Nuclear astrophysics with gamma-ray/neutron provided from high peak power laser

T. Hayakawa

National Institutes for Quantum and Radiological Science and Technology,

Contents

- Background of nuclear astrophysics
- 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”

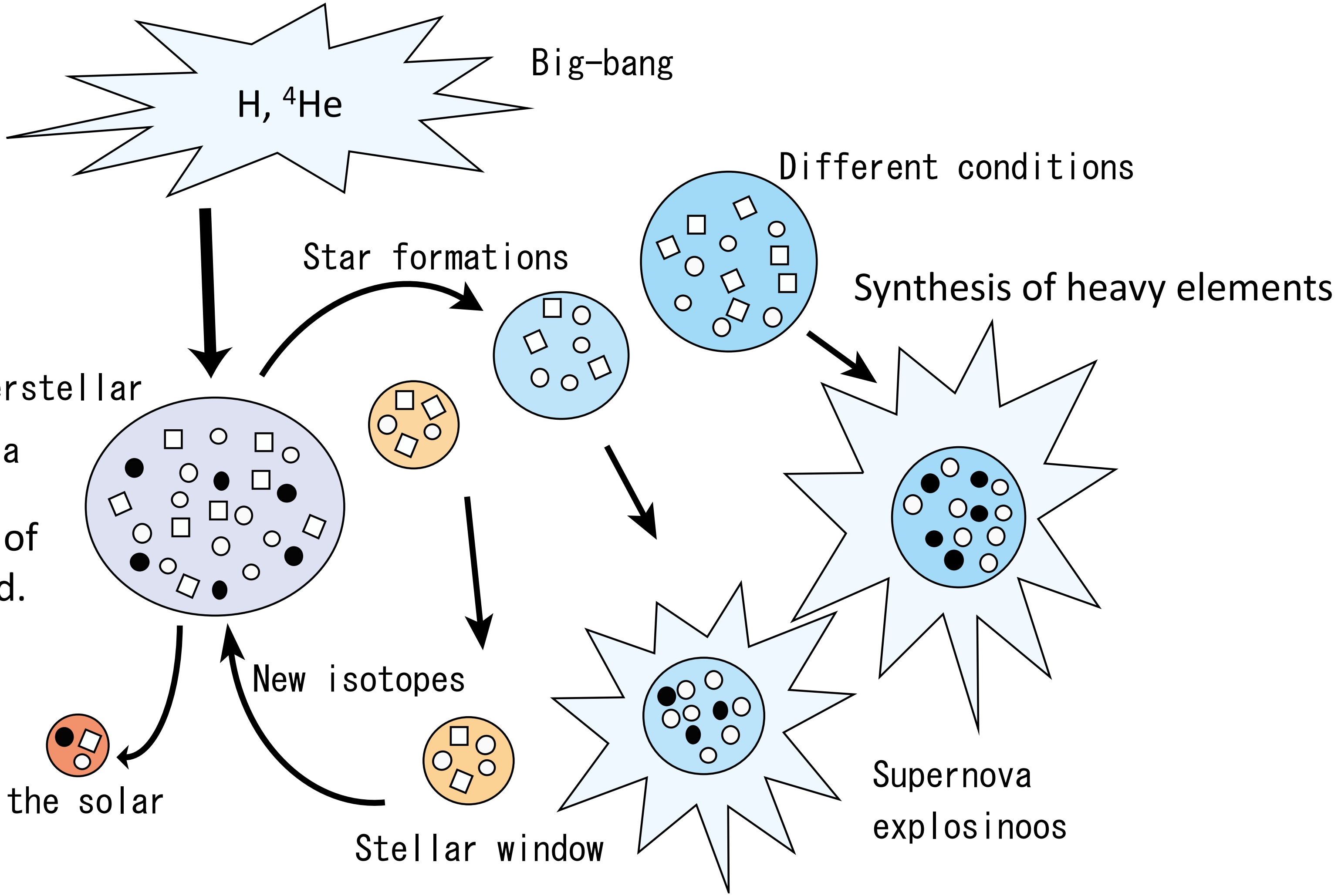
- Nuclear experiments using laser driven neutrons

  Mori, et al. Phys. Rev. C 104, 015808 (2021).

  Mori et al., J. Phys. G: Nucl. Part. Phys. 49 065103 (2022).

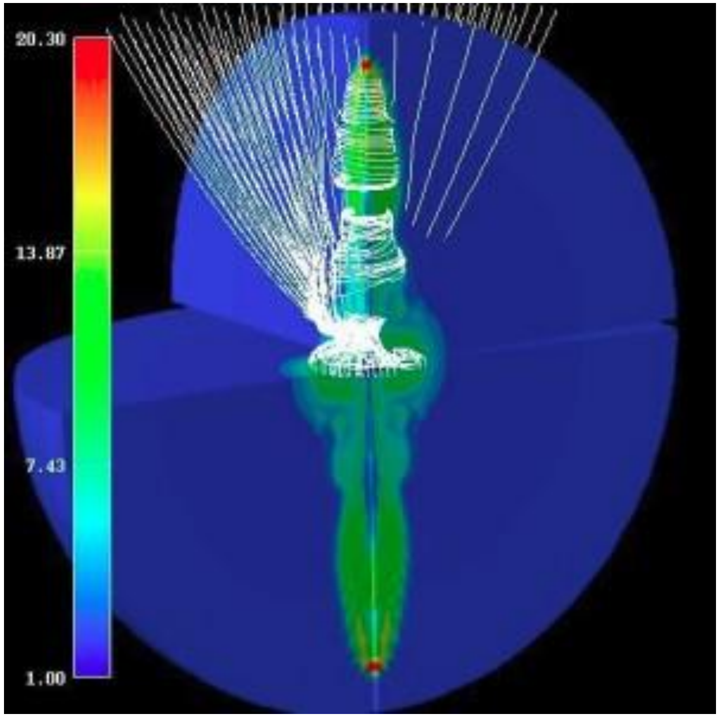
Proposal for decay acceleration by neutron generated with cosmic rays.
T. Hayakawa, et al. Communications Physics 6, 299 (2023).

Evolution of chemical materials



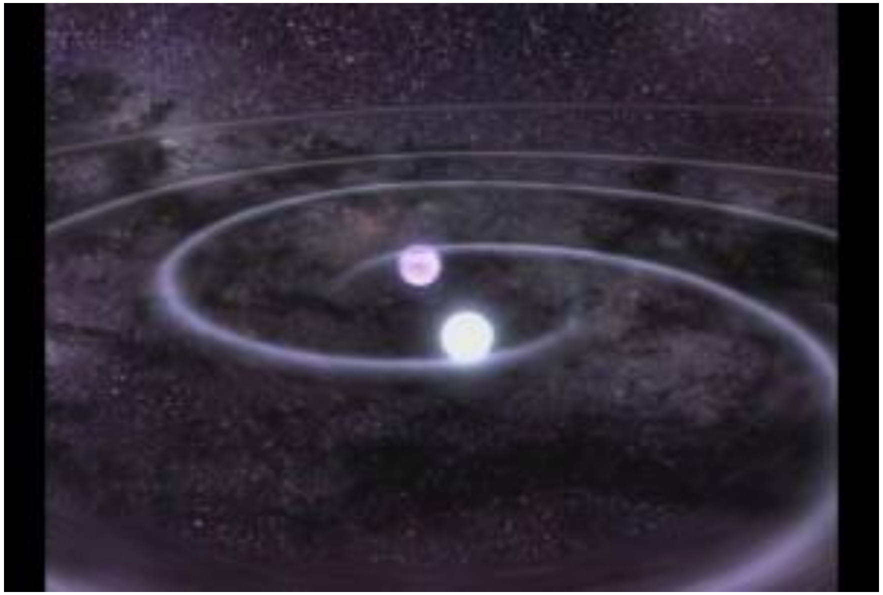
Where r–process occur ?

Magnetic hydrodynamic supernovae



http://www.jicfus.jp/jp/promotion/pr/mj/2011-2/

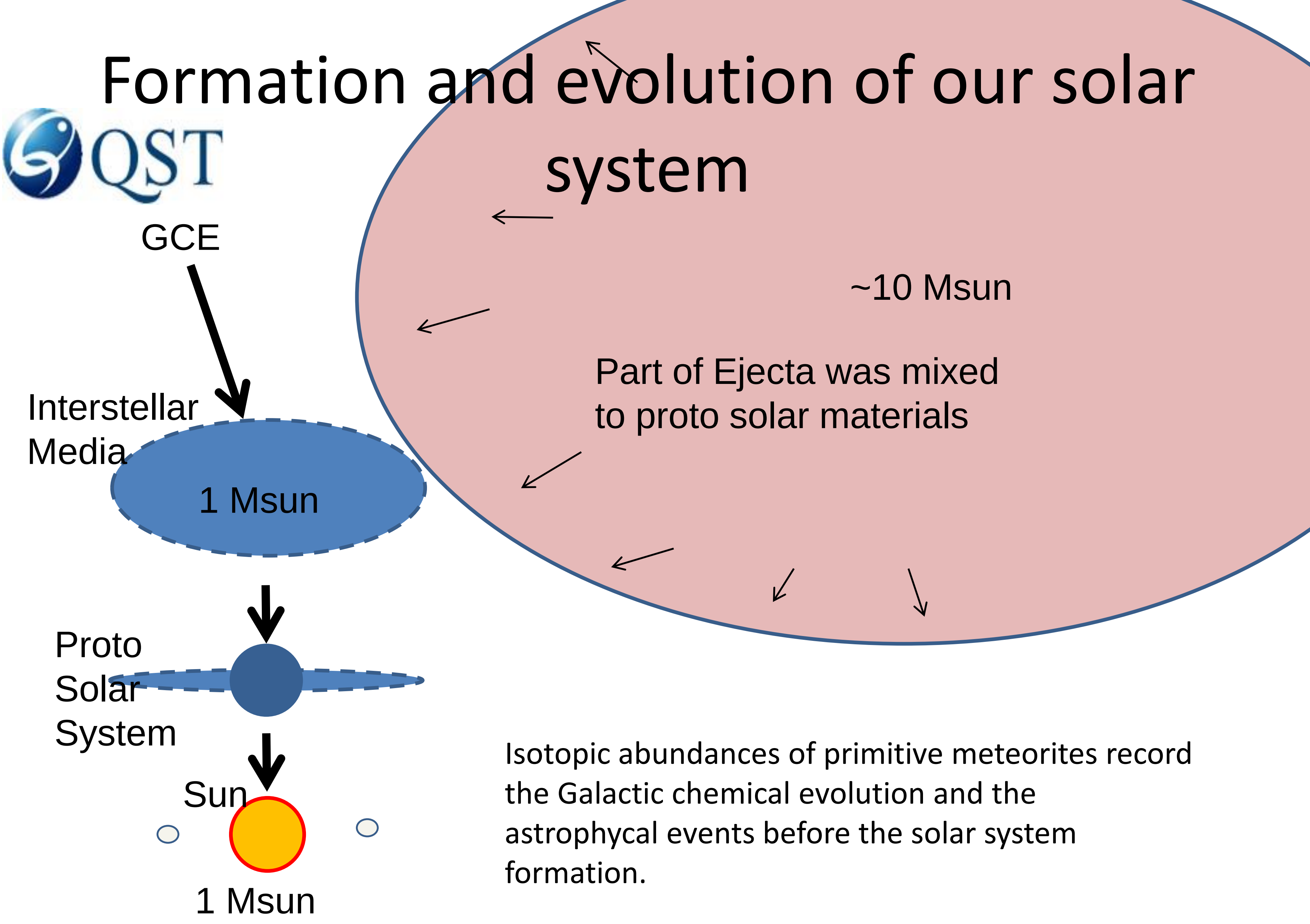
Neutron star merger



Credit: NASA Goddard

S-process and r-process are the dominant source of elements heavier than iron. However, there are many unresolved problems. For example, the astrophysical site for the r-process has been unknown.

