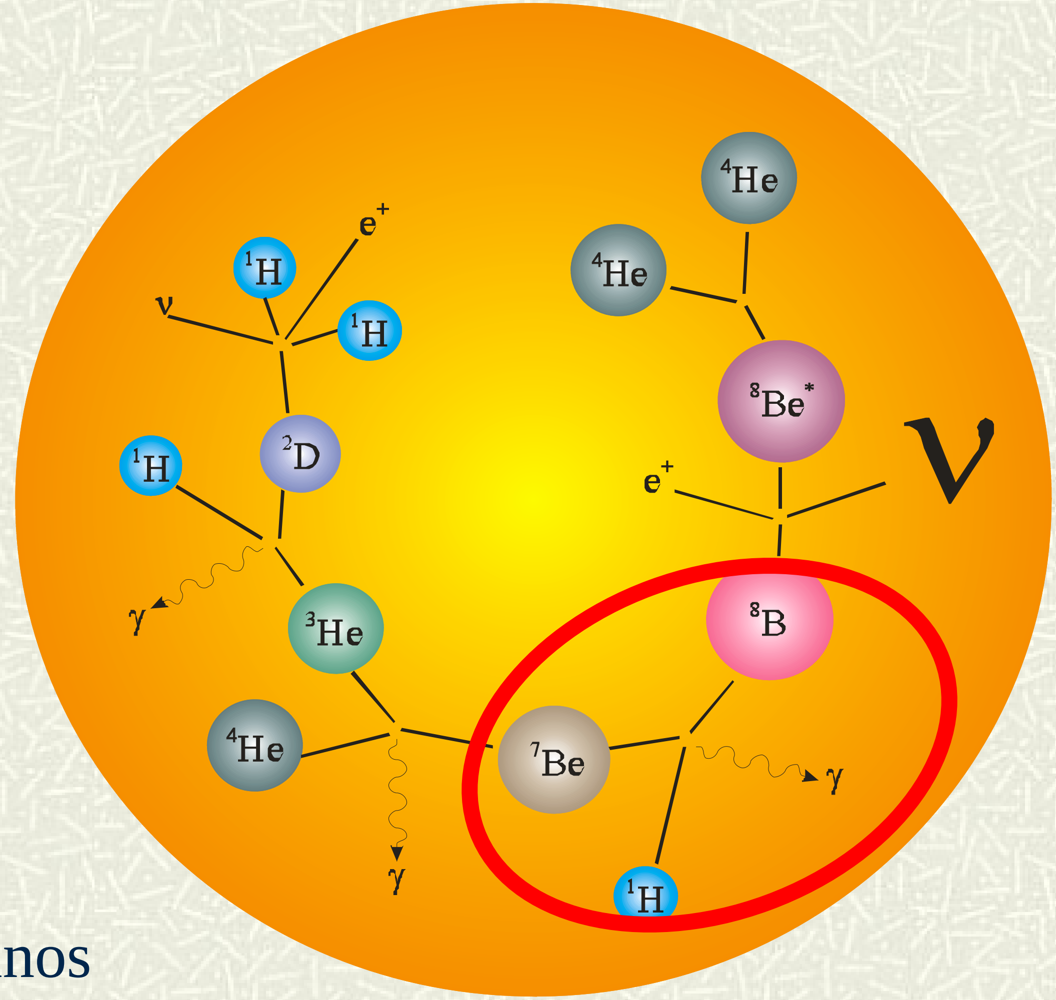


pp III chain (0.01%)



