Nulcear Astrophysics in laser deriven gamma-ray pulse

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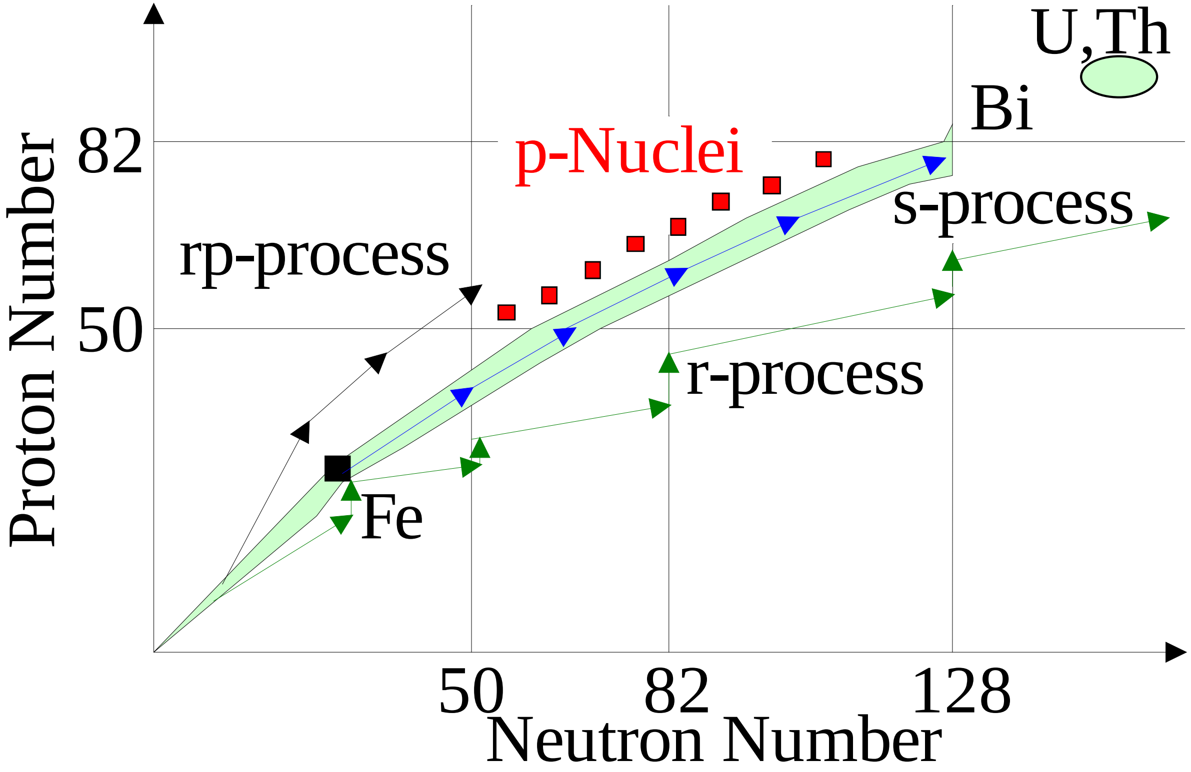
Contents

- Theoretical background of nuclear astrophysics
- Interaction between photon and nucleus
- The role of the photo-induced reaction for stellar nucleosynthesis
- Proposals for nuclear astrophysics experiments using laser driven gamma-ray pulse.

T. Hayakawa, et al. Quantum Beam Science, 1(1), 3 (2017).
“Explosive Nucleosynthesis Study Using Laser Driven *γ*-ray Pulses”

Nucleosynthesis



About 99 % of heavy element

r-Process   rapid neutron capture

site : supernova explosion

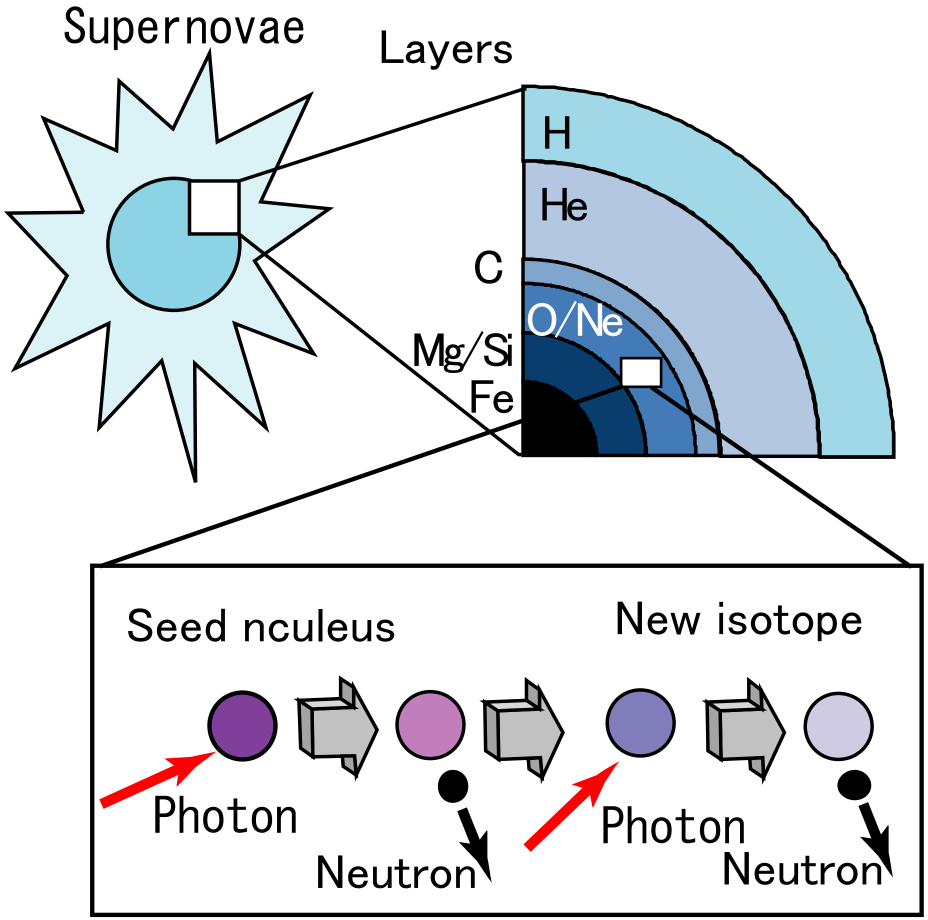
s-Process slow neutron capture

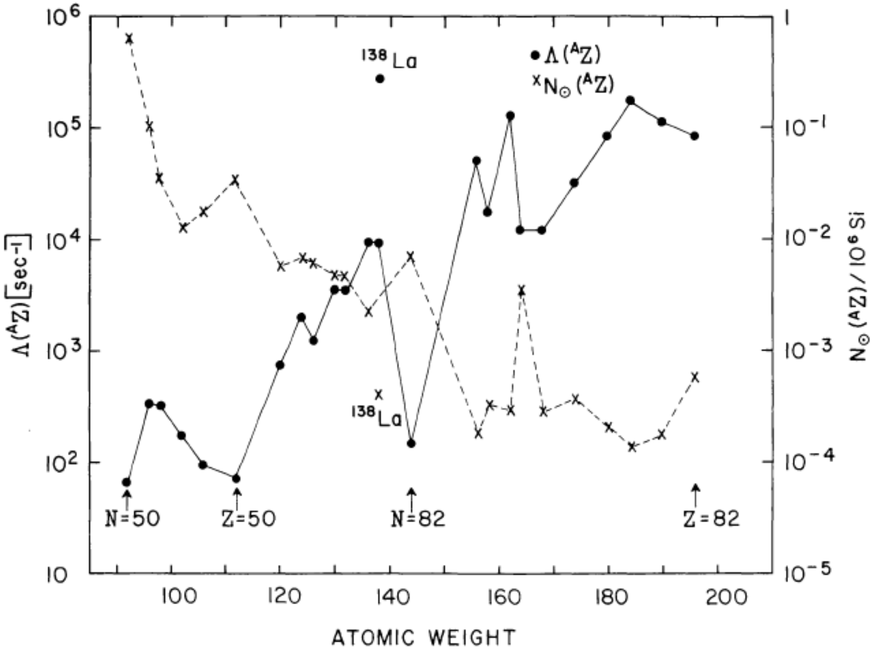
site: AGB stars,   massive star

gamma-Process: most p-nuclei are synthesized by gamma-process.

Gamma-process

Supernova explosion: S.E. Woosley et al., ApSJ 36, 285 (1978)





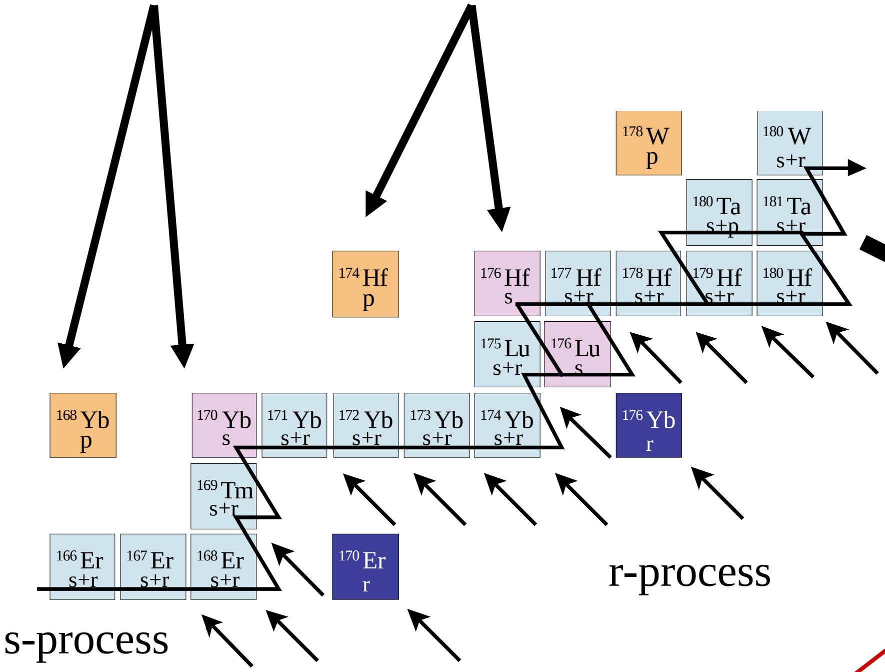
Anti-correlation between the reaction rate and the solar abundances

This is first evidence for p-nucleus origin in supernovae

Discovery of the empirical scaling law

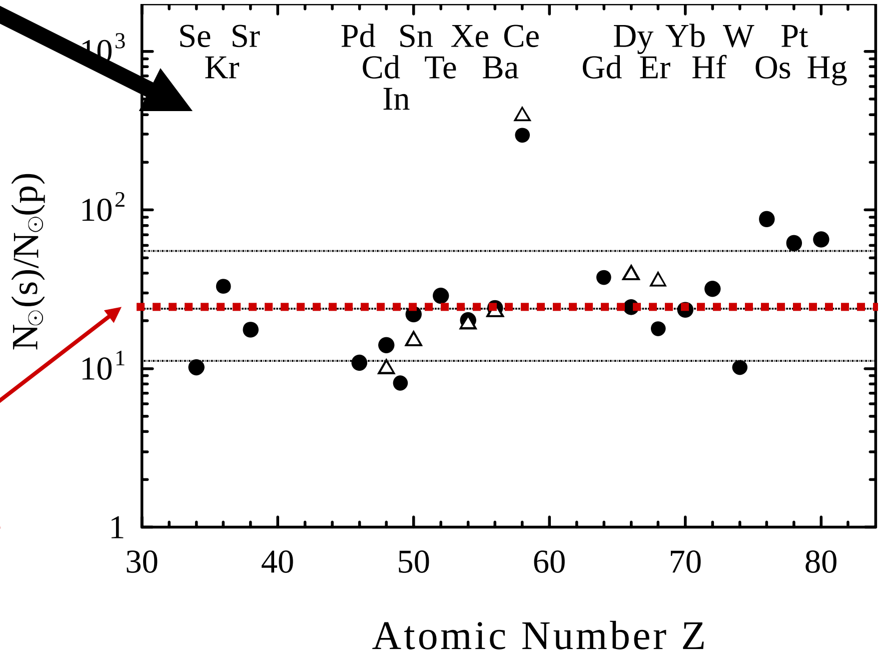
T. Hayakawa et al., Phys. Rev. Lett. 93, 161102, (2004).