Formation and evolution of our solar system



GCE

Interstellar Media

1 Msun

Proto Solar System

Sun

1 Msun

~10 Msun

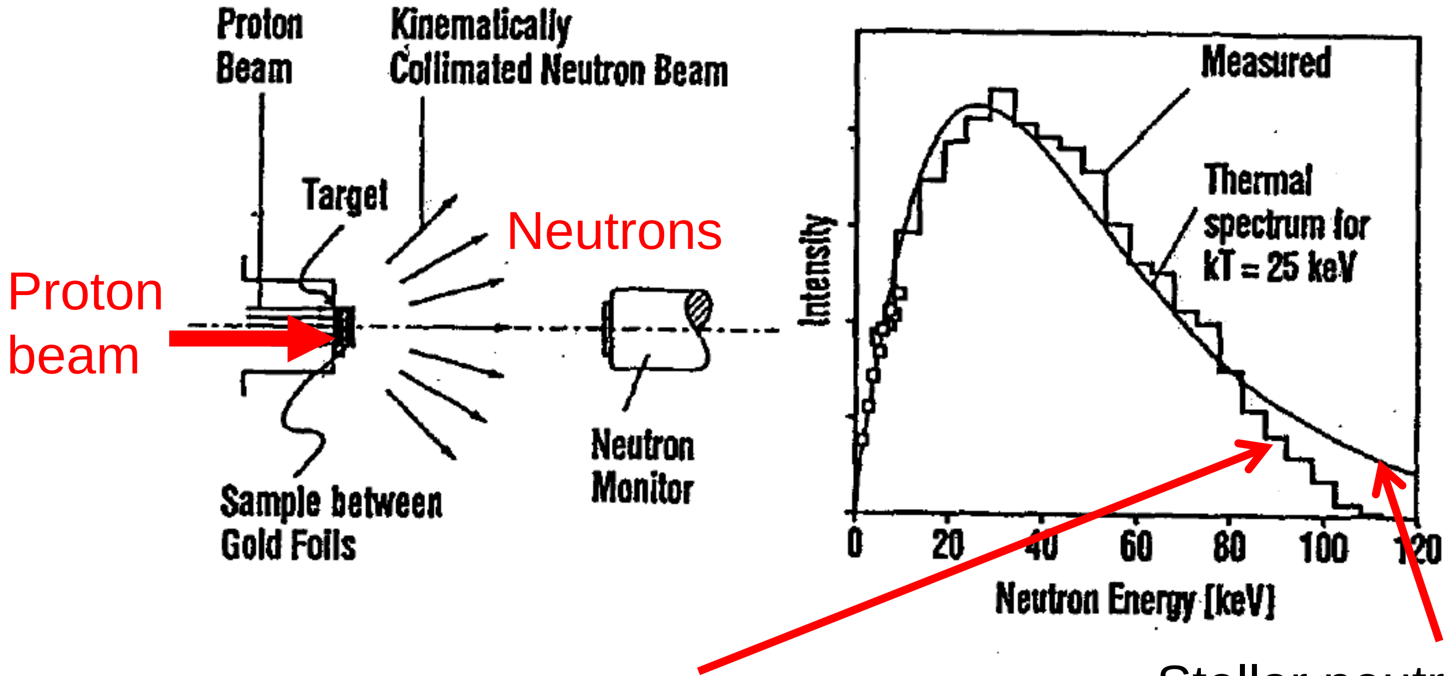
Part of Ejecta was mixed to proto solar materials

Isotopic abundances of primitive meteorites record the Galactic chemical evolution and the astrophycal events before the solar system formation.

Measurements of integrated cross sections

Neutrons

Beer, Phys. Rev. C, 21, 534 (1981)



Generated neutron energy spectrum

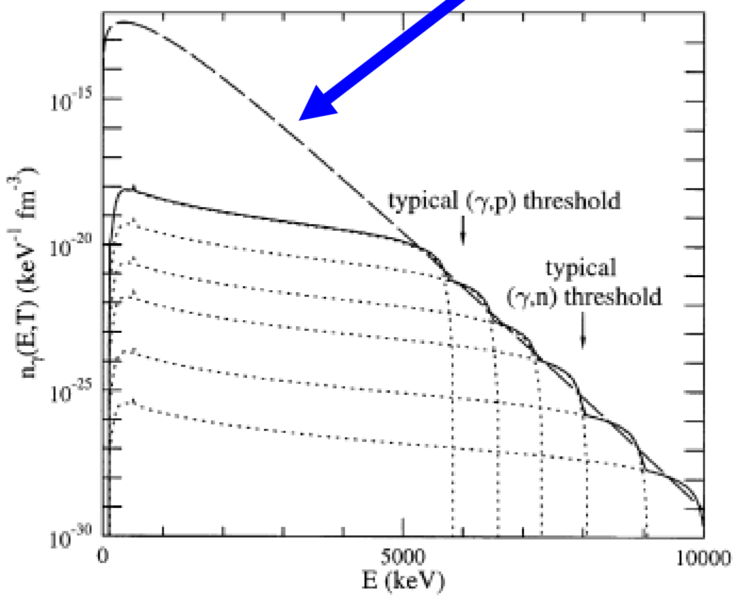
Stellar neutron energy spectrum.

By tuning the target structure and beam energy, the stellar neutron energy spectrum was simulated, and the integrated reaction cross section was directly measured.

This method has been used from 1980’s.

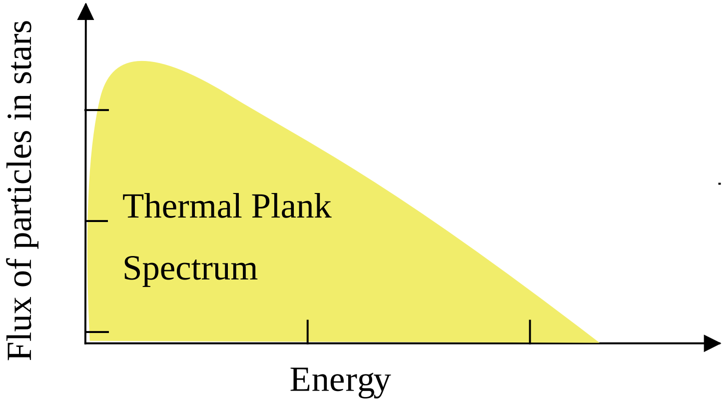
Direct measurement of stellar nuclear photoreactions

The summation of Bremsstrahlung x-rays



To simulate

Stellar photon distribution



The Bremsstrahlung x-rays with many different electron energies are used for measurement of the cross sections of nuclear photoreactions.

After the measurements, the summation of the total reaction rate is used for evaluation of the stellar nuclear reactions.
P. Mohr, et al. Phys. Lett. B, 2000

Advantage of laser-driven pulses

Continues energy → Stellar particle energy distribution.

Short pulse → Explosive phenomenon such as supernova explosion

High flux → Mutai-particle (neutrons) absorptions

Multi pulses → Direct measurement of exited nucleus

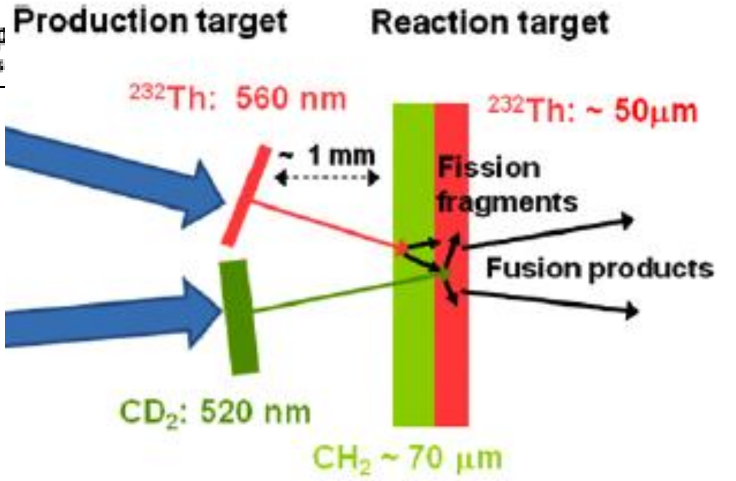
High power laser is suitable for study of nuclear astrophysics

Proposal of a new experiment
R-process study using laser induced reactions

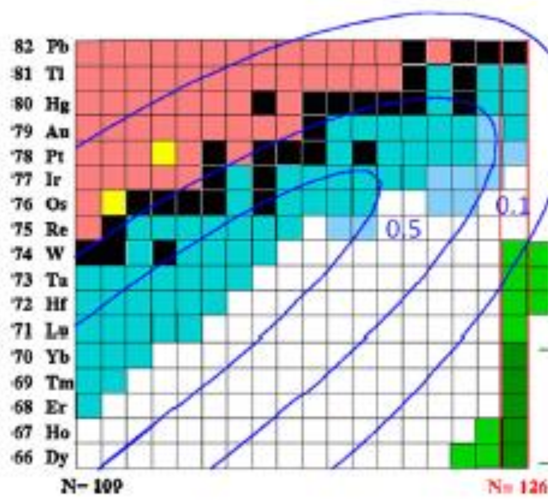
Appl Phys B (2011) 103: 471–484
DOI 10.1007/s00340-010-4261-x

Introducing the fission–fusion reaction process: using a laser-accelerated Th beam to produce neutron-rich nuclei towards the $N = 126$ waiting point of the r-process

D. Habs · P.G. Thirolf · M. Gross · K. Allinger · J. Bin ·
A. Henig · D. Kiefer · W. Ma · J. Schreiber



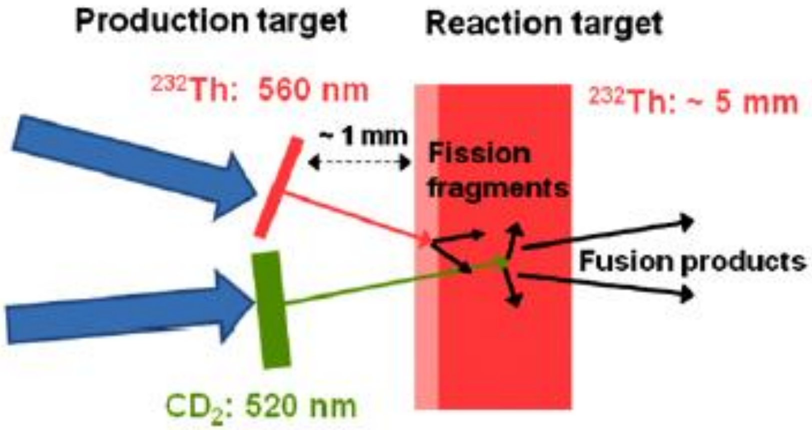
a



1.2·10^{23} W/cm^2
32 fs, 273 J, 8.5 PW

high-power, high-contrast
APOLLON laser :
focal spot: diam. ~ 3 μm

1.0·10^{22} W/cm^2
32 fs, 23 J, 0.7 PW



b

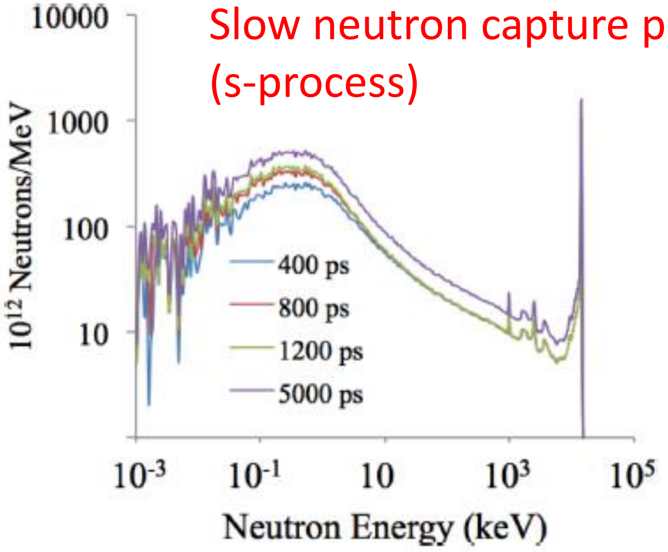
Neutron rich isotopes around N=126

One of the main subjects in ELI-NP

Proposal of
Nuclear astrophysics using high flux neutrons

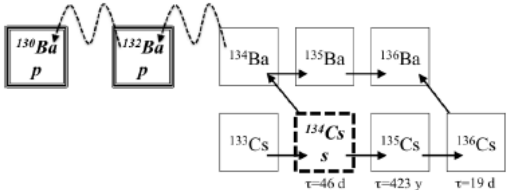
Lee A. Bernstein, Plasma Fusion Research, 9, 04404101 (2014).