The figures are adapted from J. N. Bahcall, *Neutrinos from the Sun*

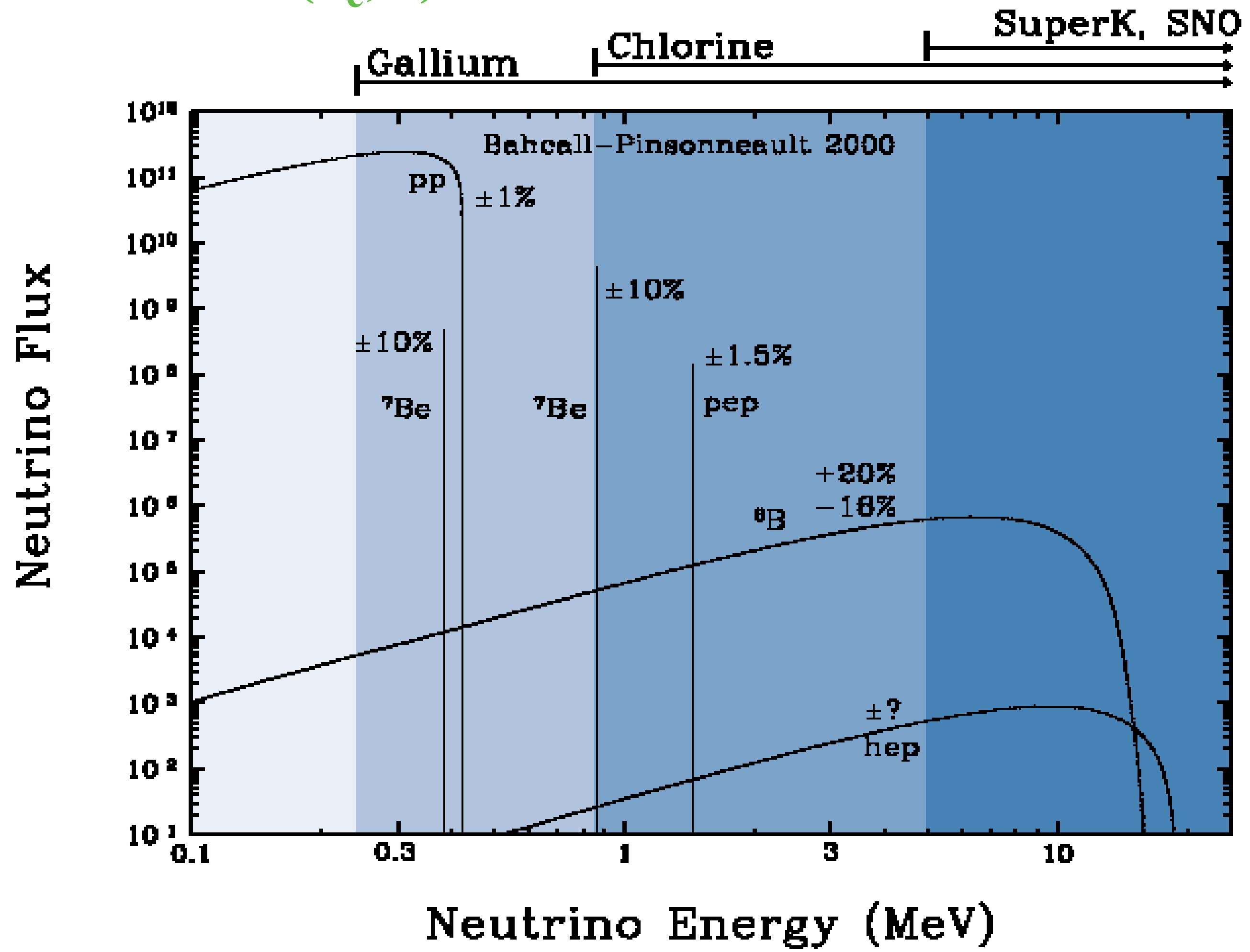
Solar neutrinos



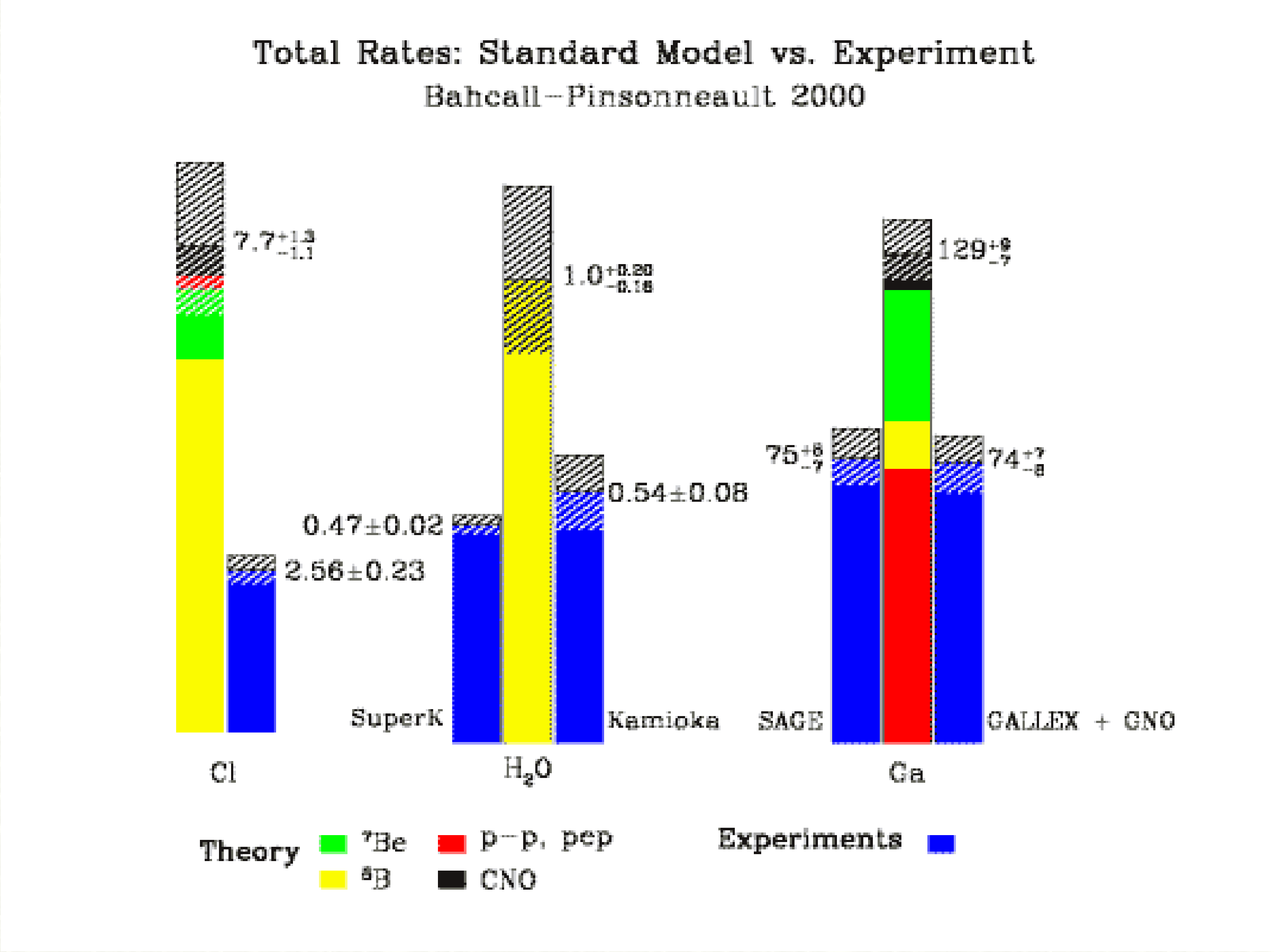
^{8}B neutrinos
pp III chain (0.01%)