27 pairs of s- and p-nuclei



Taking N(s)/N(p) taios,
where N is the isotope abundance.

For example, the ratio of ^{134}Ba (2.417%) to ^{132}Ba (0.101%) is 23.9.

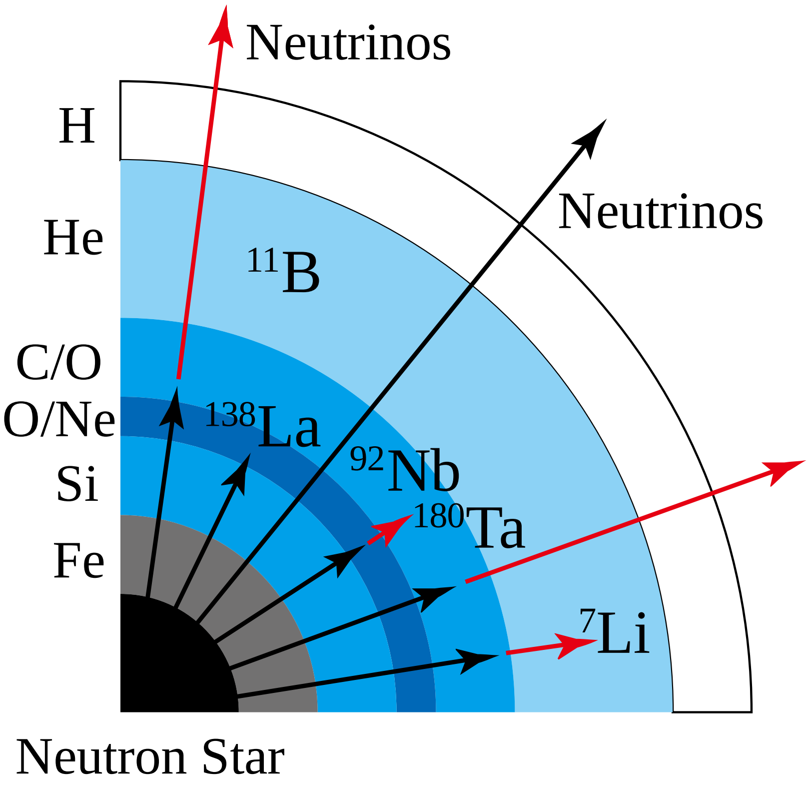


The ratios are almost constant

This the second evidence of supernova gamma-process

Supernova neutrino-process

S.Woosley, ApJ (1990) has proposed supernova neutrino-process as the origin of several heavy isotopes.



A. Heger, PLB (2005)

Calculate synthesis of ^{11}B, ^{19}F, ^{138}La, ^{180}Ta but ^{180}Ta can not be reproduced.

^{7}Li、^{11}B、T. Yoshida, PRL (2005,2006)

Synthesis, neutrino energy spectra

^{138}La, T. Hayakawa, PRC (2008, 2009)

Possibility of isomer

^{180}Ta, T. Hayakawa, PRC (2010a, 2010b)

Reproduced both of 138La and 180Ta

^{92}Nb, T. Hayakawa, ApJL (2013)