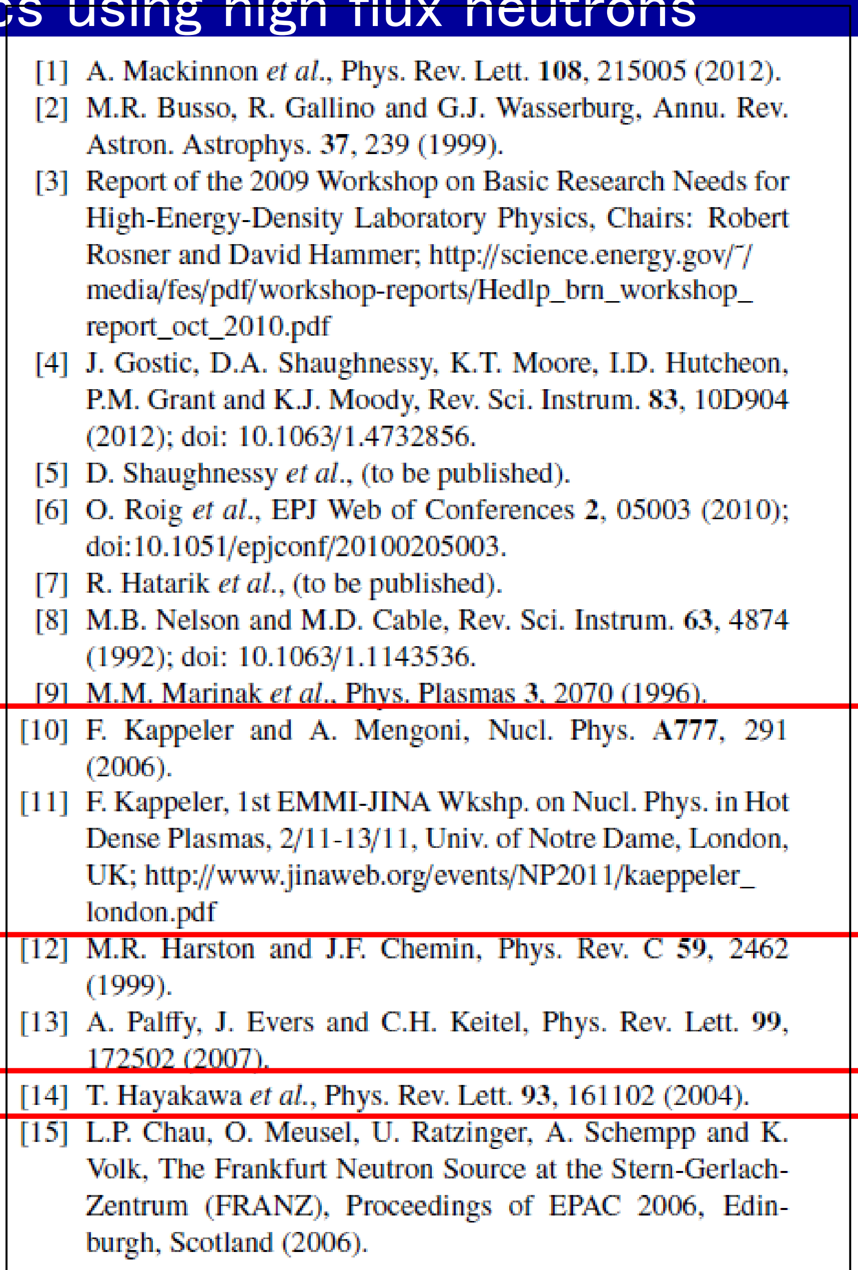
High flux neutrons with NIF



Slow neutron capture process (s-process)

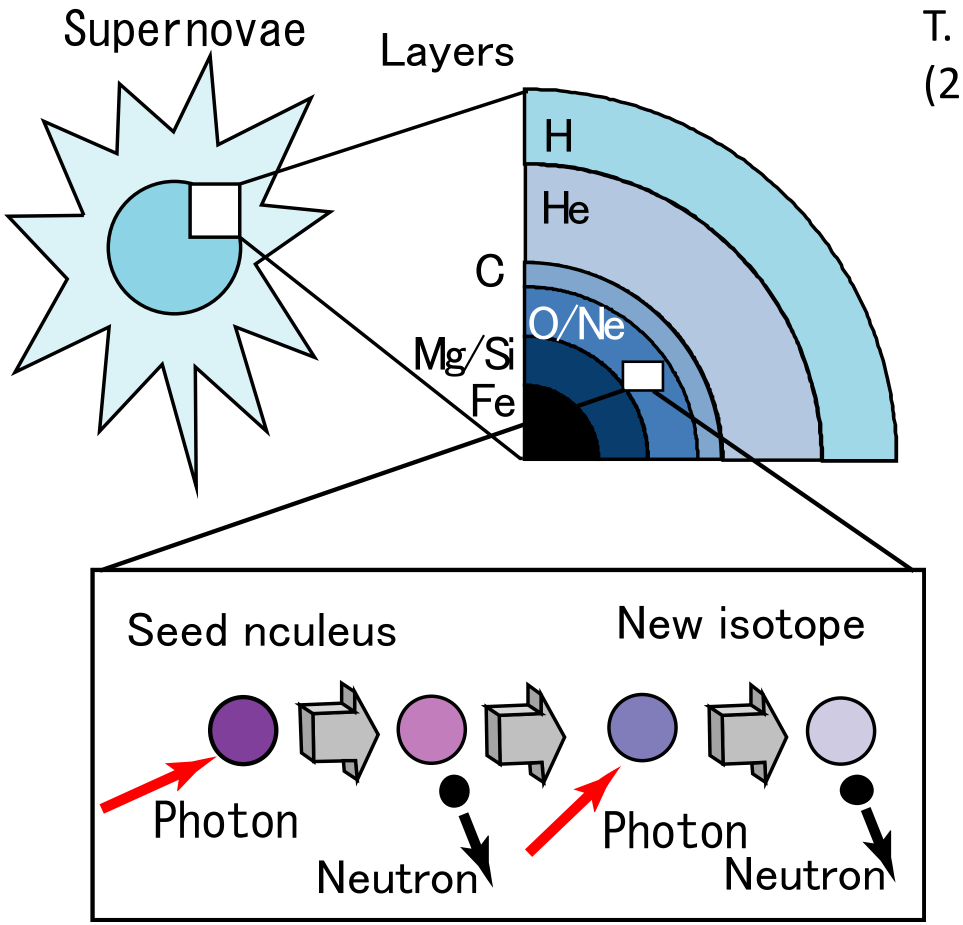
Gamma-process in supernova
The (gamma, n) reaction is inversed reaction of (n, gamma) reaction.




[1] A. Mackinnon *et al.*, Phys. Rev. Lett. **108**, 215005 (2012).
[2] M.R. Busso, R. Gallino and G.J. Wasserburg, Annu. Rev. Astron. Astrophys. **37**, 239 (1999).
[3] Report of the 2009 Workshop on Basic Research Needs for High-Energy-Density Laboratory Physics, Chairs: Robert Rosner and David Hammer; http://science.energy.gov/~/media/fes/pdf/workshop-reports/Hedlp_brn_workshop_report_oct_2010.pdf
[4] J. Gostic, D.A. Shaughnessy, K.T. Moore, I.D. Hutcheon, P.M. Grant and K.J. Moody, Rev. Sci. Instrum. **83**, 10D904 (2012); doi: 10.1063/1.4732856.
[5] D. Shaughnessy *et al.*, (to be published).
[6] O. Roig *et al.*, EPJ Web of Conferences **2**, 05003 (2010); doi:10.1051/epjconf/20100205003.
[7] R. Hatarik *et al.*, (to be published).
[8] M.B. Nelson and M.D. Cable, Rev. Sci. Instrum. **63**, 4874 (1992); doi: 10.1063/1.1143536.
[9] M.M. Marinak *et al.*, Phys. Plasmas **3**, 2070 (1996).
[10] F. Kappeler and A. Mengoni, Nucl. Phys. **A777**, 291 (2006).
[11] F. Kappeler, 1st EMMI-JINA Wkshp. on Nucl. Phys. in Hot Dense Plasmas, 2/11-13/11, Univ. of Notre Dame, London, UK; http://www.jinaweb.org/events/NP2011/kaeppeler_london.pdf
[12] M.R. Harston and J.F. Chemin, Phys. Rev. C **59**, 2462 (1999).
[13] A. Palffy, J. Evers and C.H. Keitel, Phys. Rev. Lett. **99**, 172502 (2007).
[14] T. Hayakawa *et al.*, Phys. Rev. Lett. **93**, 161102 (2004).
[15] L.P. Chau, O. Meusel, U. Ratzinger, A. Schempp and K. Volk, The Frankfurt Neutron Source at the Stern-Gerlach-Zentrum (FRANZ), Proceedings of EPAC 2006, Edinburgh, Scotland (2006).

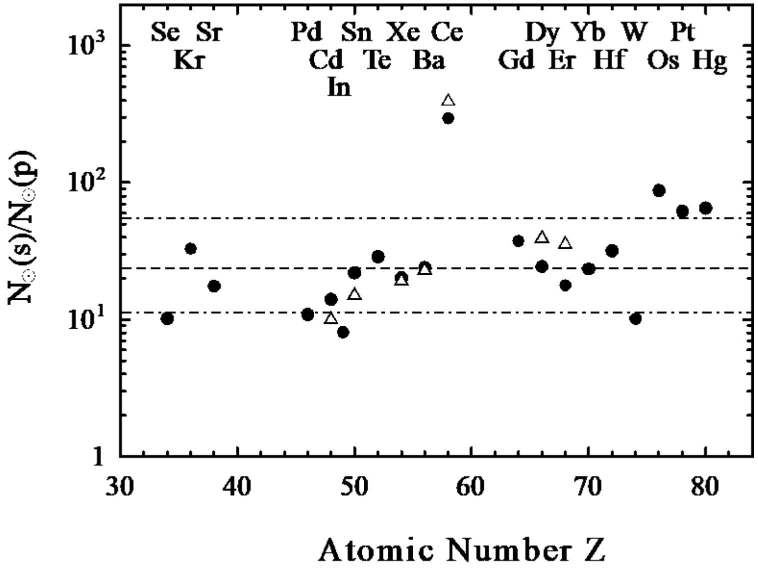
Gamma-process in supernova

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



Anti-correlation between the reaction rate and the solar abundances was found.

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



The empirical scaling law. This indicates that the p-nuclei are produced from s-nuclei.