Neutrino fluxes from the Sun (Bahcall-Pinsonneault calc)

$^{71}Ga(\nu_e,e^-)^{71}Ge$ $^{37}Cl(\nu_e,e^-)^{37}Ar$ $e^-(\nu_x, \nu_x)e^-$



Solar Model vs. Exp., before June 2001



Solar Neutrinos

June 18, 2001

Super-Kamiokande

The papers of the latest data and oscillation analyses appeared on PRL.

1) SOLAR B-8 AND HEP NEUTRINO MEASUREMENTS FROM 1258 DAYS OF SUPERKAMIOKANDE DATA.

   Published in Phys.Rev.Lett.86:5651-5655,2001

2) CONSTRAINTS ON NEUTRINO OSCILLATIONS USING 1258 DAYS OF SUPERKAMIOKANDE SOLAR NEUTRINO DATA.

   Published in Phys.Rev.Lett.86:5656-5660,2001

SNO

First results of CC measurement

MEASUREMENT OF CHARGED CURRENT INTERACTIONS PRODUCED BY B-8 SOLAR NUETRINOS AT THE SUDBURY NEUTRINO OBSERVATORY.

Published in Phys.Rev.Lett.87:071301,2001

Convincing Evidence for solar neutrino oscillations

Futher confirmed by the NC measurement by SNO, Aprl-2002

New: PRL 89, 011301,-2 (2002)

^{8}B neutrino flux: 5.21±0.27(sta)±0.38(sys) x 10^{6} $cm^{-2}s^{-1}$

Comp with SSM: 5.79·(1. ± 0.23) (Bahcall, Pinsonneault, 2004)

(using $S_{17}(20)$=20.6 eVb; PRL 92, 121301(2004))