Origin of 92Nb in meteorites

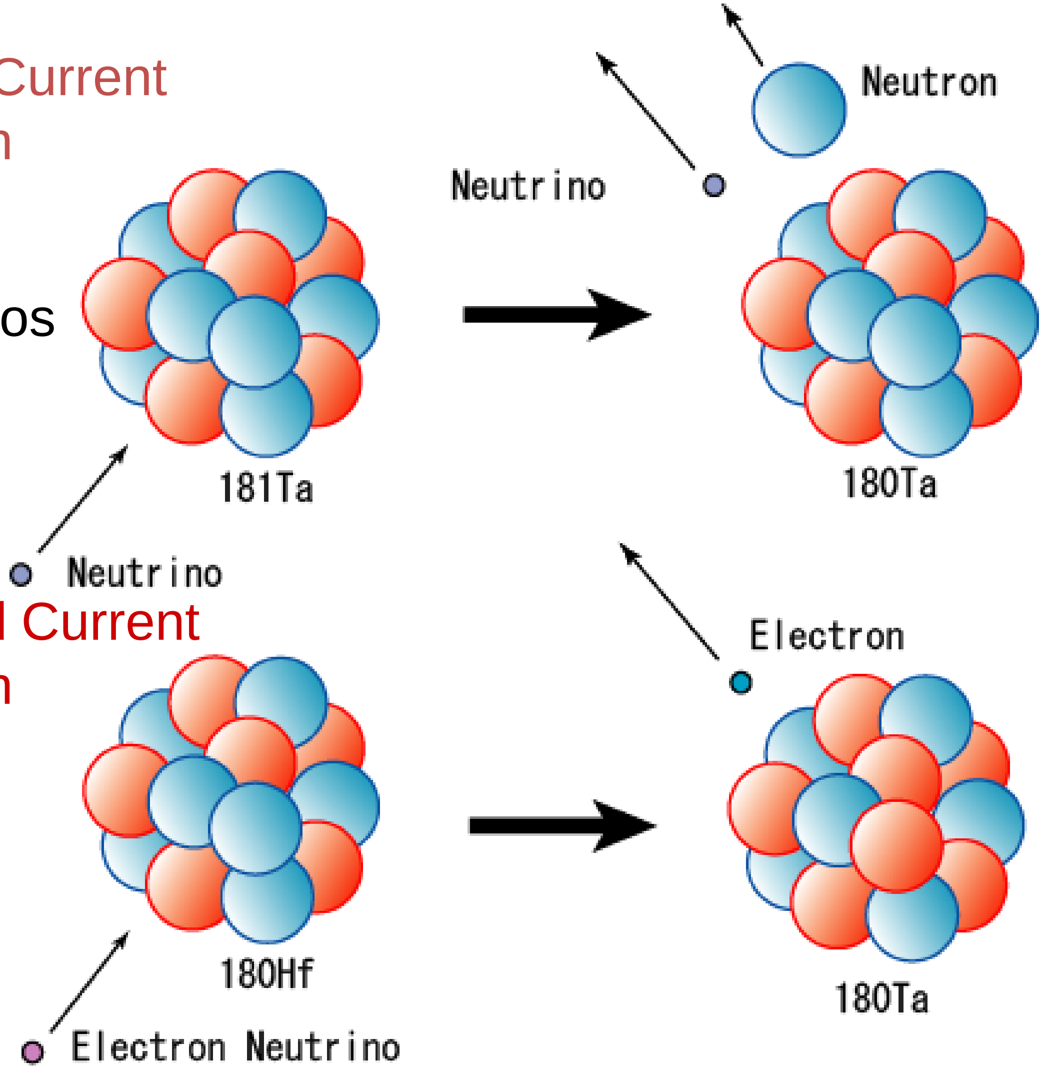
Neutrino-Nucleus Reactions

Neutral Current Reaction

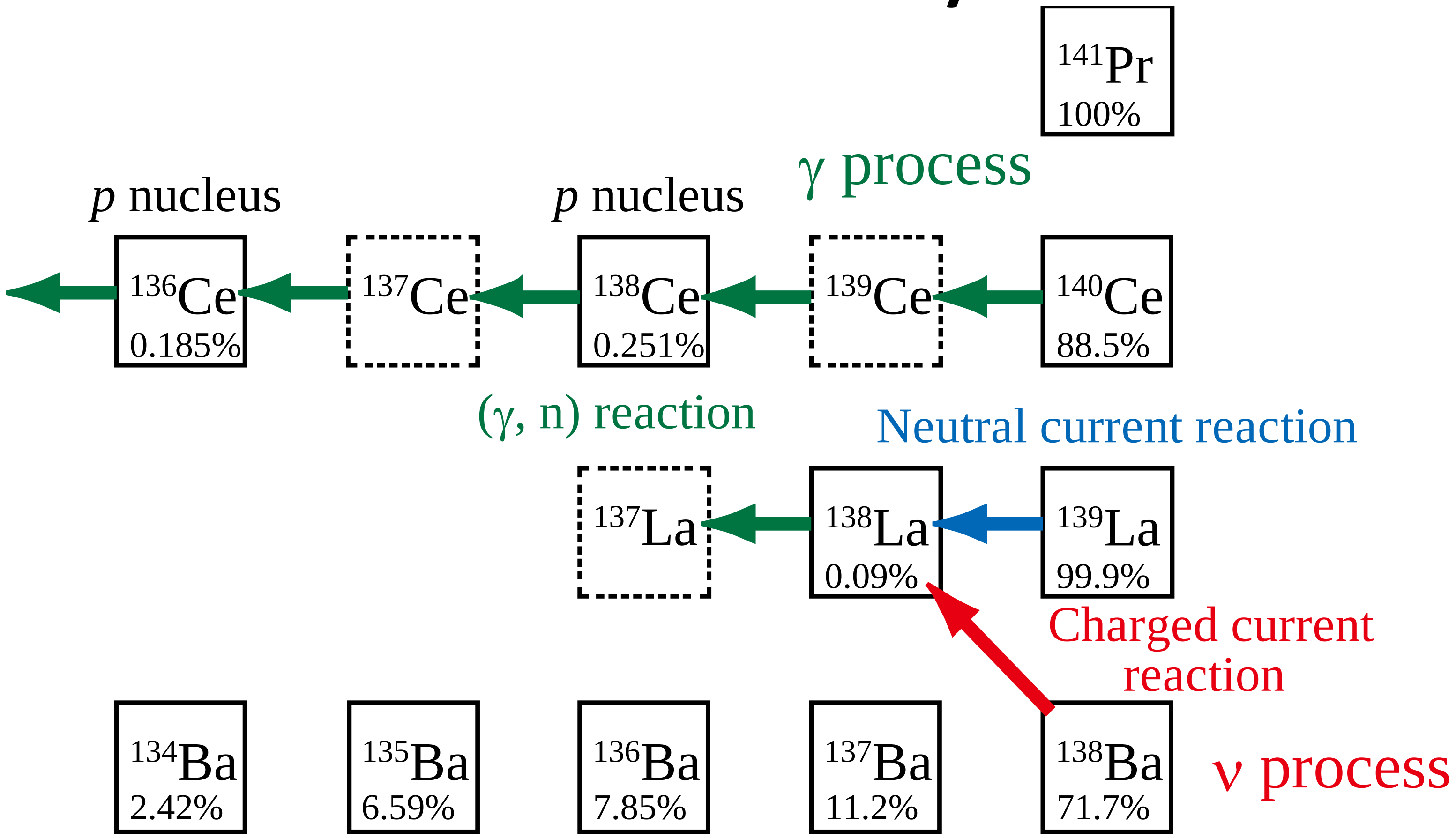
All Neutrinos

Charged Current Reaction

Electron Neutrino

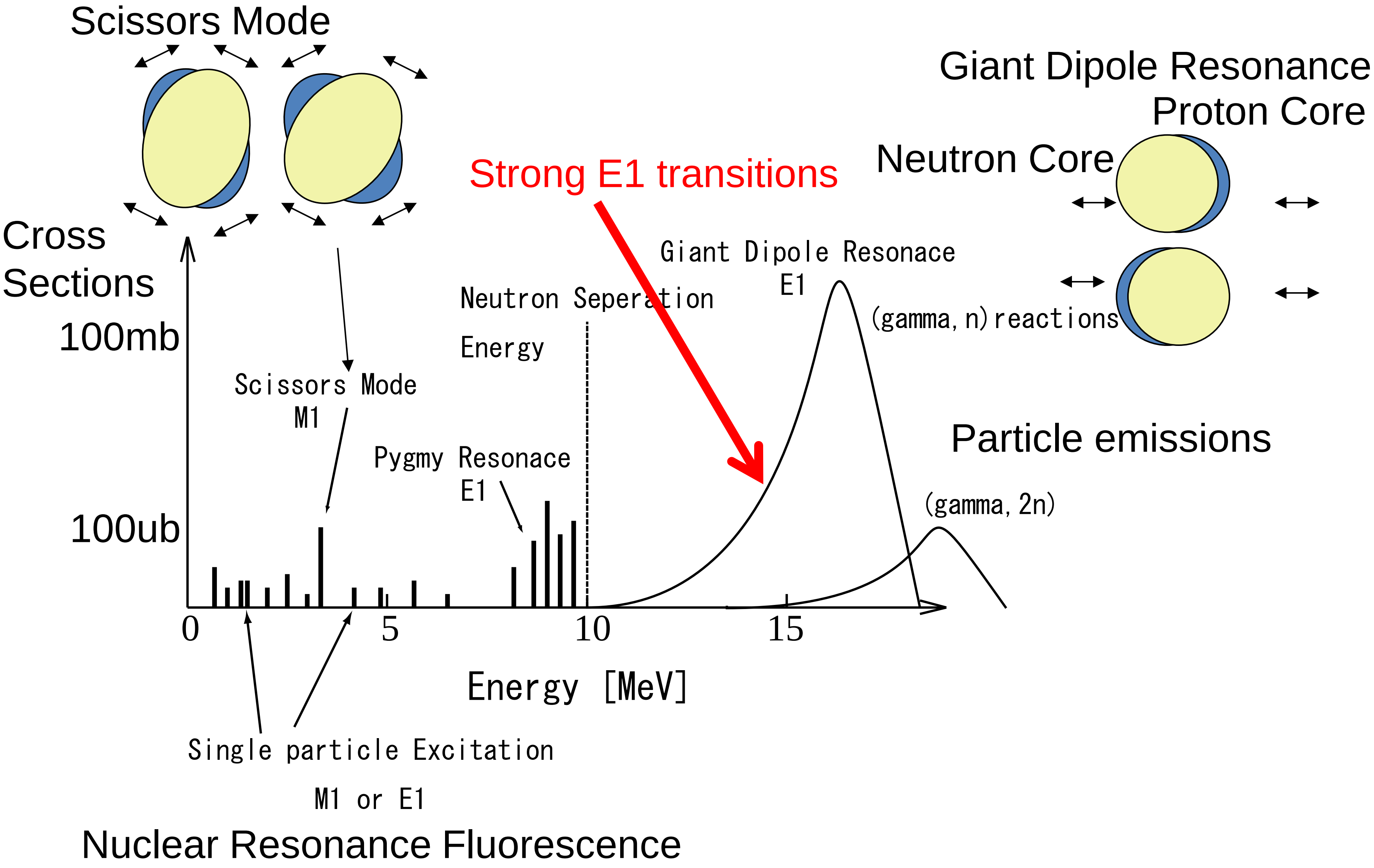


Flow of nucleosynthesis



Gamma-rays have important roles for gamma and neutrino processes.

Interaction between Photons and Nuclei



Scissors Mode

Giant Dipole Resonance

Proton Core

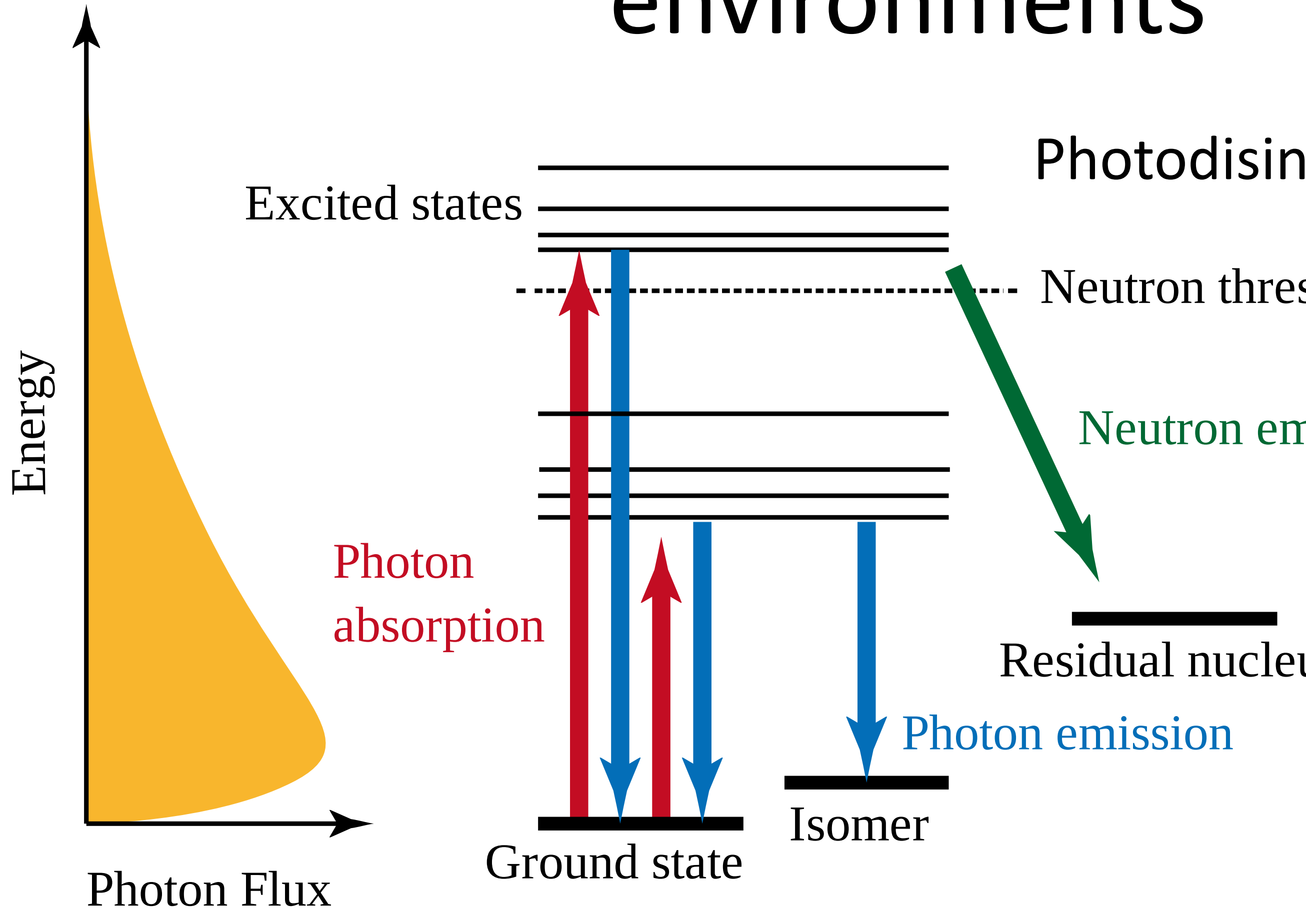
Neutron Core

Strong E1 transitions

Particle emissions

Nuclear Resonance Fluorescence

Interaction between nuclei and photons in hot temperature environments

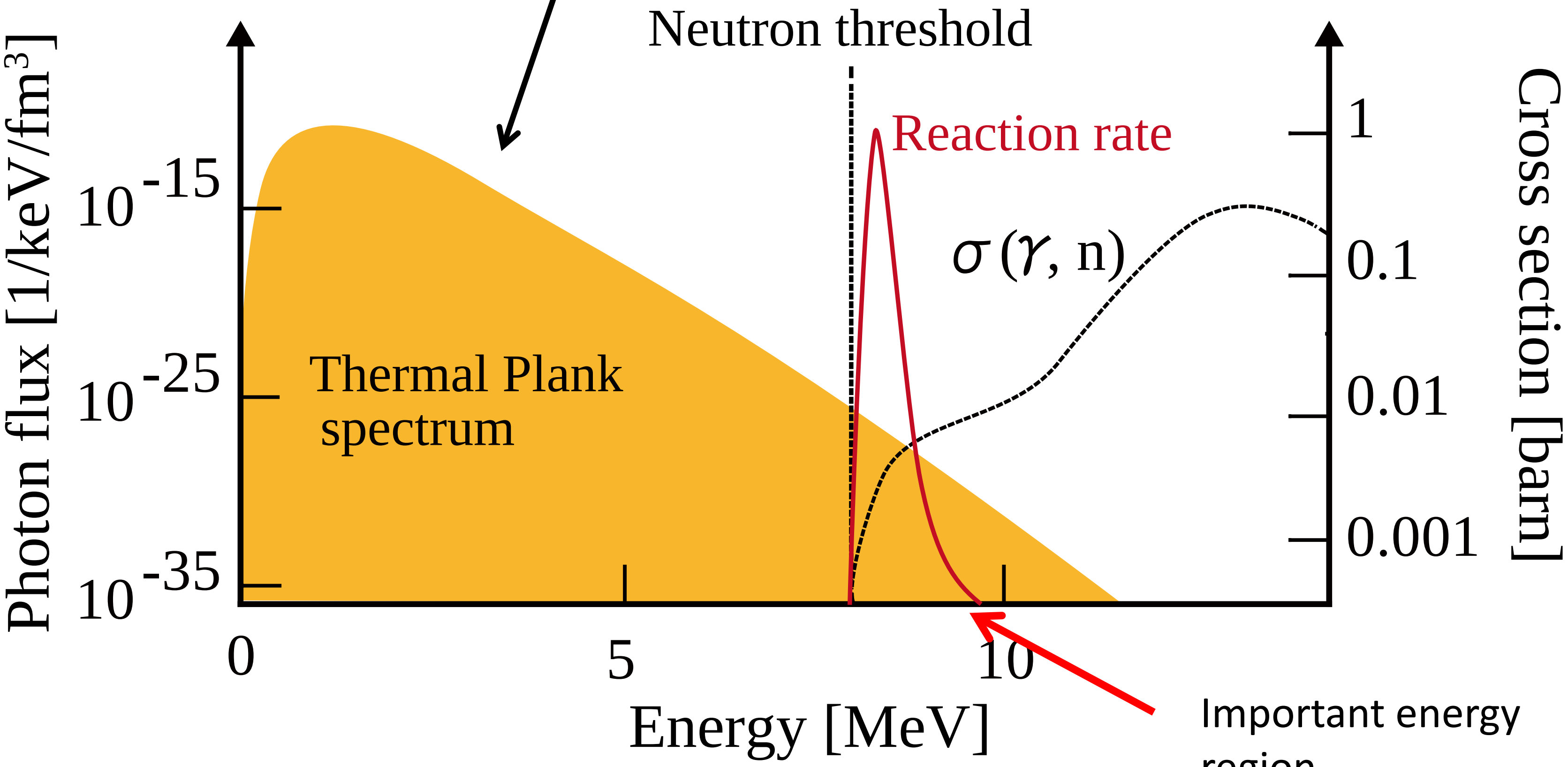


Nuclear Astrophysics

$$n_\gamma(E,T) = \left(\frac{1}{\pi}\right)^2 \left(\frac{1}{\hbar c}\right)^3 \frac{E^2}{\exp(E/kT)-1}$$

Supernova: kT = 10^9 K ~ 100 keV

Nova: kT = 10^8 K ~ 10 keV



Important energy region

Cross section measurements

Photo-Nuclear Reaction rate

光核反応率

$$\lambda(T)=\int_0^\infty \underline{c n_\gamma(E,T)}\,\underline{\sigma_\gamma(E)}\,dE$$