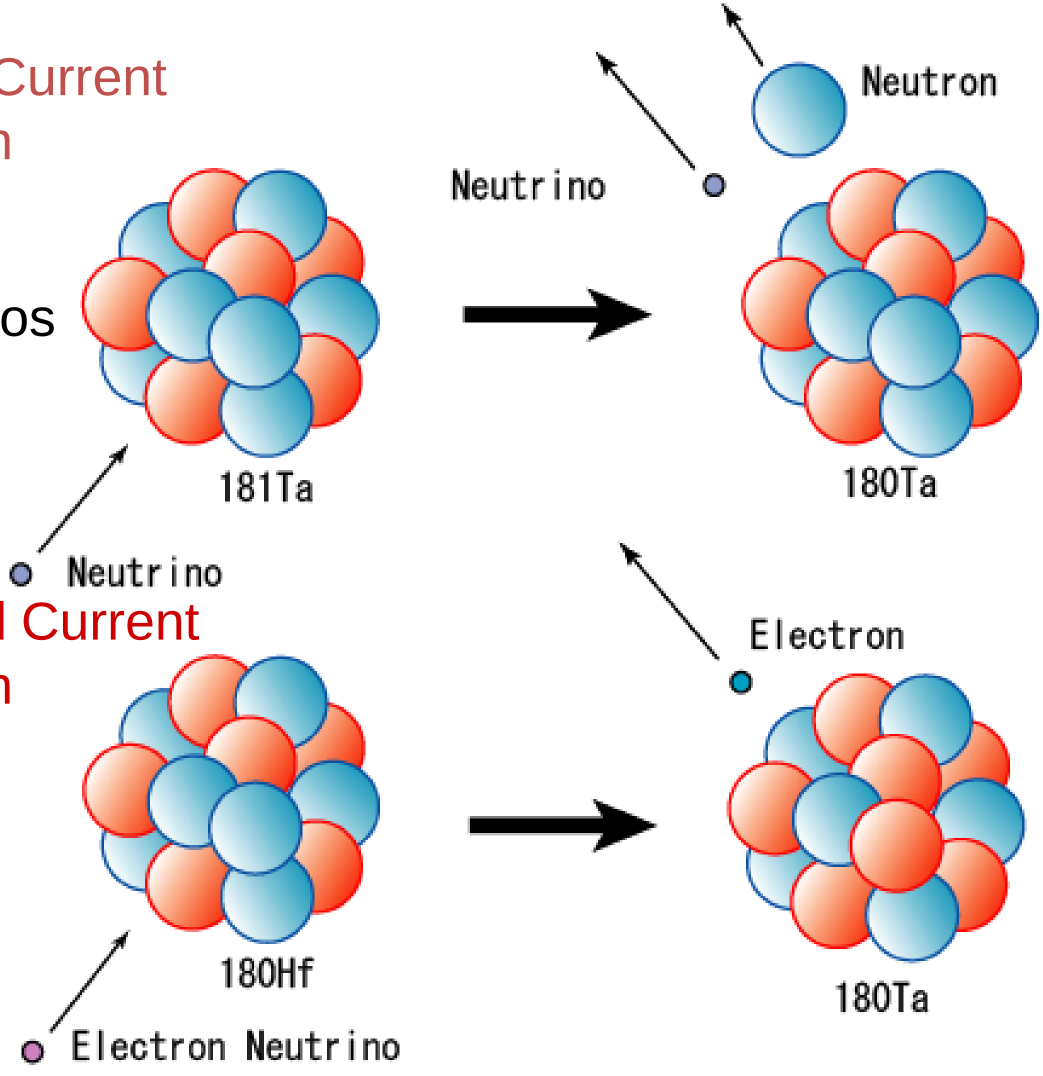
Neutrino-Nucleus Reactions

Neutral Current Reaction

All Neutrinos

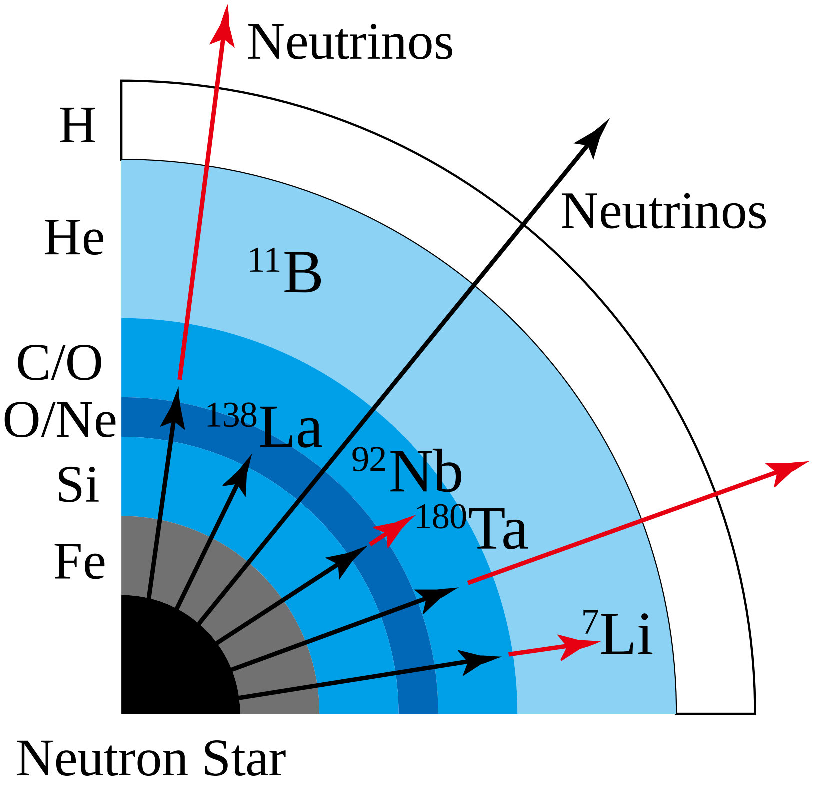
Charged Current Reaction

Electron Neutrino



Neutrino-process in supernova

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

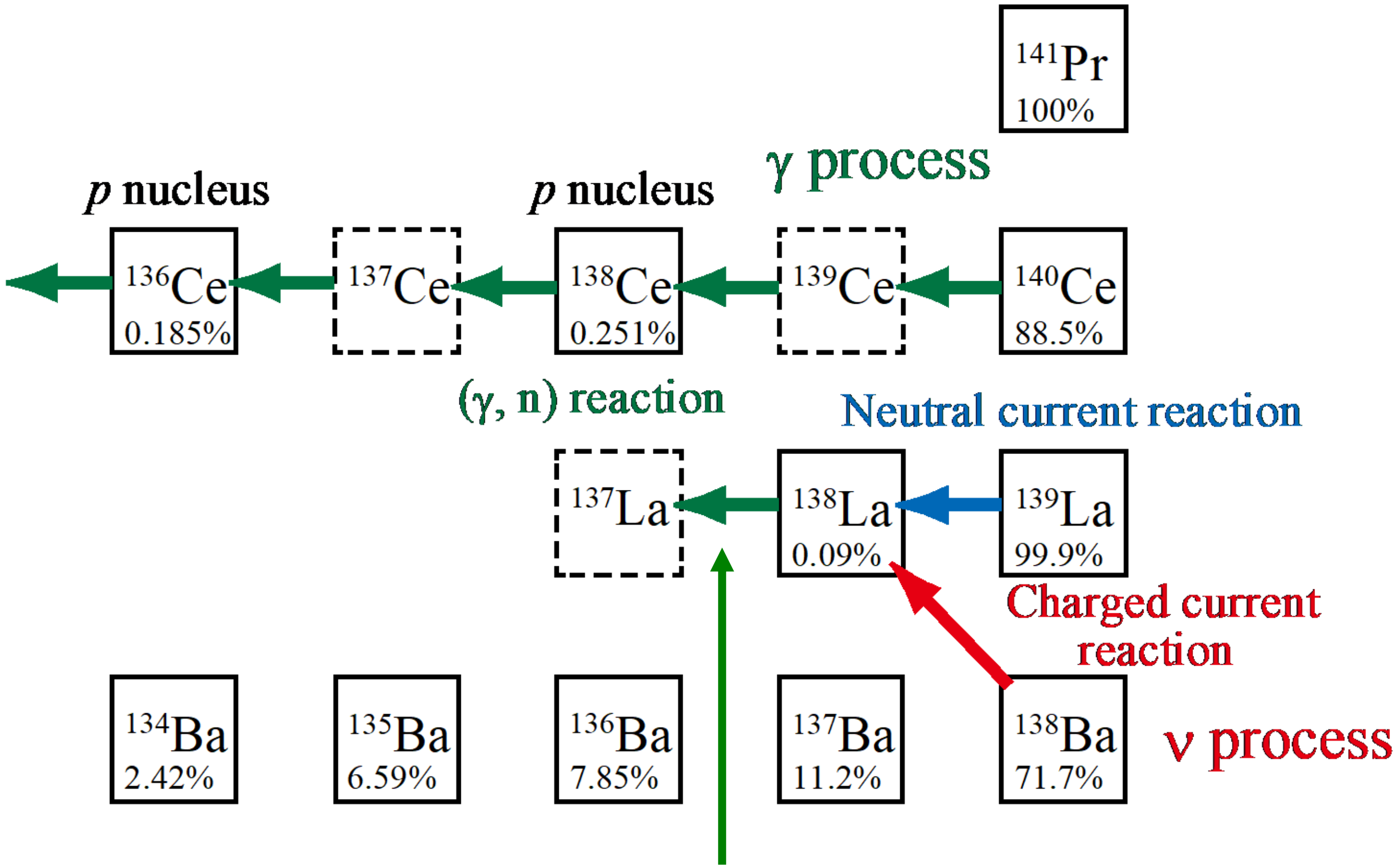


A. Heger, PLB (2005)
Calculate synthesis of ^{11}B, ^{19}F, ^{138}La, ^{180}Ta but ^{180}Ta can not be reproduced.

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

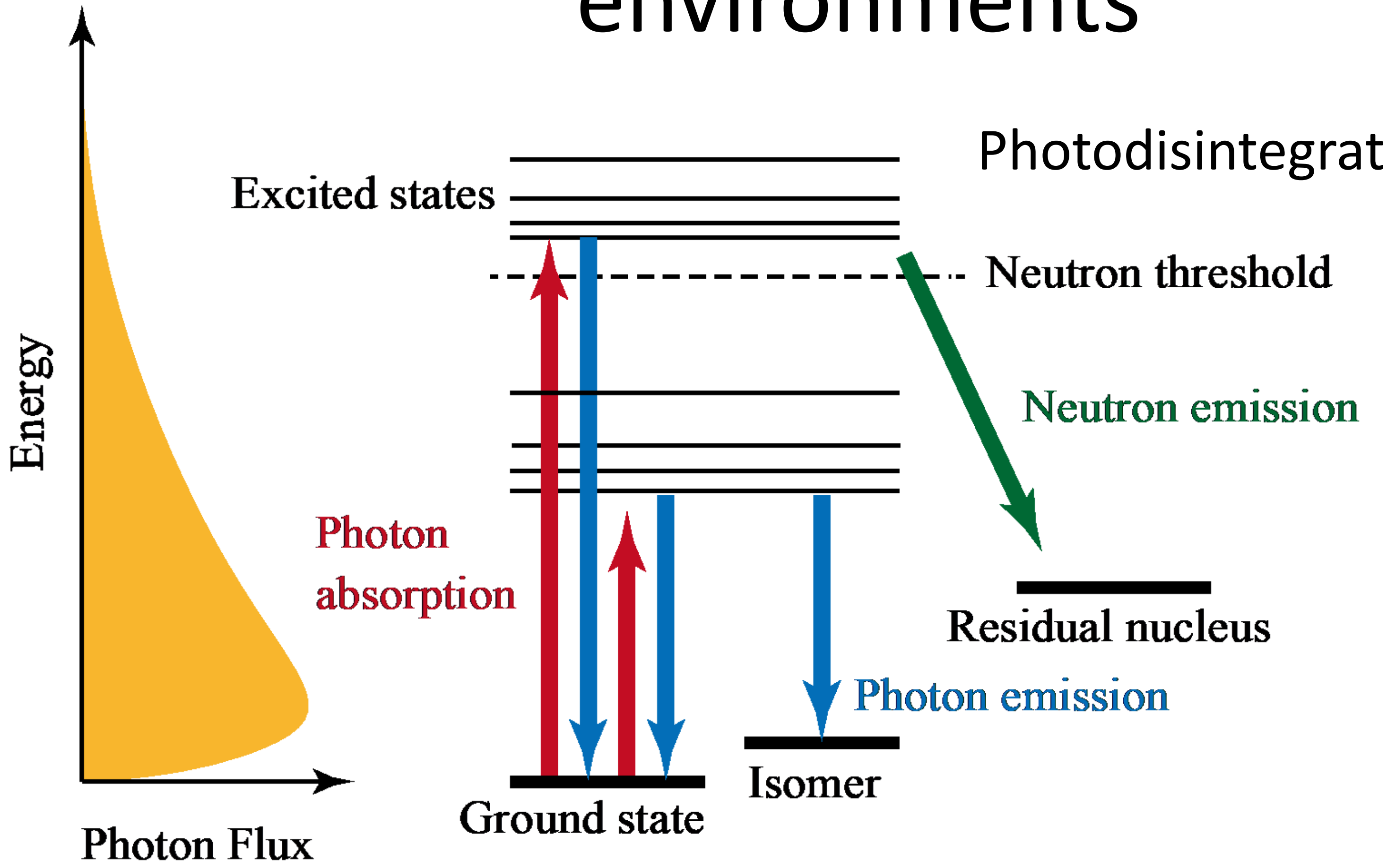
^{180}Ta, T. Hayakawa, PRC (2010a, 2010b)
Isomer production ratio of ^{180}Ta
^{92}Nb, T. Hayakawa, ApJL (2013)
Origin of ^{92}Nb in meteorites

Flow of nucleosynthesis



In neutrino-process, the dominant destruction reaction is (gamma, n) reactions.