A. Coulomb dissociation

- Radiative capture - direct

G Baur and H Rebel

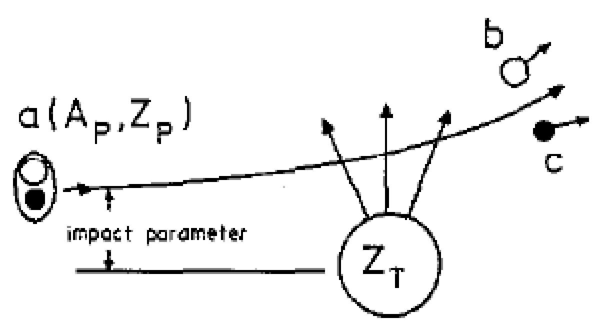
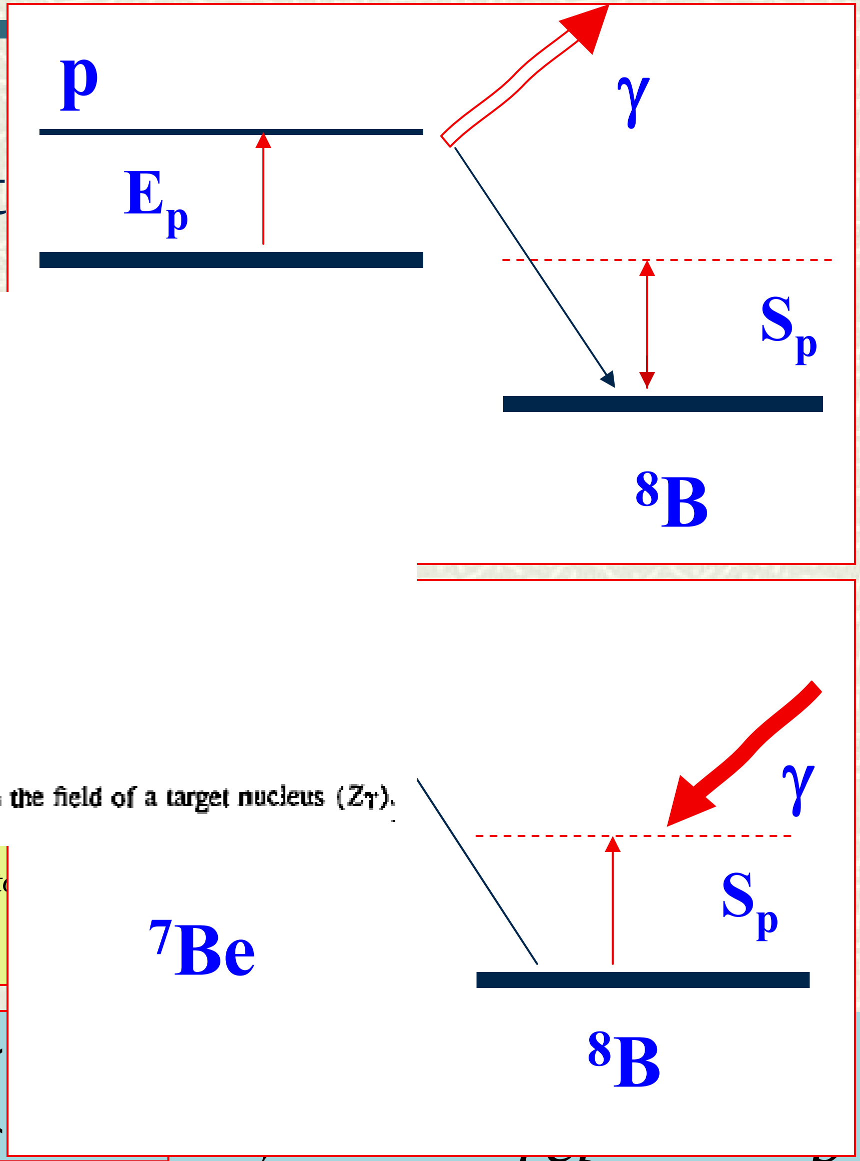


Figure 1. Coulomb dissociation of a projectile a → b + c in the field of a target nucleus (Z_T).

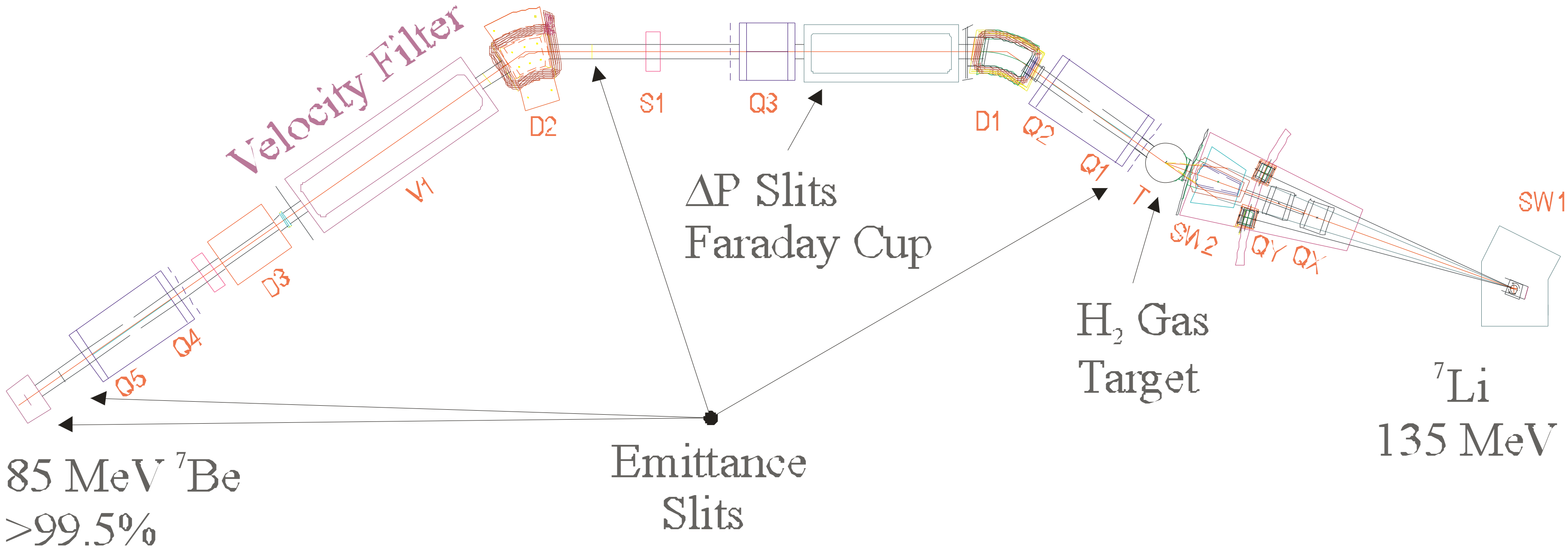
$$\frac{d^2\sigma}{dE_\gamma d\Omega}(E_\gamma,\theta) = \frac{1}{E_\gamma}\left[\frac{dN(E1,E_\gamma)}{d\Omega}\sigma_{E1}^{photo}\right.$$