光子数 プランク分布

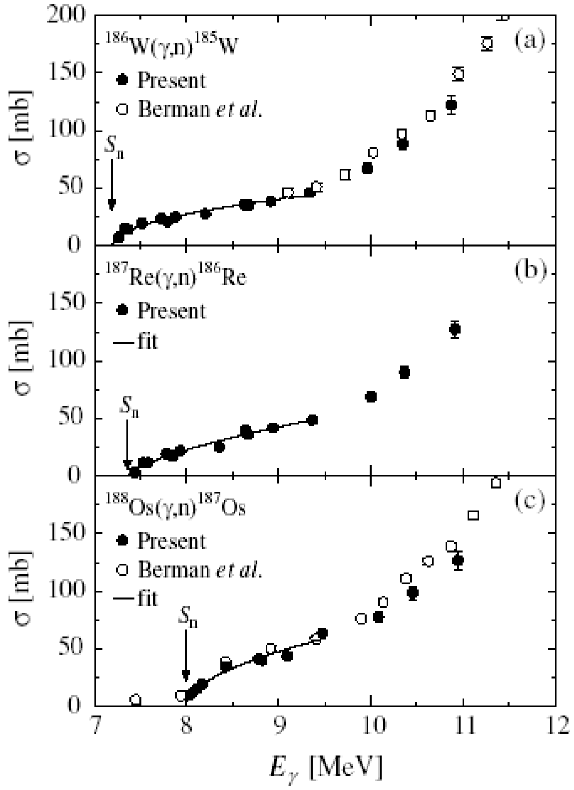
$$\left(\frac{1}{\pi}\right)^2\left(\frac{1}{\hbar c}\right)^3\frac{E^2}{\exp(E/kT)-1}$$

T=1〜3×10^{8}K

光核反応
断面積

Cross section

The cross section has been measured as a function of energy with monochromatic beam



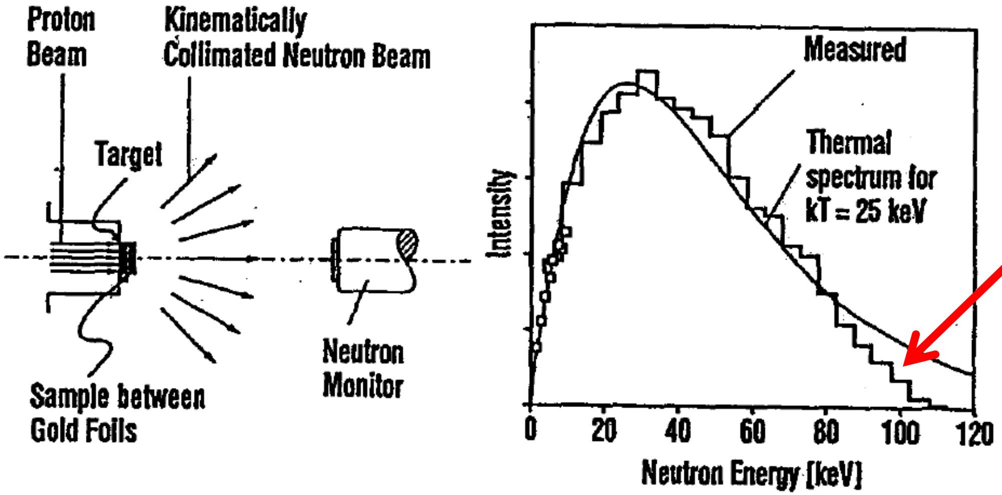
T. Shizuma, Phys. Rev. C, 72, 02580 (2005)

Using laser Compton scattering gamma-rays

In stars, the integrated reaction rate is essential physics input.

Direct measurement of integrated reaction rate

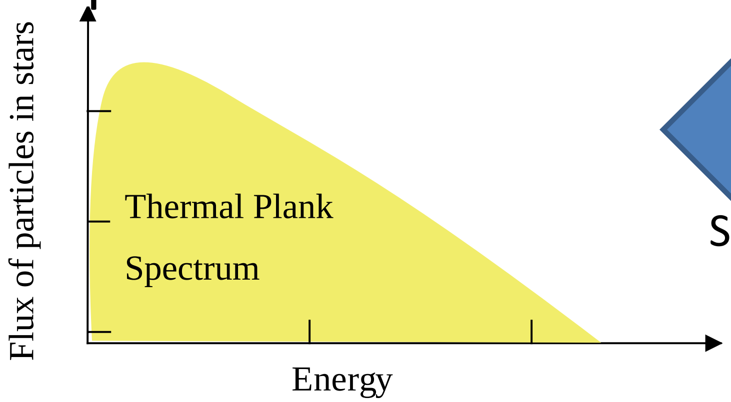
Neutrons



The neutron beam which energy distribution is similar to stellar one.

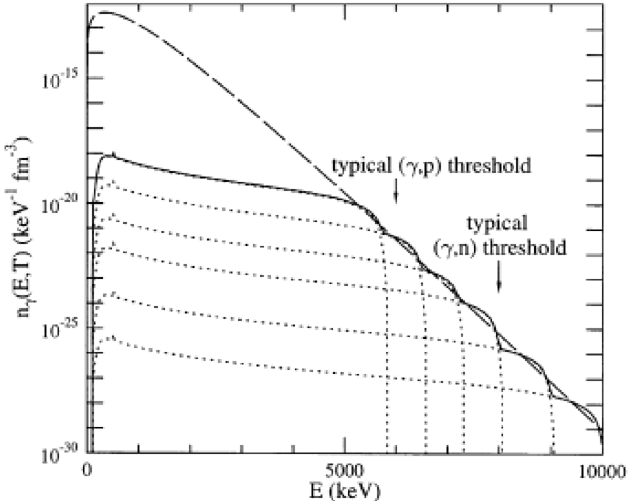
Neutrons are generated by (p, n) reactions
The energy is tuned by absorber and scattering angles

Stellar photon distribution



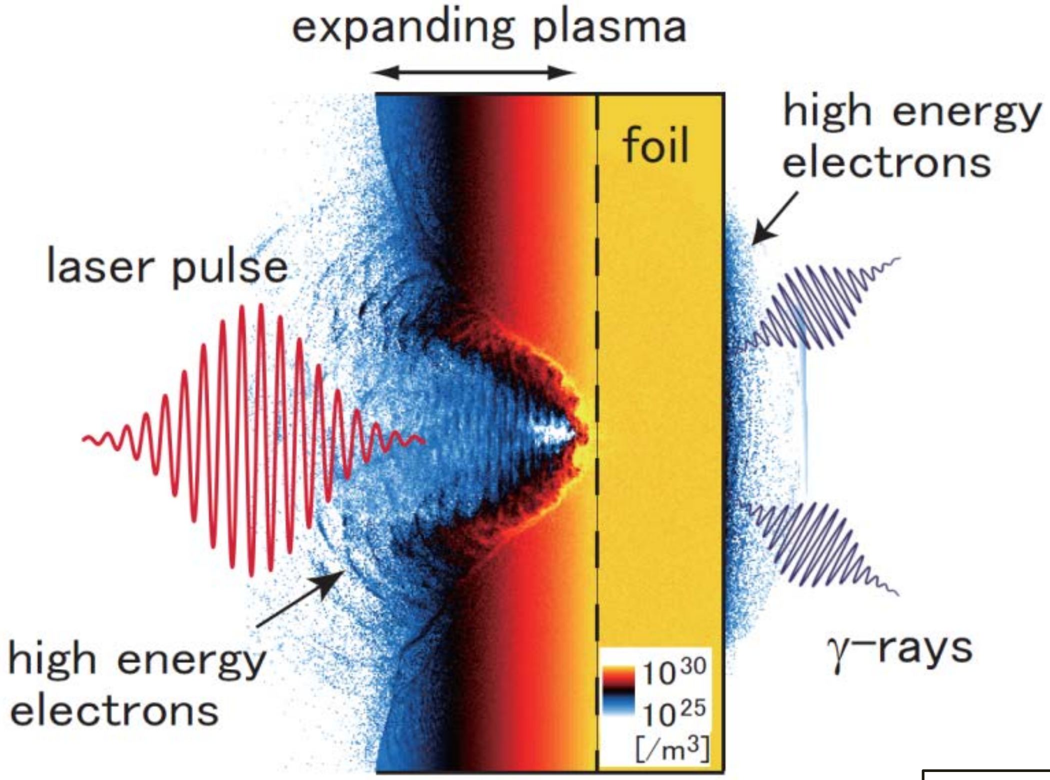
Simulation

Sum of Bremsstrahlung with different energies
Mohr, PLB, 2000



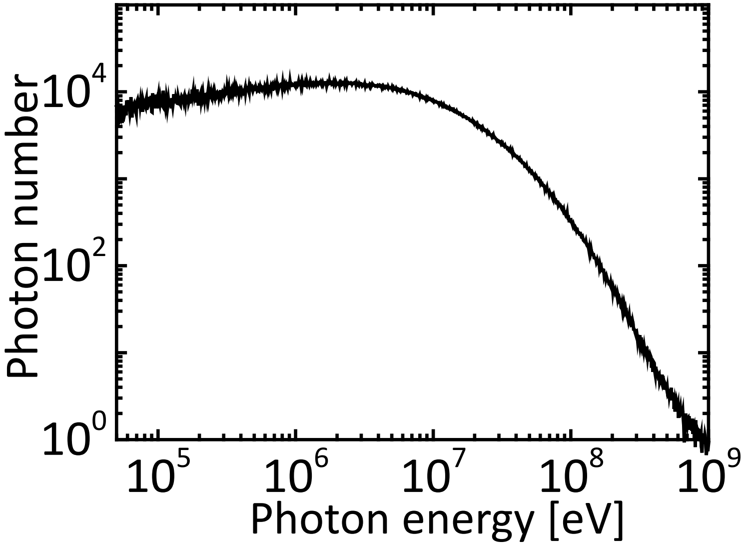
Proposal of direct measurement of photo-nuclear reaction rate in stars

Laser-driven γ-ray source via radiation reaction effect



Calculated by T. Nakamura

Energy spectrum



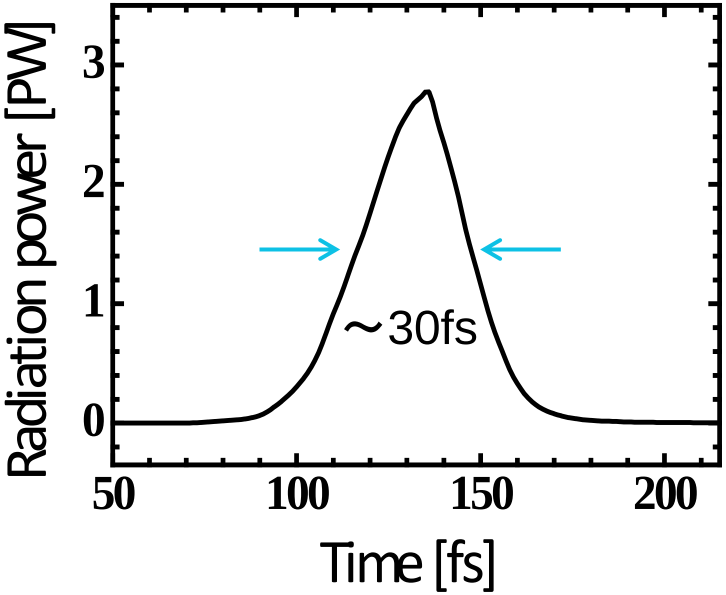
Target
- carbon foil 2g/cc
- (fully ionized)
- thickness 10 μm
- scale lenght 2.5 μm

Laser pulse
- power 10 PW
- duration 30 fs
- energy 300 J
- intensity 5×10^{22} W/cm^2
- wavelength 0.8 μm
- polarization P−pol. (in y)