Interaction between nuclei and photons in hot temperature environments

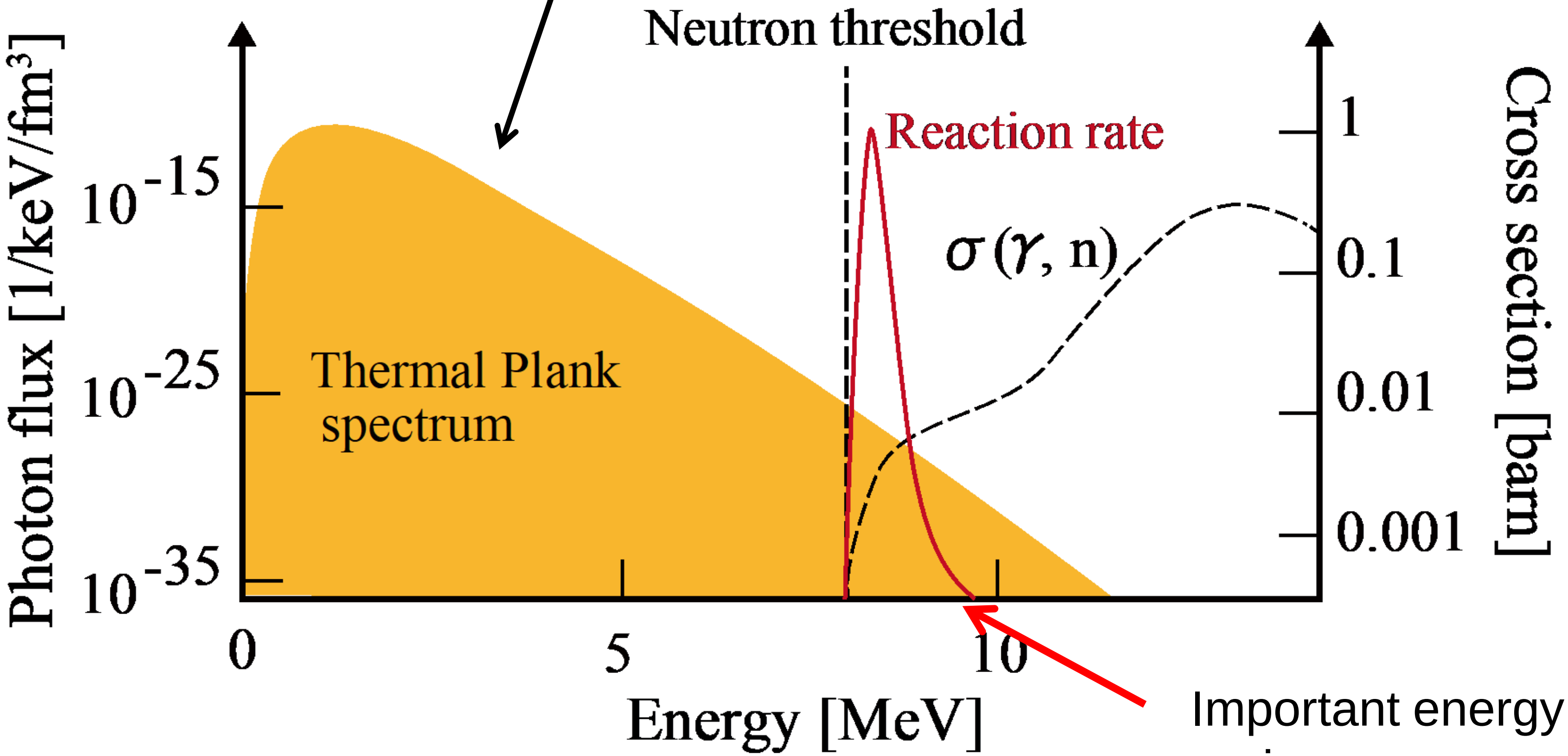


Gamma-process in supernova

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

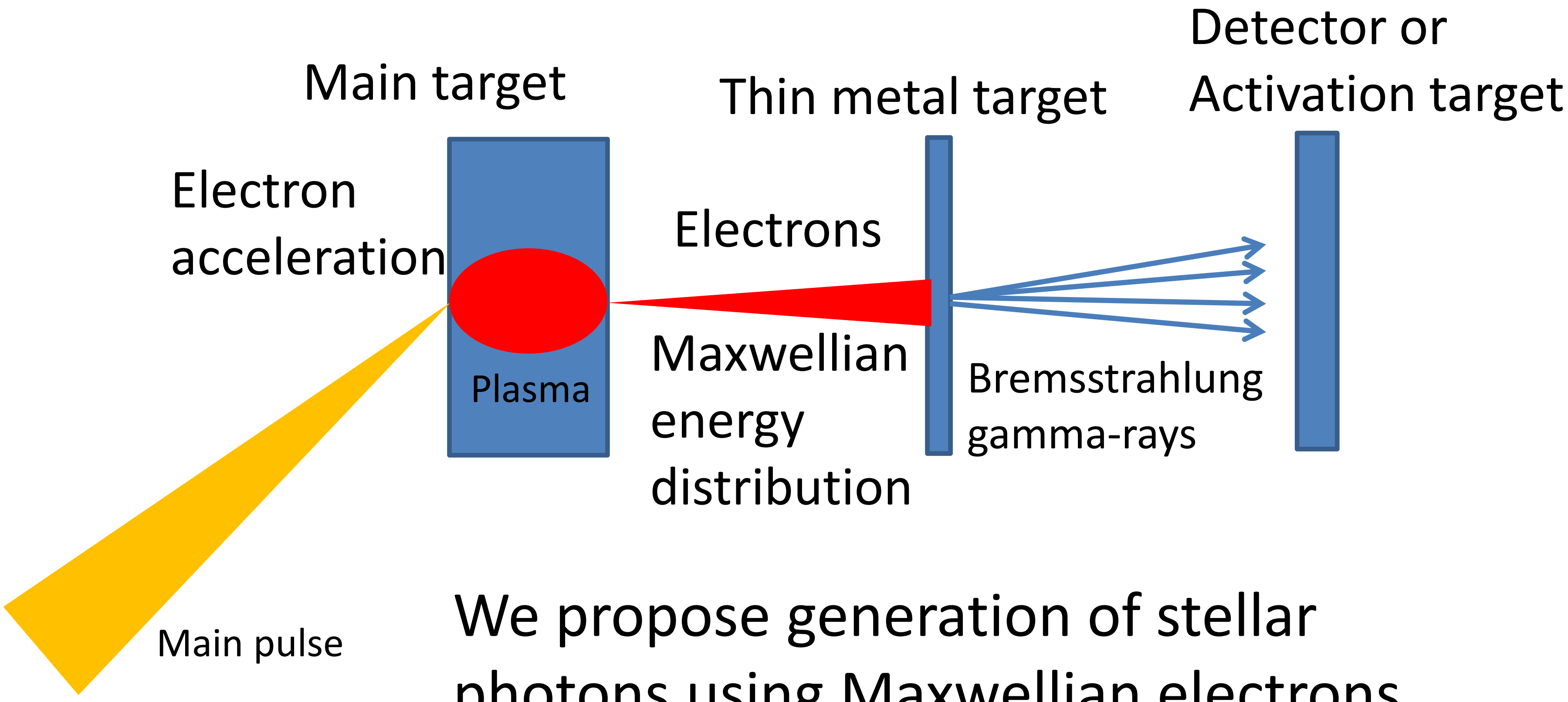
Supernova: kT = 10^9 K ~ 100 keV

Nova: kT = 10^8 K ~ 10 keV



Important energy region

Proposal of direct measurement of stellar nuclear photoreactions



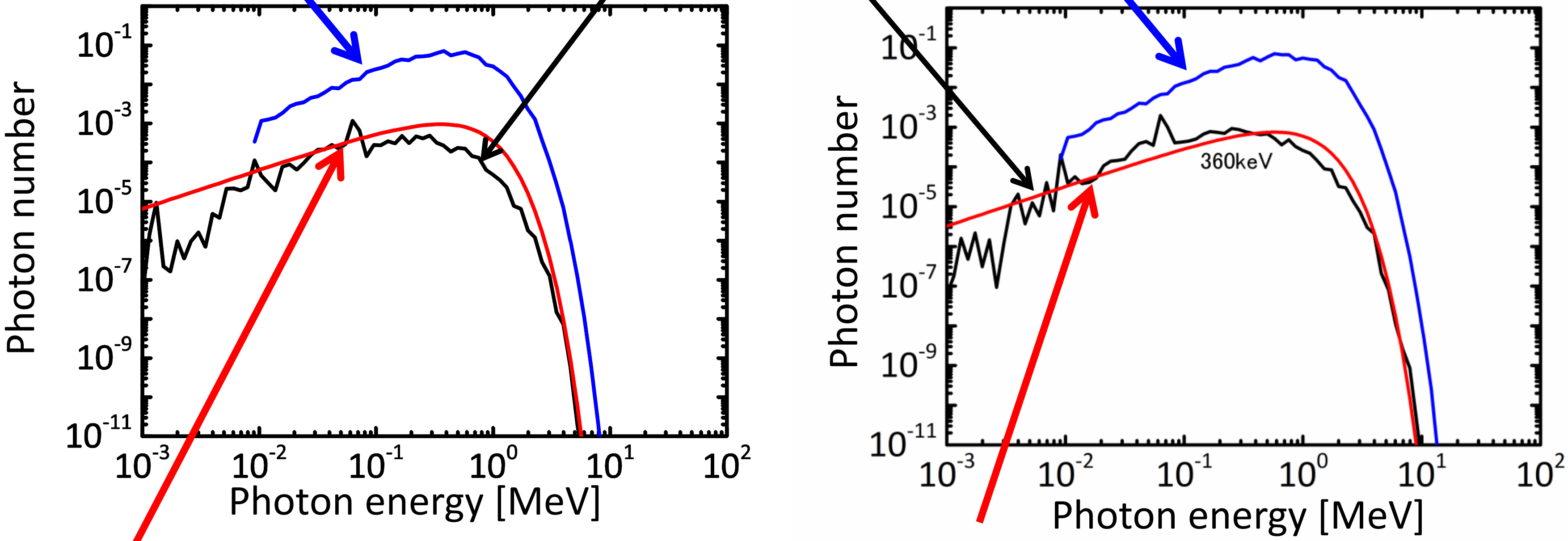
We propose generation of stellar photons using Maxwellian electrons accelerated by laser.

Calculated energy spectra

Expected Bremsstrahlung gamma-rays

Electron temperature
Te = 300 keV

Electron temperature
Te = 500 keV

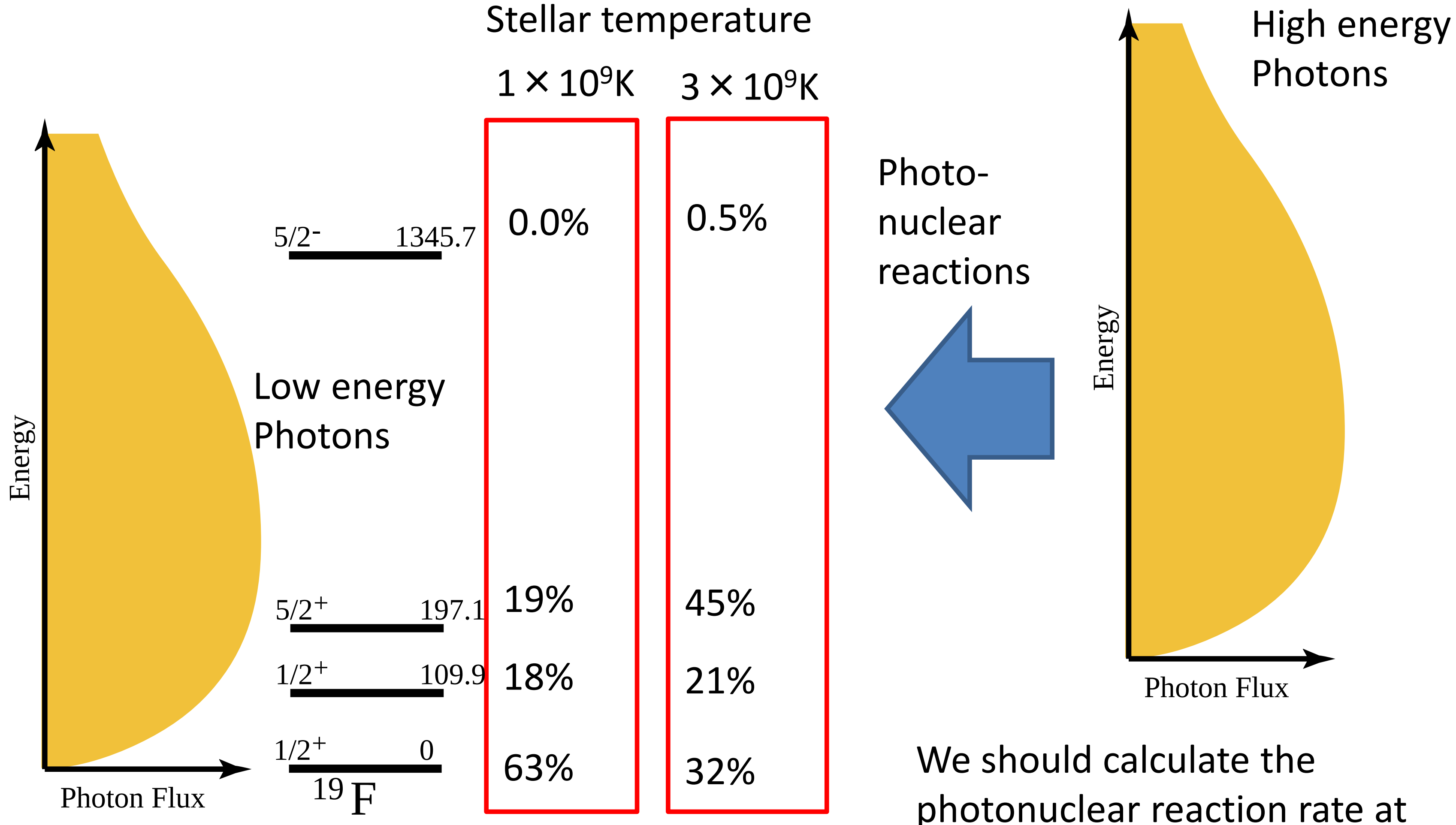


Planck Distribution of T = 225 keV

Planck Distribution of T = 360 keV

When these energy spectra, we can directly measure the stellar reaction cross section.