$$\sigma^{radcap}(E_{rel}) \propto \sigma_{E1}^{photo}($$



Momentum Achromat Recoil Separator

RB in-flight production



1.5 10^5 pps

0 5

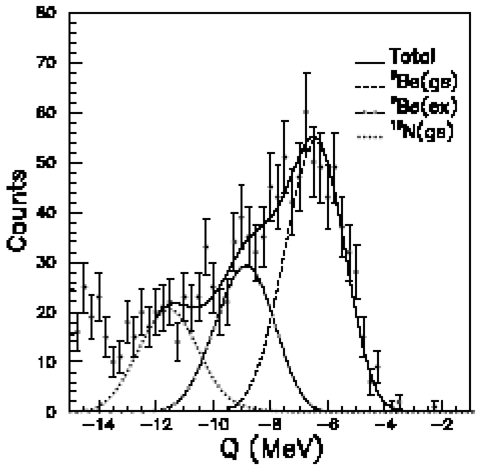
Scale (meters)

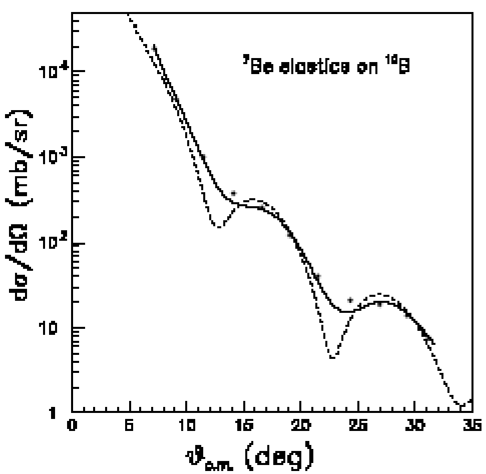
(p,xn), (p,pxn) reactions in inverse kinematics