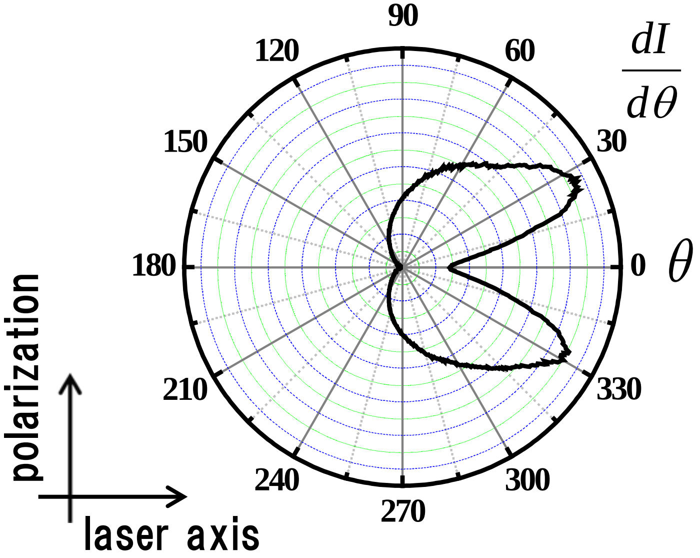
Laser-driven γ-ray beam is intense, short and well-collimated