Proposal of direct measurement of reaction on excited nucleus



Stellar temperature

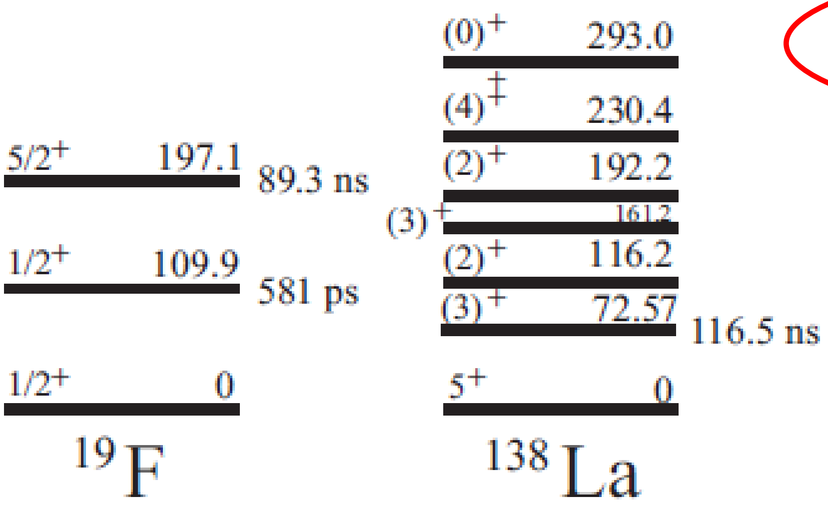
State	Energy	1×10^{9}K	3×10^{9}K
$5/2^-$	1345.7	0.0%	0.5%
$5/2^+$	197.1	19%	45%
$1/2^+$	109.9	18%	21%
$1/2^+$	0	63%	32%

Excited probability of each state

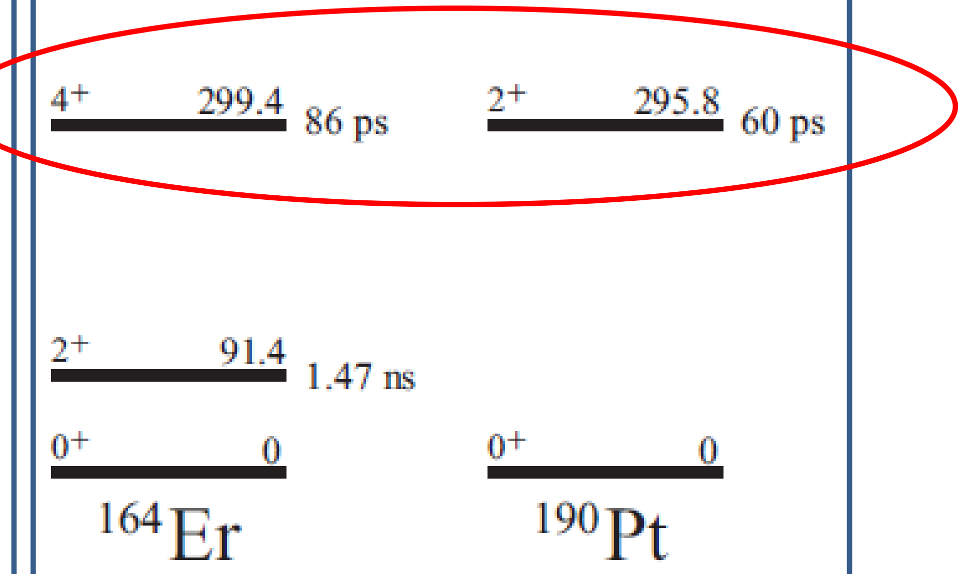
We should calculate the photonuclear reaction rate at excited states

Candidates

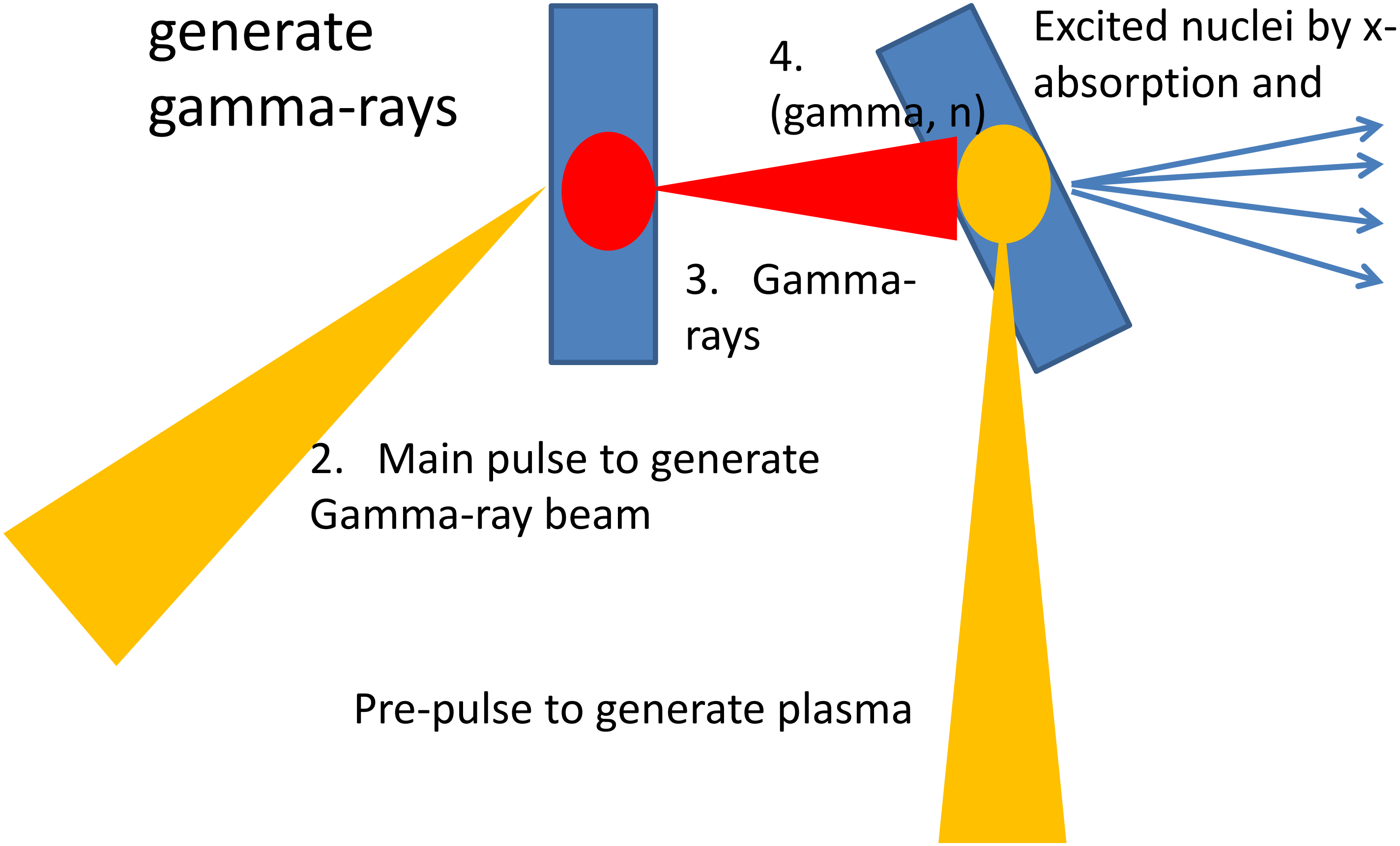
Neutrino process



Gamma process



Proposal of two-pulse method



Main target to generate gamma-rays

4. (gamma, n)

Excited nuclei by x-ray absorption and

5. Neutron, proton, etc.

3. Gamma-rays

2. Main pulse to generate Gamma-ray beam

Pre-pulse to generate plasma

Estimation

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.

Neutron capture on excited ^{171}Tm

^{171}Tm is a branching point in s-process. The branching ratio depends on the temperature in stars.

T. Heftrich, Phys. Rev. C. 99, 065810 (2019)

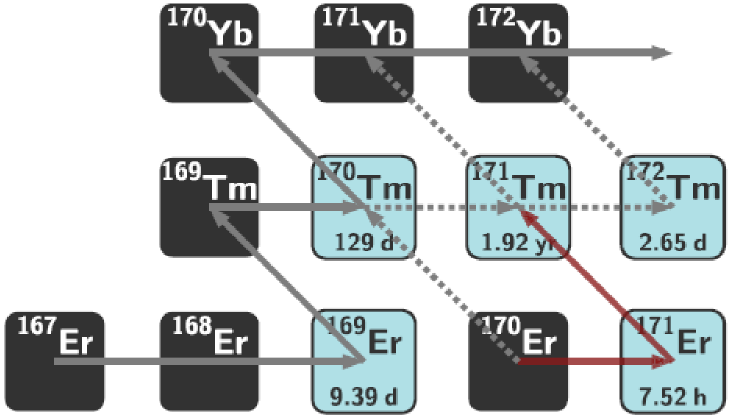
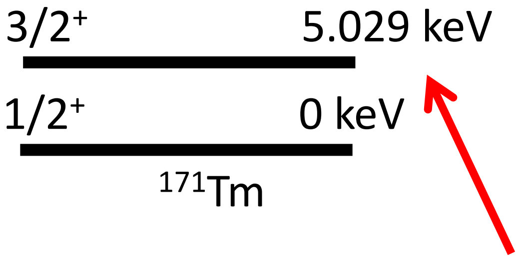


FIG. 1. The *s*-process reaction path between Er and Yb depicted by grey arrows. Secondary paths are represented by dashed lines. The radioactive isotopes ^{170}Tm and ^{171}Tm act as branch points and can be used to study the neutron density during the main component of the *s* process.

Nuclear structure of ^{171}Tm



This state is excited in s-process environment of T=5-100 keV.

We need the neutron capture cross section on the excited state.

This idea may be proposed in NIF, but I cannot find the reference.

Topics

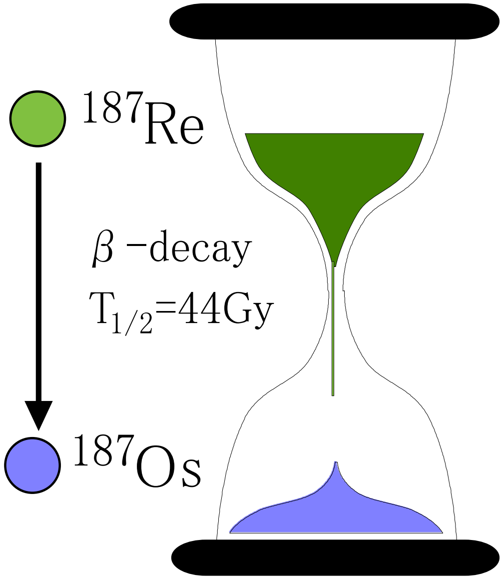
1. Role of neutrons in nuclear astrophysics

   Stellar nucleosynthesis, pre-solar history, cosmic-rays

2. Neutron capture reaction cross section measurement using conventional accelerators

3. Nuclear experiments using laser-driven neutrons with LFEX laser at Osaka University.

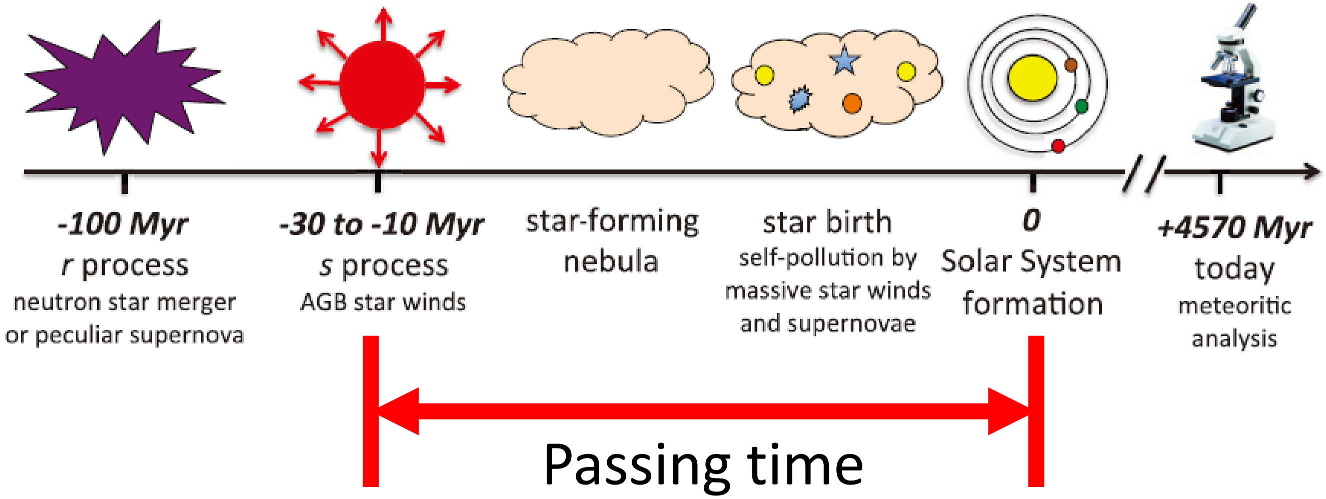
Nuclear Cosmochronometers



Long-lived nuclides	Process
^{235}U, ^{238}U, ^{232}Th, ^{187}Re	r-process
^{40}K	supernova, s-process
^{87}Rb	s-process
^{176}Lu	gamma, s-process