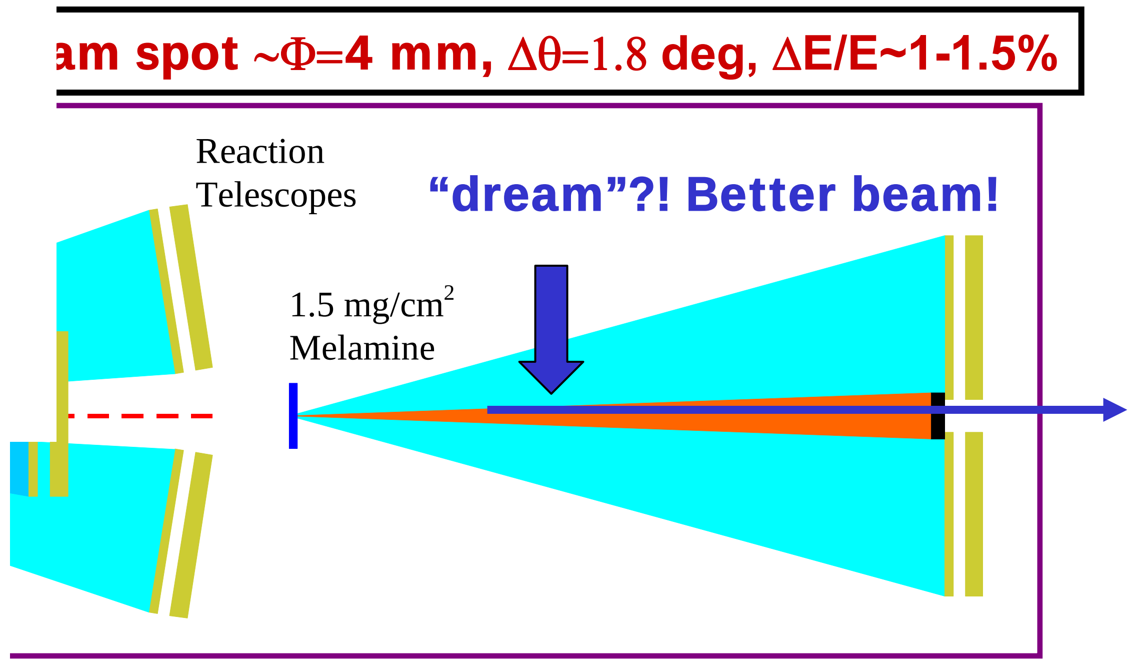
Transfer reactions for ANCs

$^{10}B(^{7}Be,^{8}B)^{9}Be$

$^{14}N(^{7}Be,^{8}B)^{13}C$







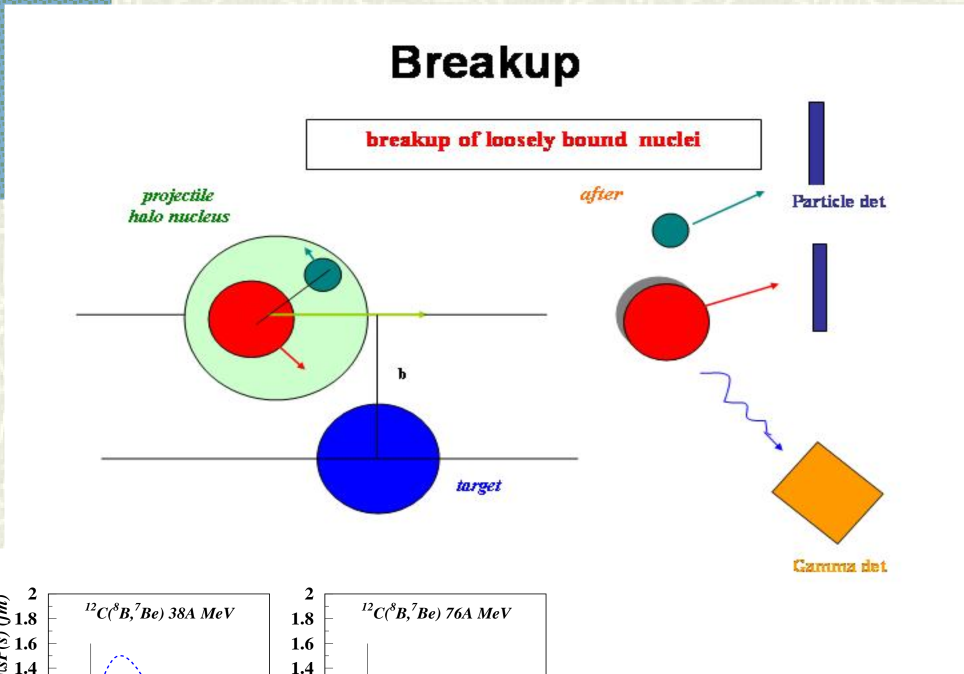
ly Detector: 1 mm Si strip detector

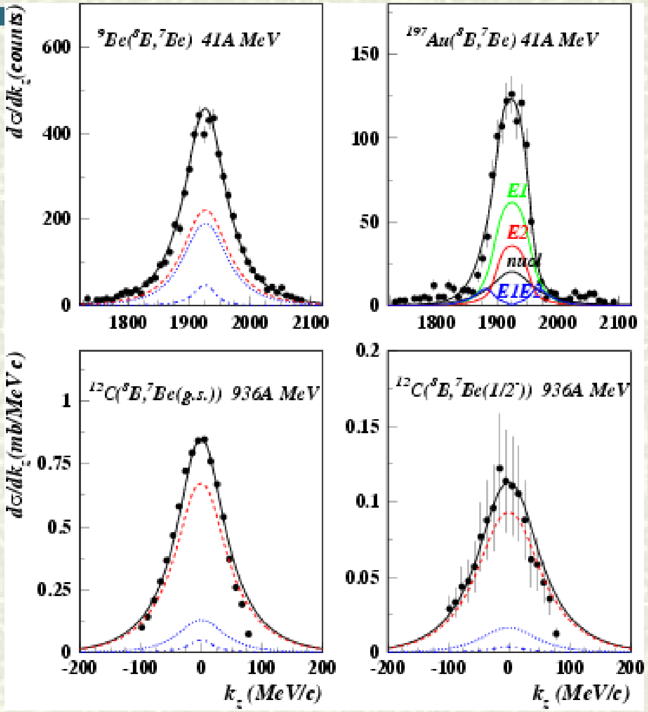
'elescopes:

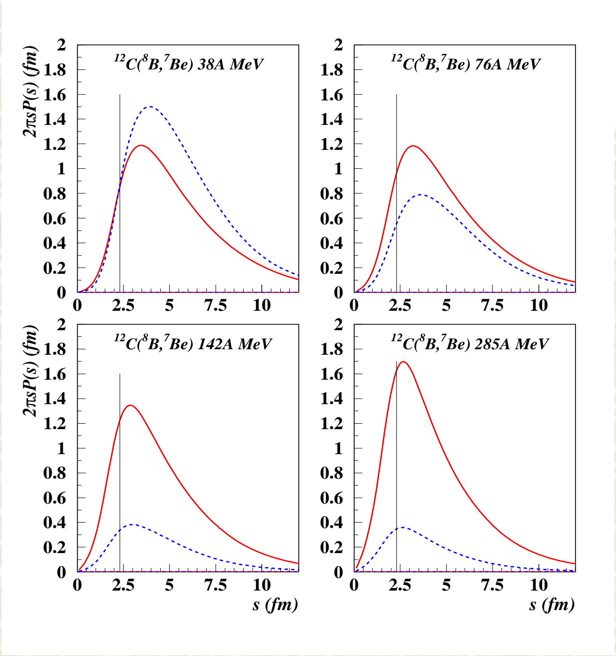
5 μm Si strip detector

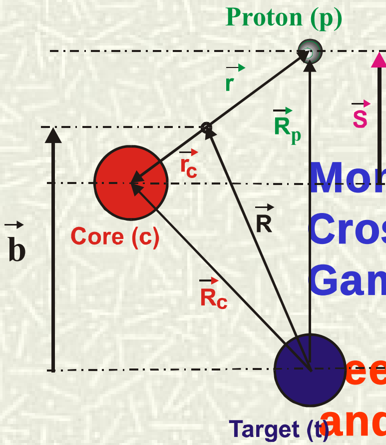
- 1 mm Si detector

C. Breakup (one-nucleon removal r.)









Momentum distributions → *nlj*

Cross section → ANC (only!!!)