Calculated by T. Nakamura

γ-ray power



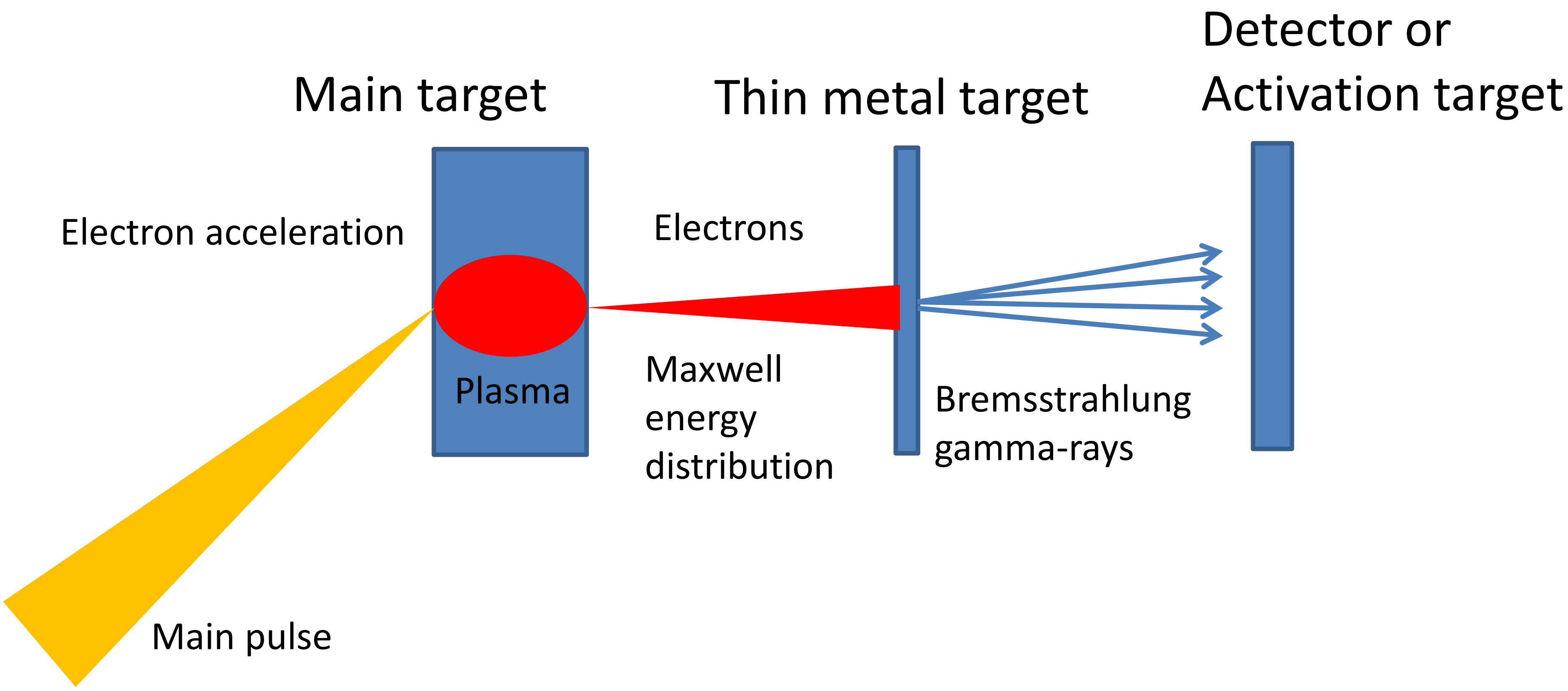
γ-rays angular distribution



Estimated photon number is ～ 10^{14}

γ-ray transport becomes imoprtant for understanding laser-plasma interactions

Bremsstrahlung by Maxwell distribution electrons



Detector or
Activation target

Main target

Thin metal target

Electron acceleration

Electrons

Plasma

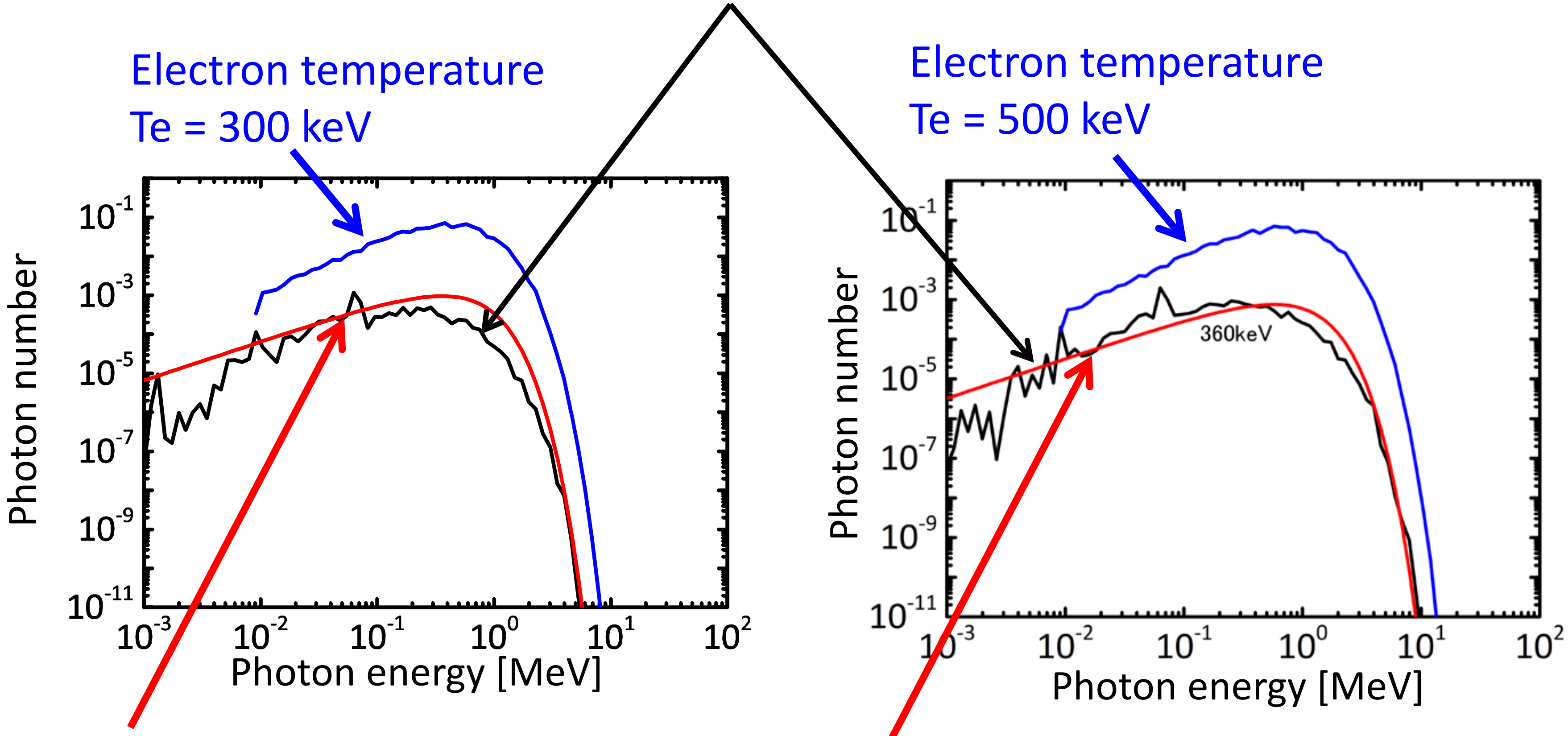
Maxwell
energy
distribution

Bremsstrahlung
gamma-rays

Main pulse

Calculated gamma-ray energies

Generated Bremsstrahlung gamma-rays



Electron temperature

Te = 300 keV

Electron temperature

Te = 500 keV

Planck Distribution of T = 225 keV

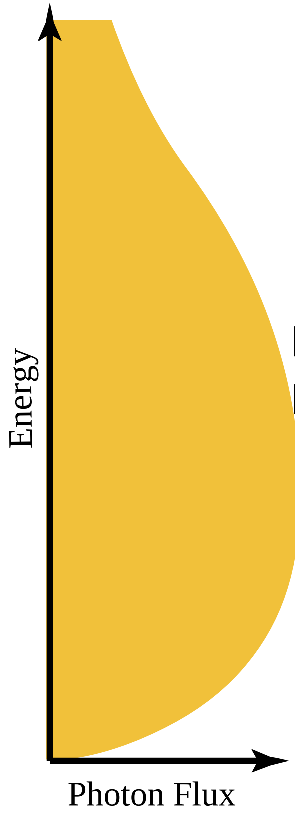
Planck Distribution of T = 360 keV

Calculated with Phits by T. Nakamura

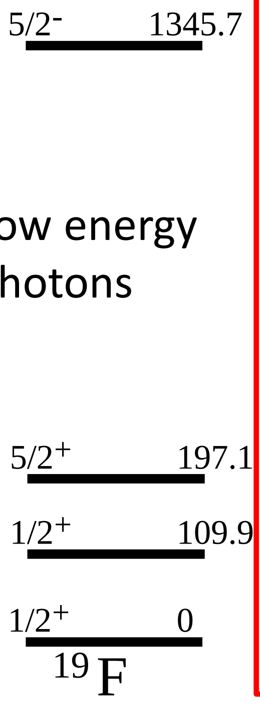
Cross section on excited states

Stellar reaction rate

Initial condition



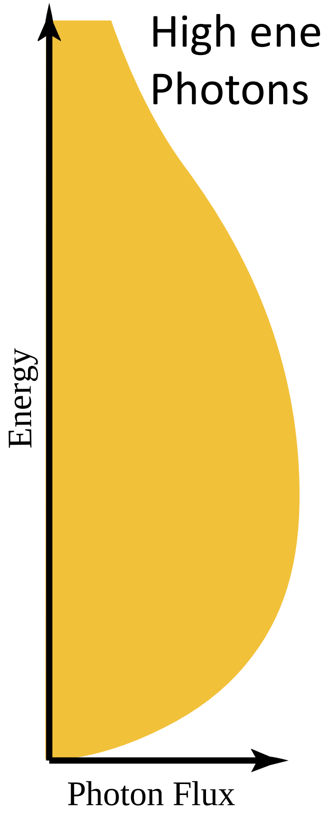
Low energy
Photons



	1×10^9K	3×10^9K
5/2- 1345.7	0.0%	0.5%
5/2+ 197.1	19%	45%
1/2+ 109.9	18%	21%
1/2+ 0	63%	32%

Excited states are
populated by photons

Photo-
nuclear
reactions

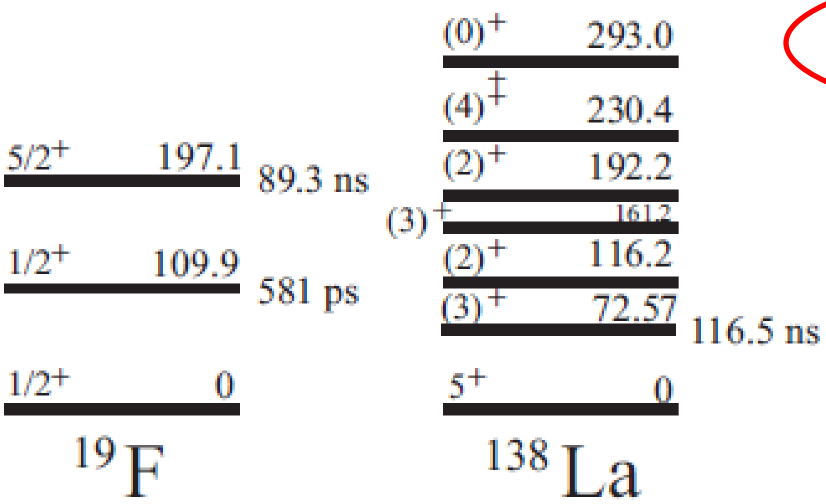


High energy
Photons

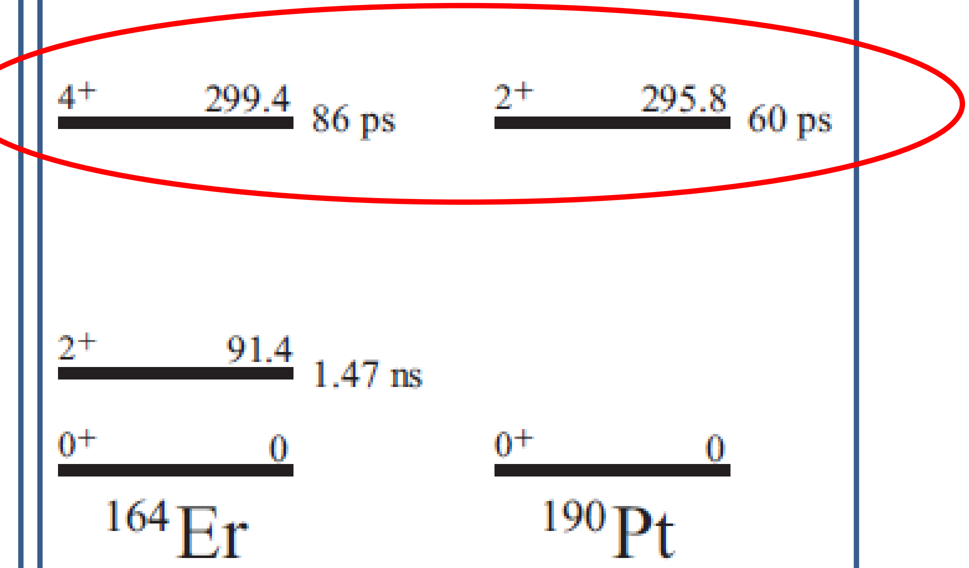
We should calculate the photonuclear reaction rate at excited states

Candidates

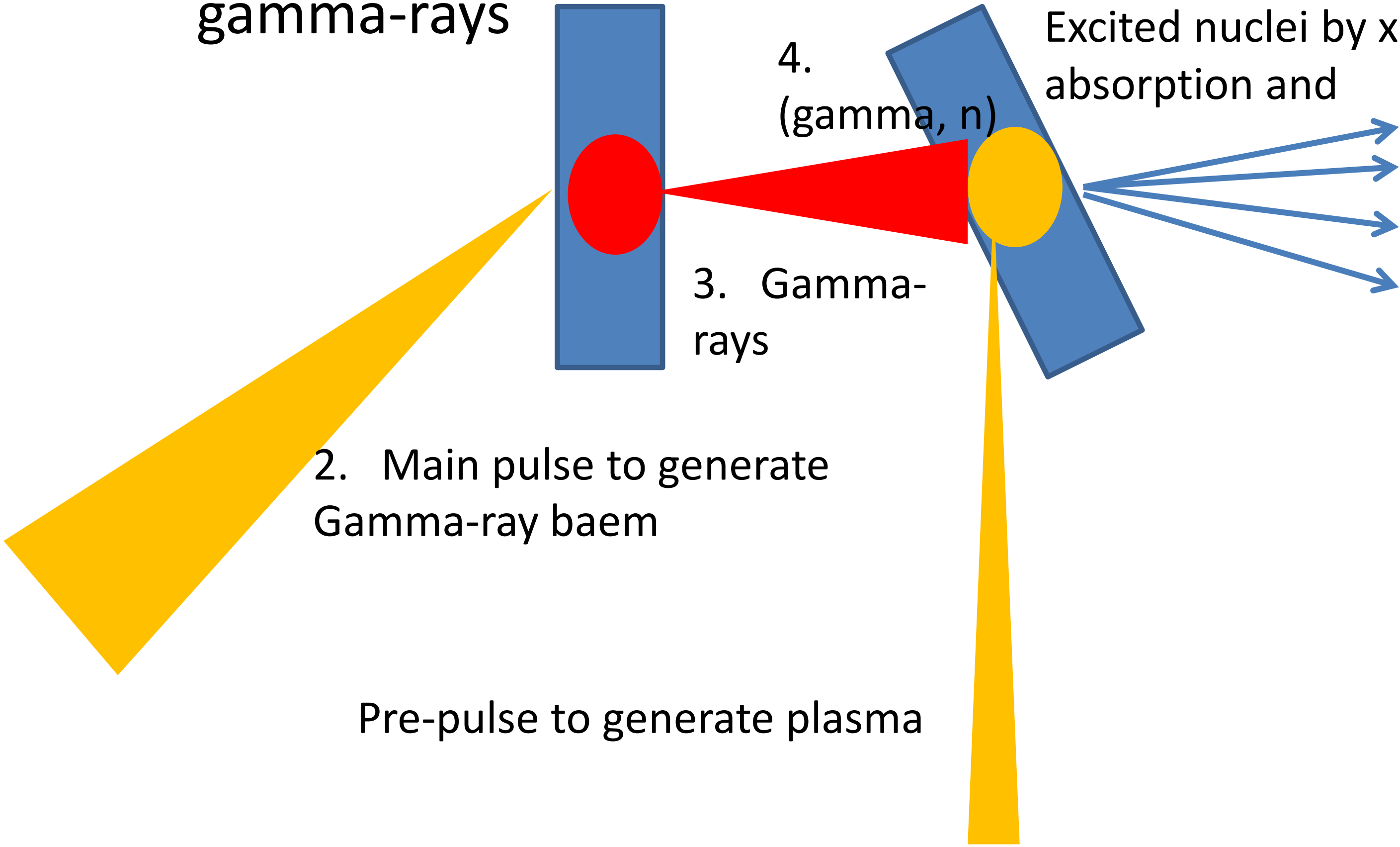
Neutrino process



Gamma process



Two-pulse method by Kotaki-san



Main target to generate gamma-rays

Isotope target of astrophysical interest

4. (gamma, n)

Excited nuclei by x-ray absorption and

5. Neutron, proton, etc.

3. Gamma-rays

2. Main pulse to generate Gamma-ray baem

Pre-pulse to generate plasma

Estimation by Nakamura-san

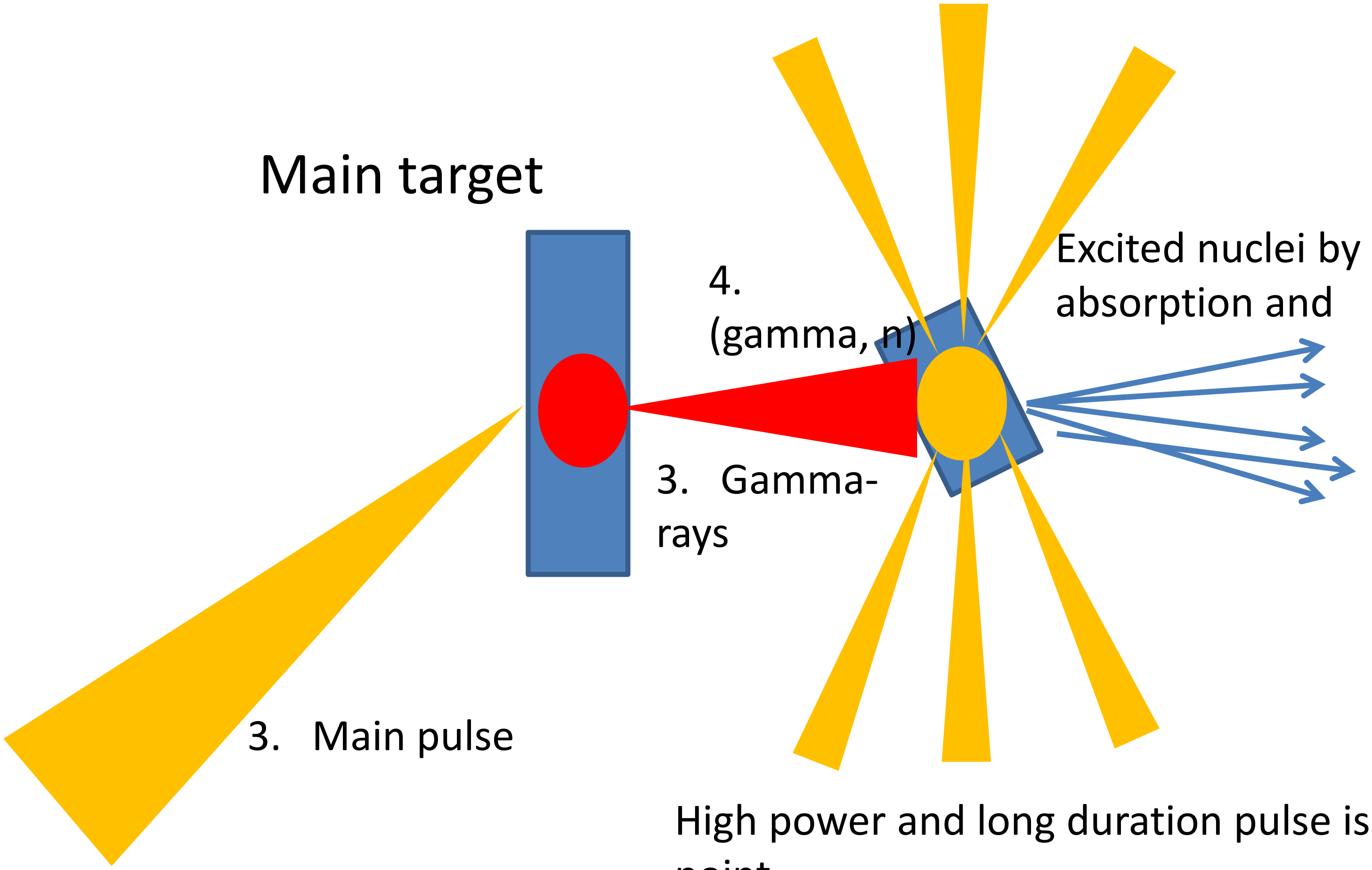
The excited state at 109 keV has a half-life of 0.59 ns. If the life of the plasma is long than 0.59 ns, this state can be populated.

When the target absorb the laser pulse with an energy of 1 J, the life of the plasma with L = 10 um and electron density of 10^24 and an average energy of 100 keV, the life of the plasma is approximately 100 fs.

0.59 ns is too long

We need a pre-pulse with pulse width longer than ns.