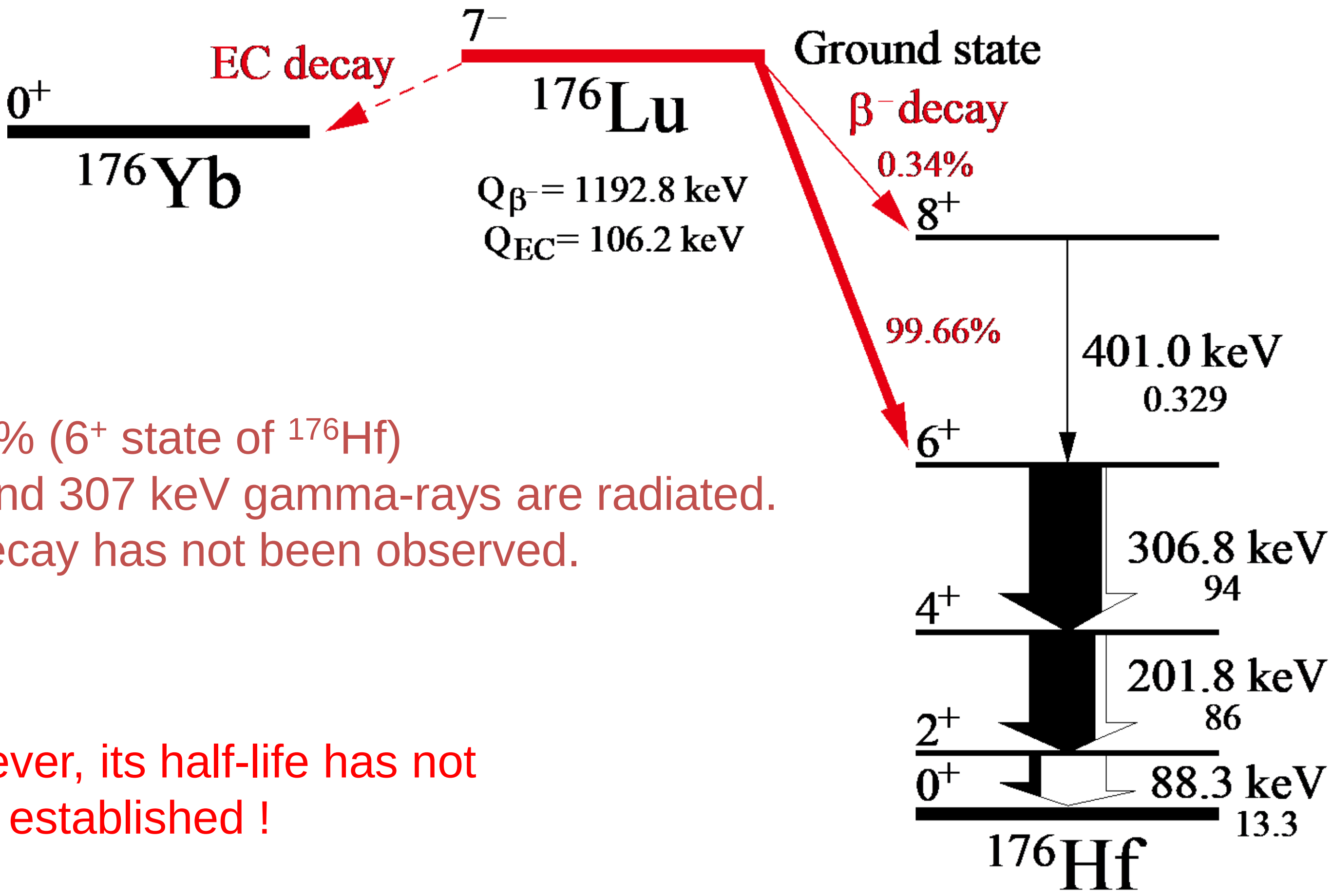
Lugaro, Science (2014).

Fig. 3. Schematic timeline of the solar system formation. The *r* process LE contributed ^{129}I to the early solar system, the *s* process LE contributed ^{107}Pd and ^{182}Hf, and self-pollution of the star-forming region contributed the lighter, shorter-lived radionuclides, such as ^{26}Al.



Nuclear thermometer in ^{176}Lu

^{176}Lu decays to ^{176}Hf with a half-life of about 4 x 10^{10} y.
The ^{176}Hf-^{176}Lu system could be used as a nuclear chronometer.



- 99.66% (6^+ state of ^{176}Hf)
- 202 and 307 keV gamma-rays are radiated.
- EC decay has not been observed.

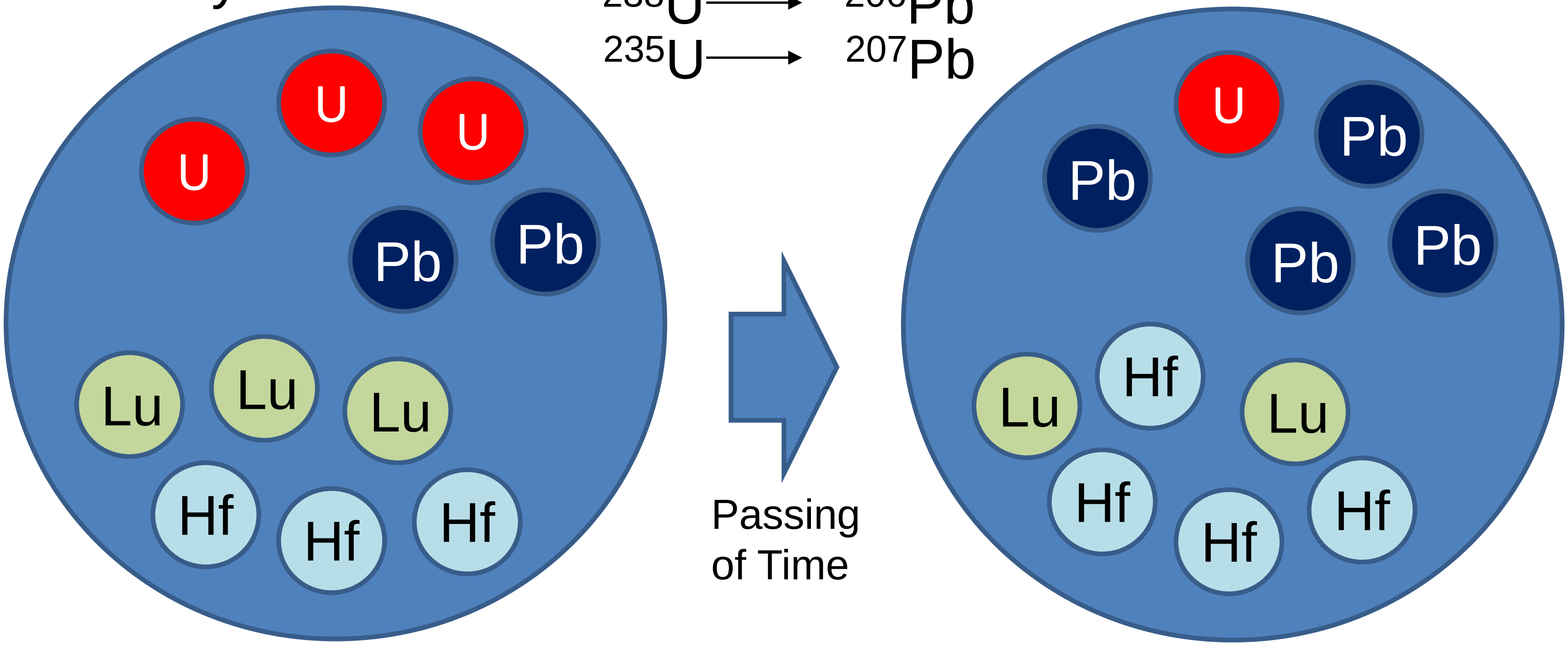
However, its half-life has not been established !

The isochron method with the known age

Closed system

$^{238}U \longrightarrow {}^{206}Pb$

$^{235}U \longrightarrow {}^{207}Pb$



Passing of Time

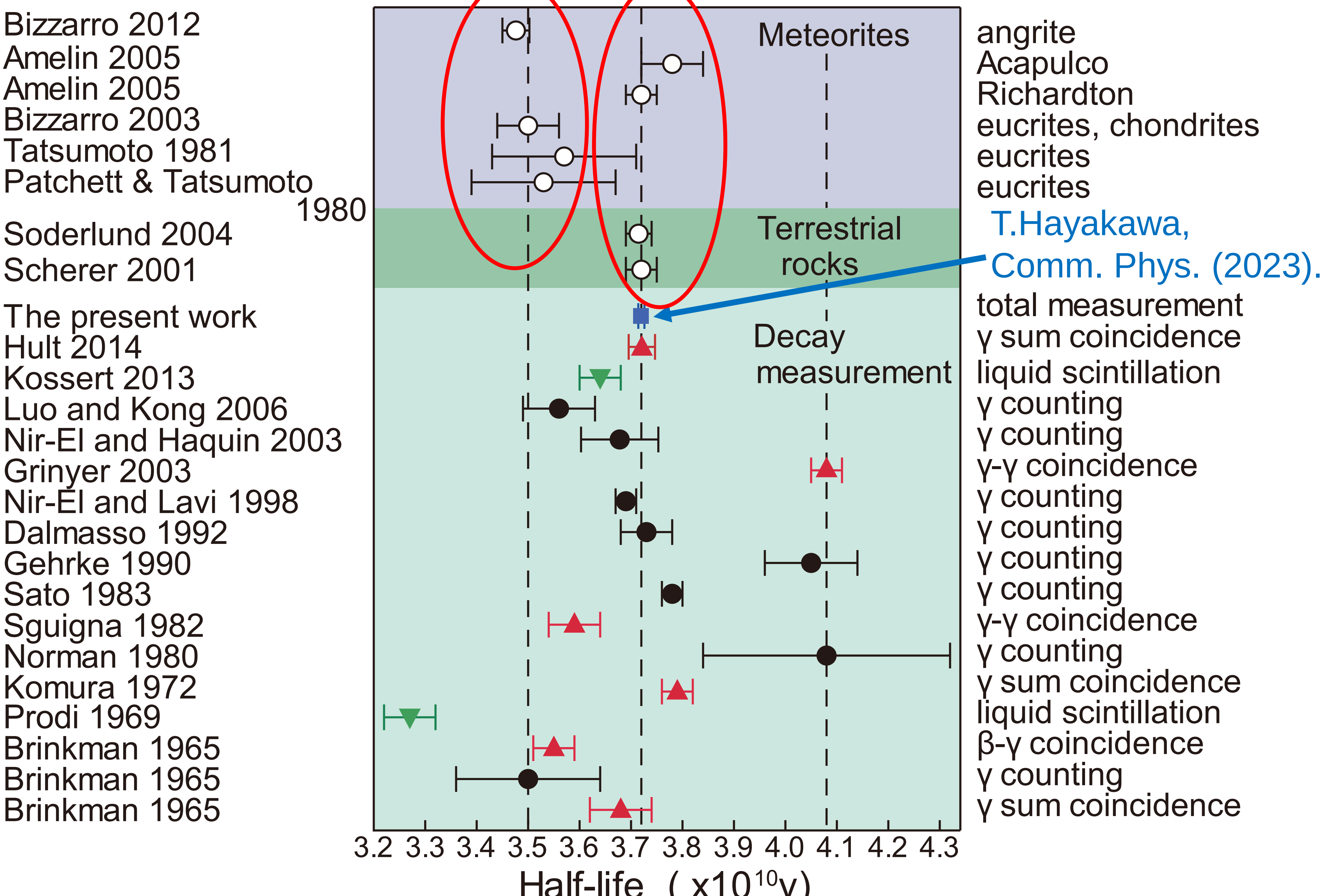
At the formation of the parent body

At present

Radioisotopes decay to their daughter nuclei inside of meteorites.