Gamma rays → config mixing

Need: $V_{p\text{-}target}$ & $V_{core\text{-}target}$ and reaction mechanism

Calc: F. Carstoiu; Data: see later

Summary of the ANC extracted from ^{8}B breakup with different interactions

Data from:

F. Negoita et al, Phys Rev C 54, 1787 (1996)

B. Blank et al, Nucl Phys A624, 242 (1997)

D. Cortina-Gil e a, EuroPhys J. 10A, 49 (2001).

R. E. Warner et al. – BAPS 47, 59 (2002).

J. Enders e.a., Phys Rev C 67, 064302 (2003)

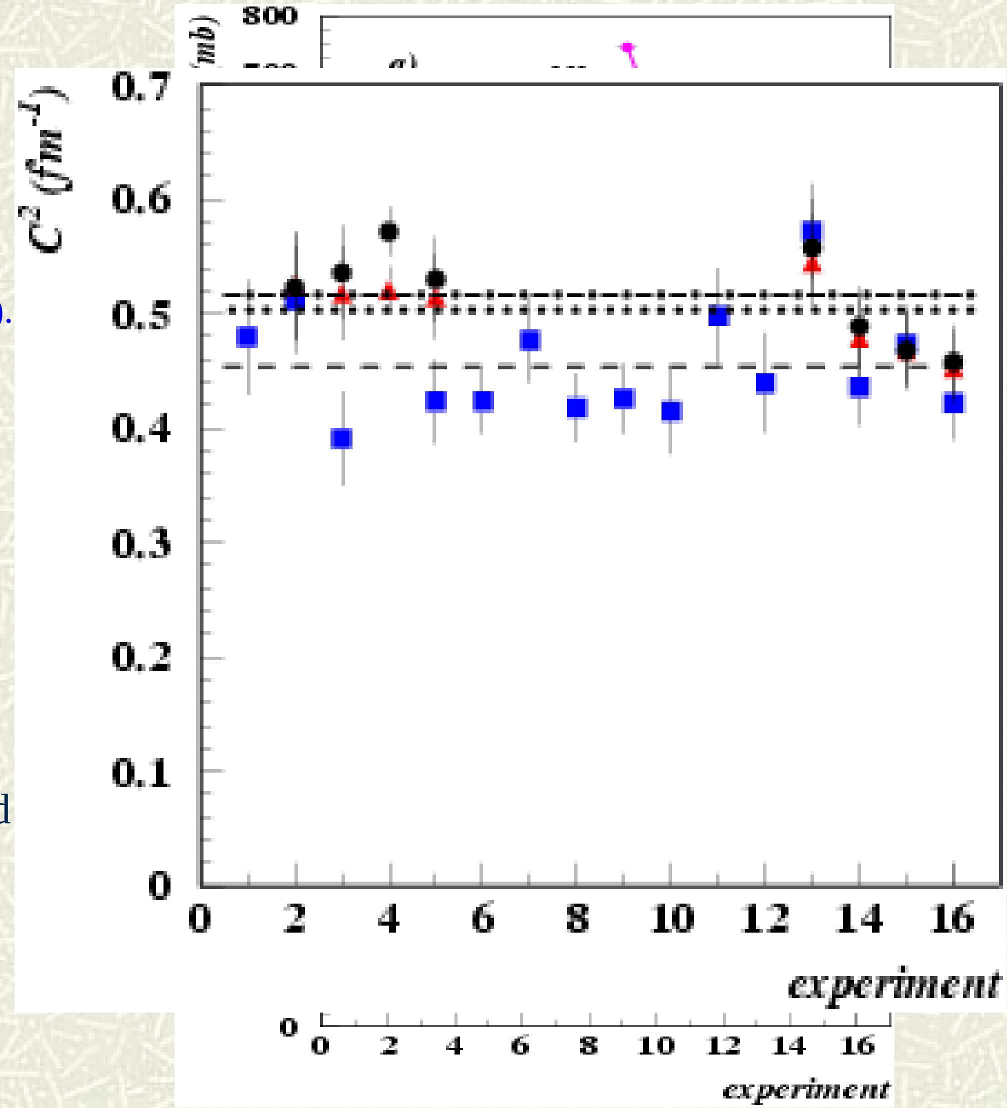
Summary of results:

The calculations with 3 different effective nucleon-nucleon interactions are kept and shown:

JLM (blue squares),

"standard" μ=1.5 fm (black points) and

Ray (red triangles).