Experiment using fusion laser



Main target

4. (gamma, n)

Excited nuclei by x-ray absorption and

3. Gamma-rays

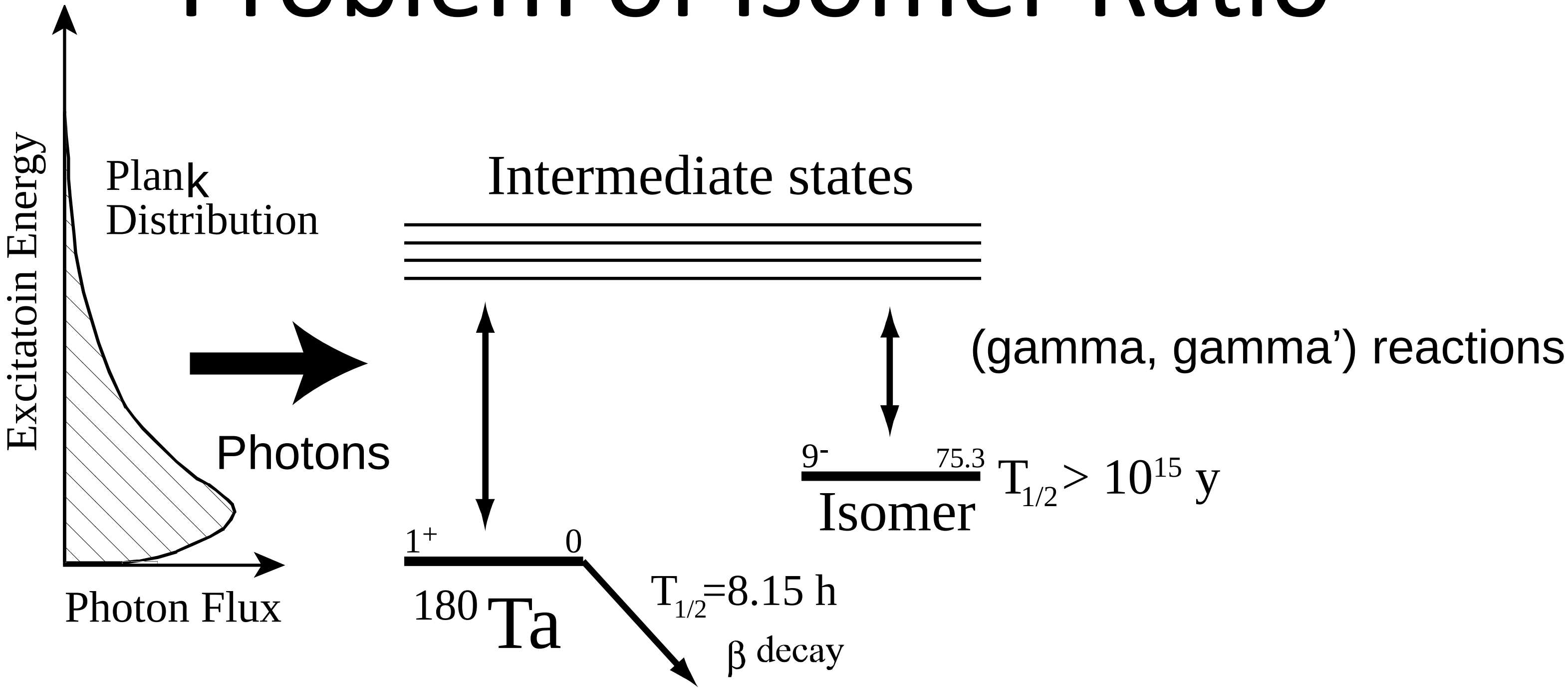
5. Neutron, proton, etc.

3. Main pulse

High power and long duration pulse is a key point.

Transition probability between the ground state and isomer

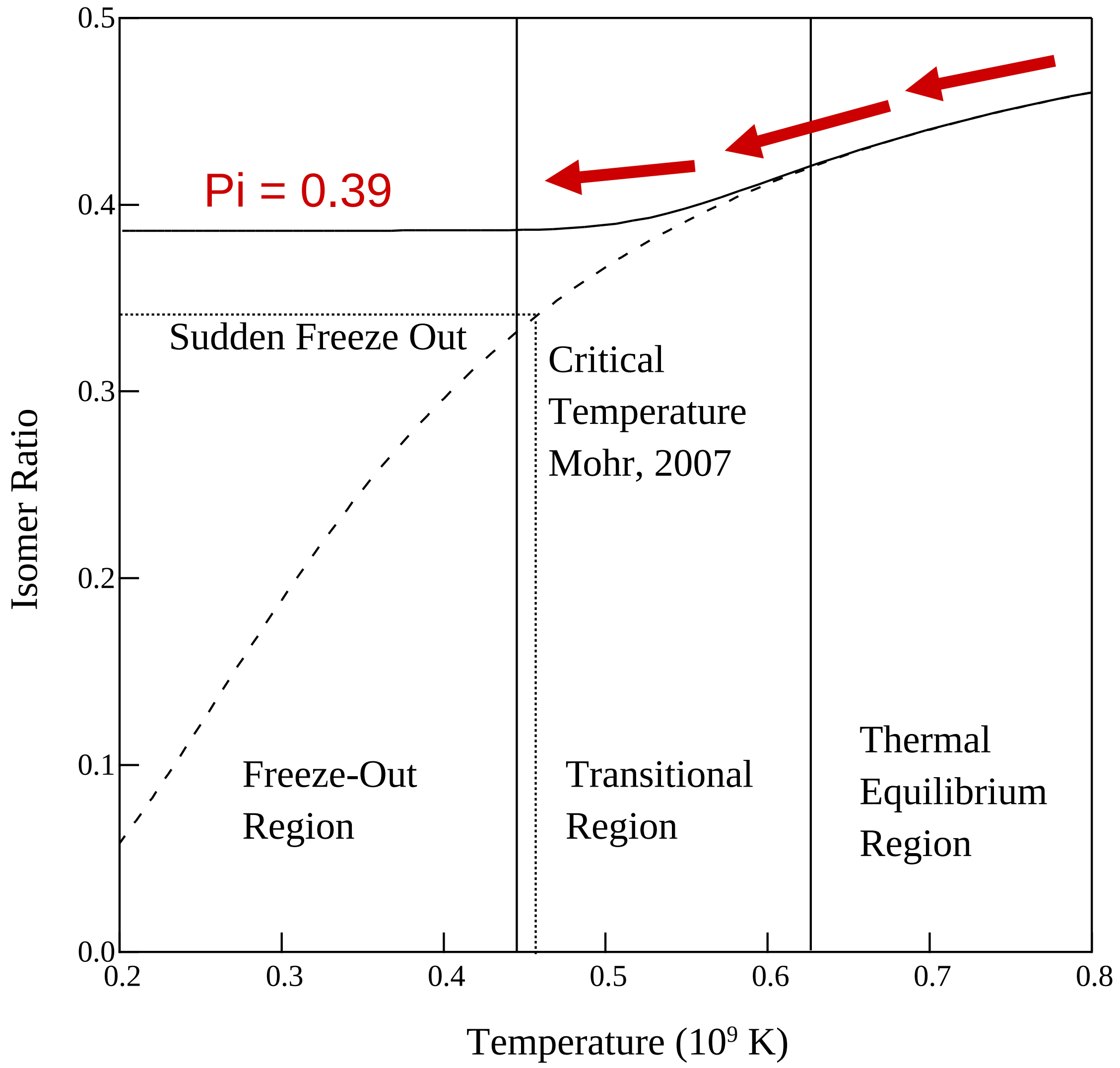
Problem of Isomer Ratio



- The two states are linked by (gamma,gamma') reactions.
- Transition rate is determined by the temperature.
- The isomer residual ratio depends on the change of the temperature.

Previous two studies (Heger, 2005, Byelikov, 2007) pointed out that they can not calculate ^{180}Ta abundance until the isomer residual ratio is determined.

Time-dependent isomer ratio



T = exp(-t / τ)

τ =1s

Init : T9 = 1.0

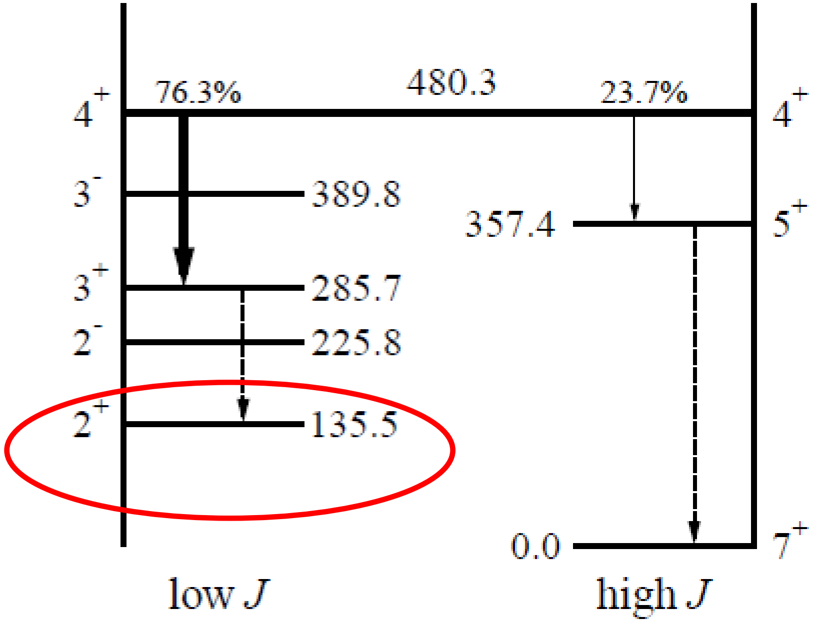
We perform the time-dependent calculations.

In the cases of τ =0.3 or 3 s, results are almost same.

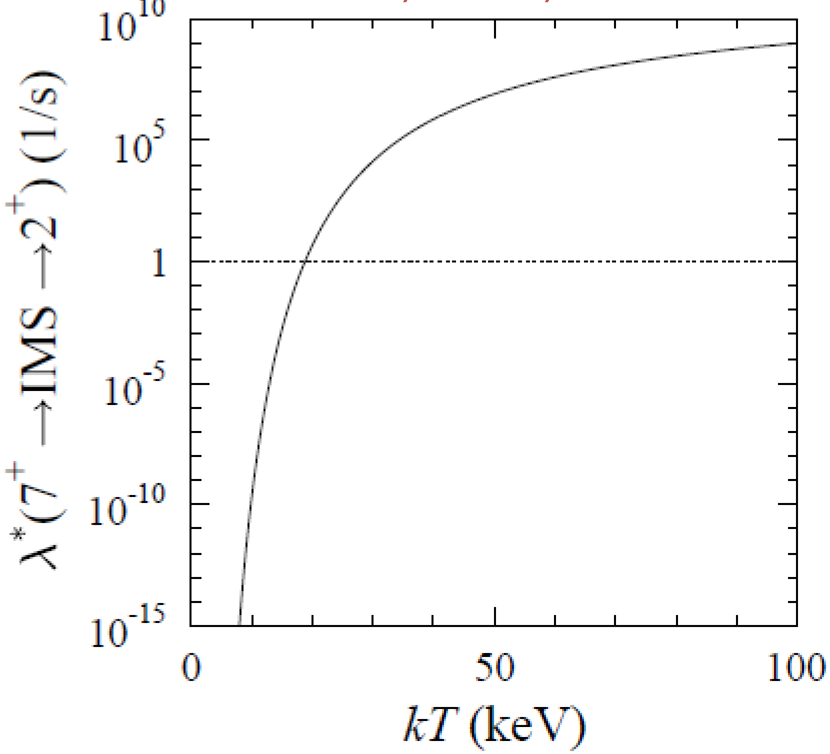
T. Hayakawa et al., Phys. Rev. C 81, 052801(R) (2010)

Isomer in ^{92}Nb

There is an isomer at 136 keV in ^{92}Nb, which beta-decays away with a half-life of only 10 d.