S_{17} astrophysical factor (ours)

New: $S_{17}(0)$ = 18.0 ± 1.9 eV•b
(G Tabacaru ea, PRC 73, 2006)

^{8}B breakup

$$S_{17}(0) = \frac{38.6 \text{ eV b}}{\text{fm}^{-1}} \left(C^2_{p3/2} + C^2_{p1/2}\right)$$

- **JLM S_{17}=17.4±2.1 eVb** no weights
- **"standard" S_{17}=19.6±1.2 eVb**
- **Ray S_{17}=20.0±1.6 eVb**

Average all:
C^2_{tot} = 0.483 ± 0.050 fm^{-1}
S_{17}=18.7±1.9 eVb

(all points, no weights)

Published: LT et al.- PRC 69, 2004

For comparison:

- (^{7}Be,^{8}B) proton transfer at 12 MeV/u

A. Azhari e.a. – two targets:

^{10}B $S_{17}(0)$ = 18.4 ± 2.5 eVb (PRL '99)

~~^{14}N $S_{17}(0)$ = 16.9 ± 1.9 eVb (PRC '99)~~

Average: Phys Rev C 63, 055803 (2001)

~~$S_{17}(0)$ = 17.3 ± 1.8 eVb~~

- ^{13}C(^{7}Li,^{8}Li)^{12}C at 9 MeV/u

(LT e.a., PRC 66, June 2003))

C^2_{tot} = 0.455 ± 0.047 fm^{-1}

$S_{17}(0)$ = 17.6 ± 1.7 eVb

New average: $S_{17}(0)$ = 18.2 ± 1.8 eV•b

Neutrinos from Standard Solar Model

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What Do We (Not) Know Theoretically about Solar Neutrino Fluxes?

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(Received 16 December 2003; published 25 March 2004)

conservation). Comparing the measured values with the theoretical predictions, we find for BP04:

$$\phi(pp)_{\mathrm{measured}} = (1.02 \pm 0.02 \pm 0.01)\phi(pp)_{\mathrm{theory}}, \qquad (1)$$

$$\phi(^8\mathrm{B})_{\mathrm{measured}} = (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}}, \qquad (2)$$

$$\phi(^7\mathrm{Be})_{\mathrm{measured}} = (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^7\mathrm{Be})_{\mathrm{theory}}. \qquad (3)$$

In Eqs. (1)–(3), the 1σ experimental uncertainties are

surement error of the ^{8}B neutrino flux is smaller than the uncertainty in the theoretical calculation, but the opposite is true for the p-p and ^{7}Be neutrino fluxes.

used improved values for direct measurements of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section, $S_{20\,\mathrm{keV}}(^7\mathrm{Be}+p) = 20.6 \pm 0.8$ eV b [5], and the calculated p-p, $S_0(pp) = 3.94(1 \pm 0.004) \times 10^{-25}$ MeV b, and hep, $S_0(hep) = (8.6 \pm 1.3) \times 10^{-20}$ keV b, cross sections [6]. The reactions that produce the ^{8}B and hep neutrinos are rare; changes in their production cross sections affect, respectively, only the ^{8}B and hep fluxes. The 15% increase in the calculated ^{8}B neutrino flux, which is primarily due to a more accurate cross section for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$, is the only significant change in the best estimate fluxes.

future work, ino fluxes on cross section measured to better than ±5% (1σ) (a factor of 2 improvement) in order that the uncertainty in this reaction not limit the interpretation of future ^{7}Be solar neutrino experiments.

Using our value(s): $S_{17}(0) = 18.7 \pm 1.9$ eVb => $S_{17}(20) = 18.0$

$\mathbf{\Phi_{exp}(^8B) = [1.03 \pm 0.08 \pm 0.23]\ \Phi_{th}(^8B)}$

Conclusions – "other methods"

- Useful to have various methods/tools at hand
- Medium size facilities useful:
  - may get things done sooner and cheaper!
  - Valuable for (hands-on) education of students and postdocs!
  - Competition is healthy and necessary!

Nuclear physics for astrophysics. Summary

Indirect methods

- transfer reactions (proton or neutron)
  - E ~ 10 MeV/nucleon
  - Better beams (energy resol, emittance)
  - Magnetic spectrometers at 0° – resolution, large acceptance, raytrace reconstr.
- breakup
  - ~ 30-100 MeV/nucleon
  - Can neutron breakup be used for (n,γ)?! (yes, but need n-nucleus potentials)
- Spectroscopic info
  - J^{π}, E_{res}, Γ, (masses, etc…) – a variety of tools at hand
  - Resonant elastic scattering: E<10 MeV/nucleon. H_2 and He targets.
  - Better models: structure and reaction theories
- Need more checks between indirect methods and direct measurements!
- Better models/data to predict OMP, make Glauber calc, spectroscopy…

Direct methods: inverse kinematics measurements on windowless gas targets with direct detection of product (magnetic separation). E=0-5 MeV/nucleon. All nucleonic species.

K150 Beam Lines