Mohr, PRC, 2016

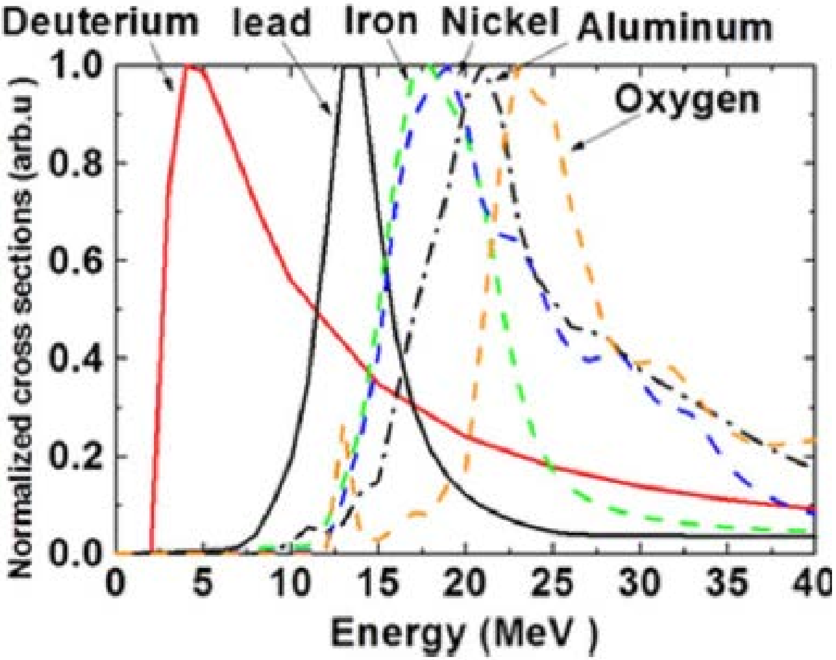


Mohr calculated the transition rate between the isomer and the ground state using a thermal equilibrium model.
The result is that the isomer does not affect.

Detection techniques

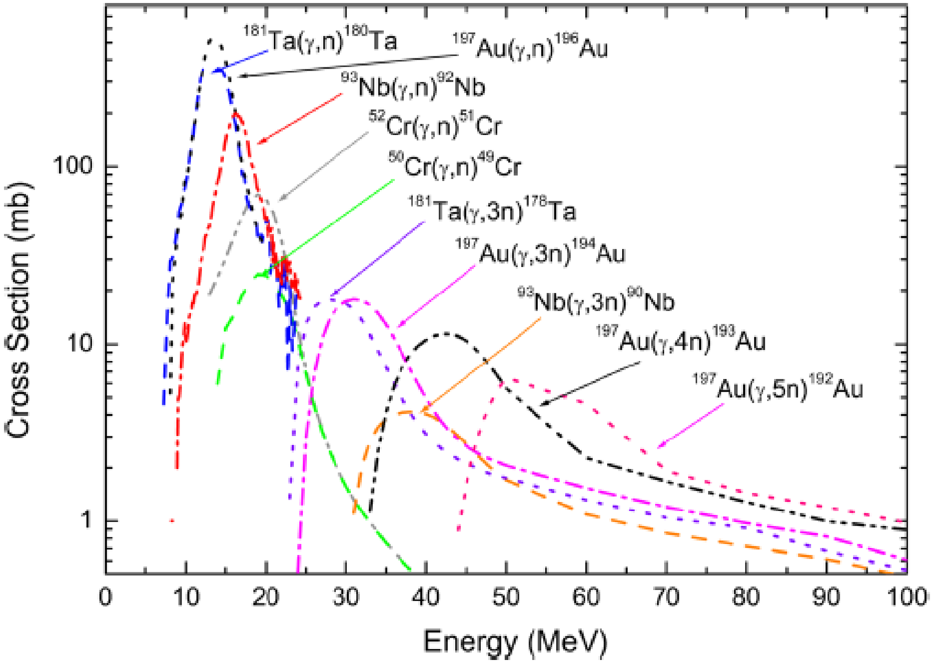
Pulsed gamma-ray should be converted to particles, of which energy distribution can be measured.

Activation methods



Sakata RSI (2014)

Günthe, Phys. Plas, 2011



Cross section of (gamma, n) reactions of various materials

In stellar reaction rate, the threshold is critical.
In the case of bremsstrahlung and narrow energy photons, the peak energy of GDR is important.

Deuterium cannot produce unstable isotopes.
Lead is the lowest energy among GDR.

Activation by neutrons following (gamma, n) reactions

Gamma-rays are converted to neutrons by (gamma, n) reactions.
Neutrons are measured by bubble detector after slowdown by polyethylene.

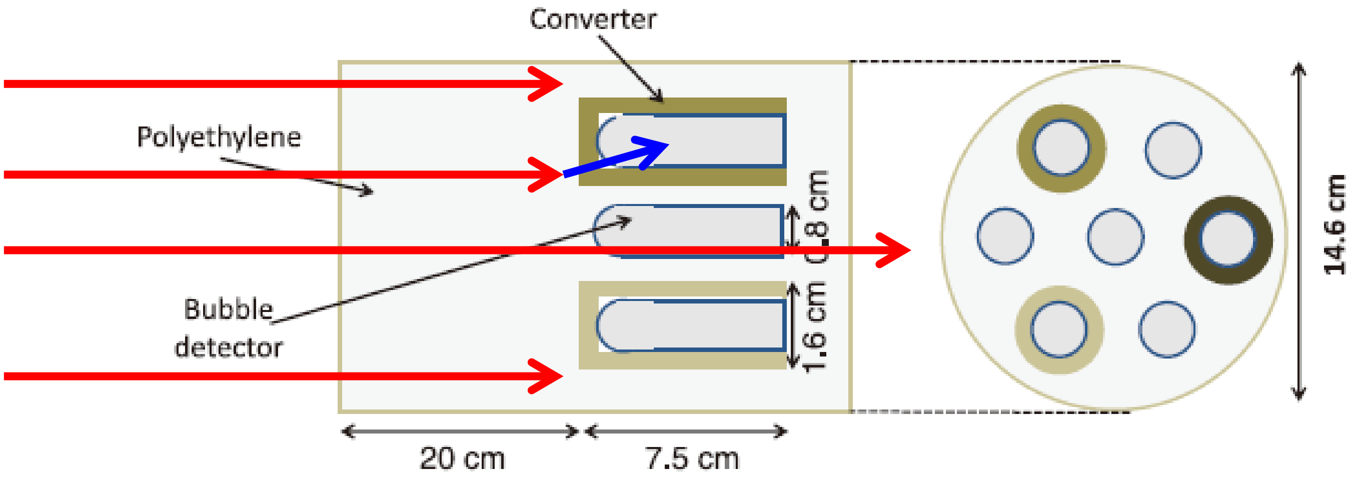
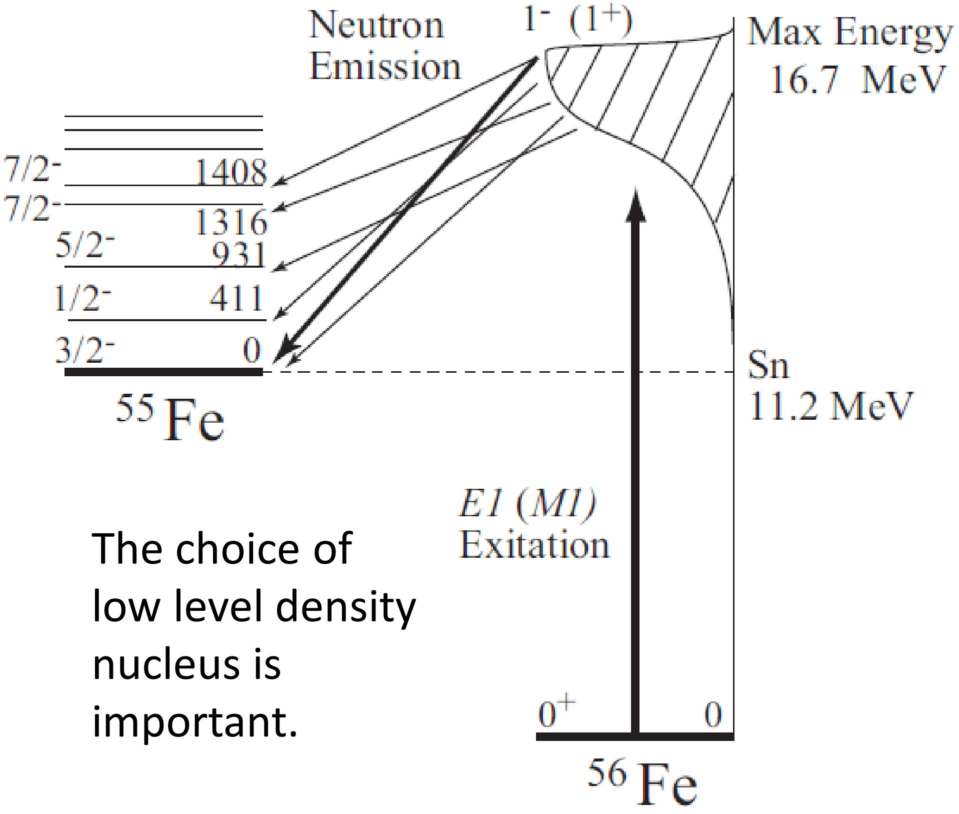


FIG. 2. Schematic of the x-ray spectrometer covering a photon energy range of 10–20 MeV. Five-millimeter-thick cylindrical converters made of lead, iron, and aluminum cover the bubble detectors those have the same threshold energy (0.6 MeV). Uncovered bubble detectors are also allocated to measure the background signal.

Sakata et al. Rev. Sci. Instrum. **85**, 11D629 (2014)

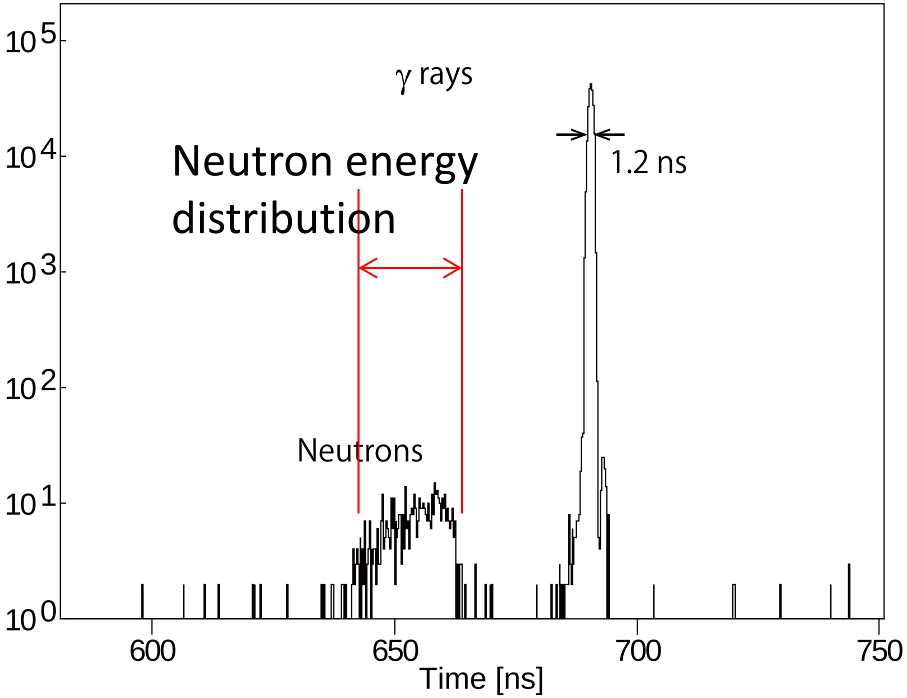
This method has an advantage that they can use a material cannot produce radioisotope.

Time-of-flight to measure neutrons following (gamma, n) reactions



The choice of low level density nucleus is important.

Neutrons from ^{56}Fe(gamma, n) reactions



Using laser Compton scattering gamma-rays at NewSUBARU

T. Hayakawa, et al., Phys. Rev. C. 93, 044313 (2016).

Summary

- Photons play important roles in stellar nucleosynthesis including gamma-process and neutrino-process.
- Continues gamma-ray energy is an advantage to simulate stellar environments.
- The short pulse is effective to study explosive nucleosynthesis in supernovae
- A key point is how to generate such gamma-ray pulse.
- Proposals for nuclear astrophysics experiments using laser driven gamma-ray pulse.

T. Hayakawa, et al. Quantum Beam Science, 1(1), 3 (2017).
"Explosive Nucleosynthesis Study Using Laser Driven *γ*-ray Pulses"