$^{176}Lu \longrightarrow {}^{176}Hf$

Measured half-life



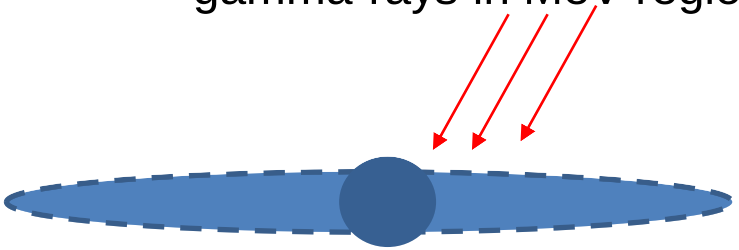
T.Hayakawa, Comm. Phys. (2023).

Decay acceleration by photons

Decay of 176Lu was accelerated by photons from sun or galaxy.

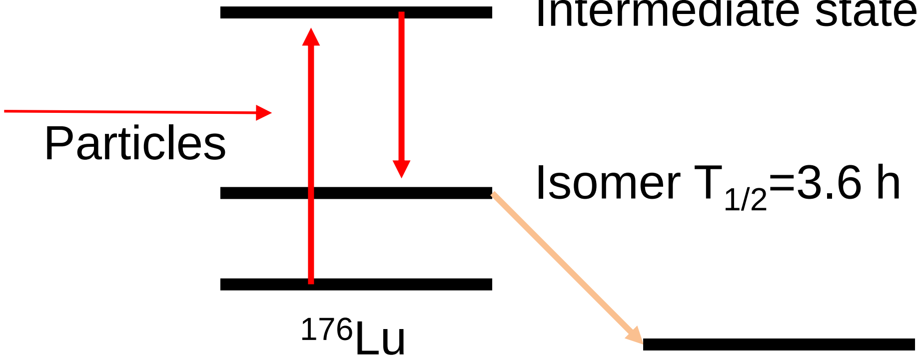
Albarede, Geochemica et Cosmochimica Acta, 70,1261 (2006)

gamma-rays in MeV region



Possible gamma-ray sources.

i) Young sun
ii) Radio activities such as ^{60}Co
iii) Gamma-ray burst
iv) Supernova cluster



Intermediate states

Particles

Isomer $T_{1/2}$=3.6 h

^{176}Lu

^{176}Hf

Thrane, ApJ, 717, 861 (2010)

i) Neutrinos from SNe
ii) High energy cosmic rays (protons) accelerated by SNe

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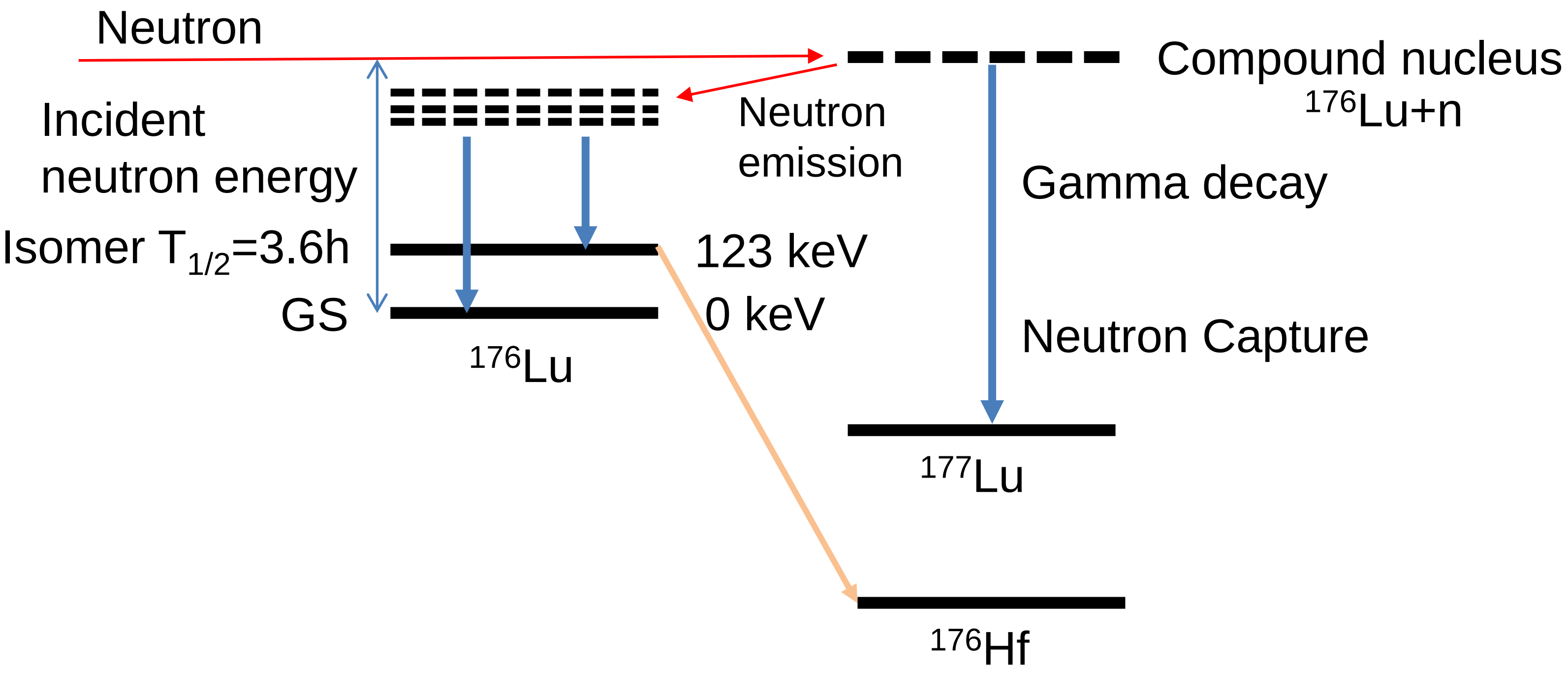
^{10}Be in primitive meteorites is considered to be produced by galactic cosmic-rays and/or solar energic particles.

Bekaert et al., Sci. Adv. 2021; 7 : eabg8329

Isomer transition probability by neutrons

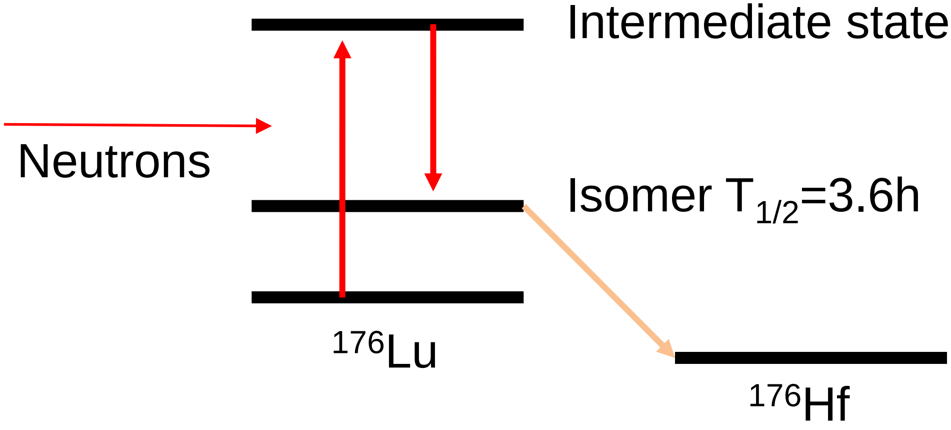


The threshold energy of 176Lu(n, n')176Lum reaction corresponding to the excitation energy of the isomer of 123 keV.

The 176Lu(n, n')176Lum reaction may occur in the energy range from 123 keV to a few MeV.

For example, ^{115}In(n, n')^{115}In^{m} reactions are well known, but the nuclear data for ^{176}Lu is poor.

Isomer transition probability by neutrons



Intermediate states on ^{177}Lu

Neutrons

Isomer $T_{1/2}$=3.6h

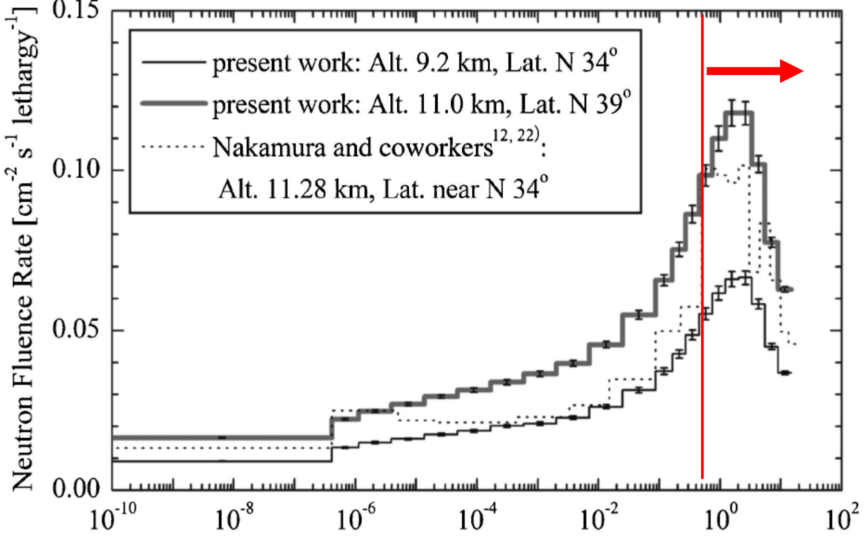
^{176}Lu

^{176}Hf

High energy cosmic-ray could produce many protons and neutrons by spallation reactions.

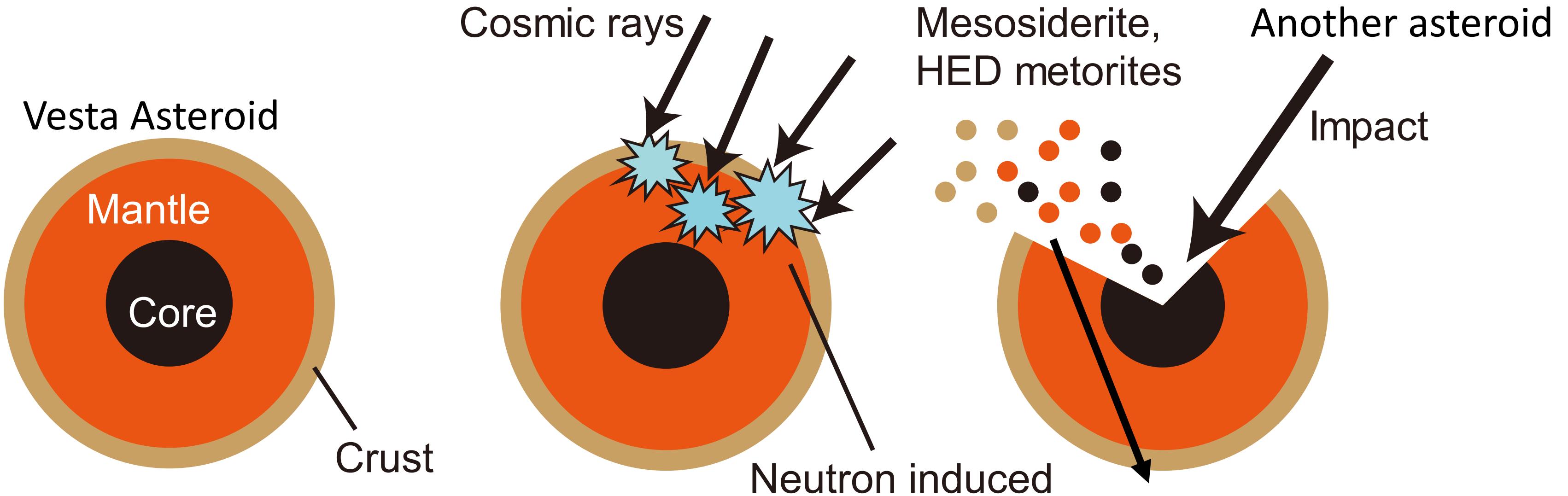
For example, ^{115}In(n, n’)^{115}In^{m} reactions are well known, but the nuclear data for ^{176}Lu is poor.

YA JIMA, JNST, 47, 31 (2015)



The energy spectrum of cosmic-ray neutrons is similar with that generated by high power laser.

Mesosiderite came from Vesta



Vesta Asteroid

Mantle

Core

Crust

Cosmic rays

Neutron induced reactions

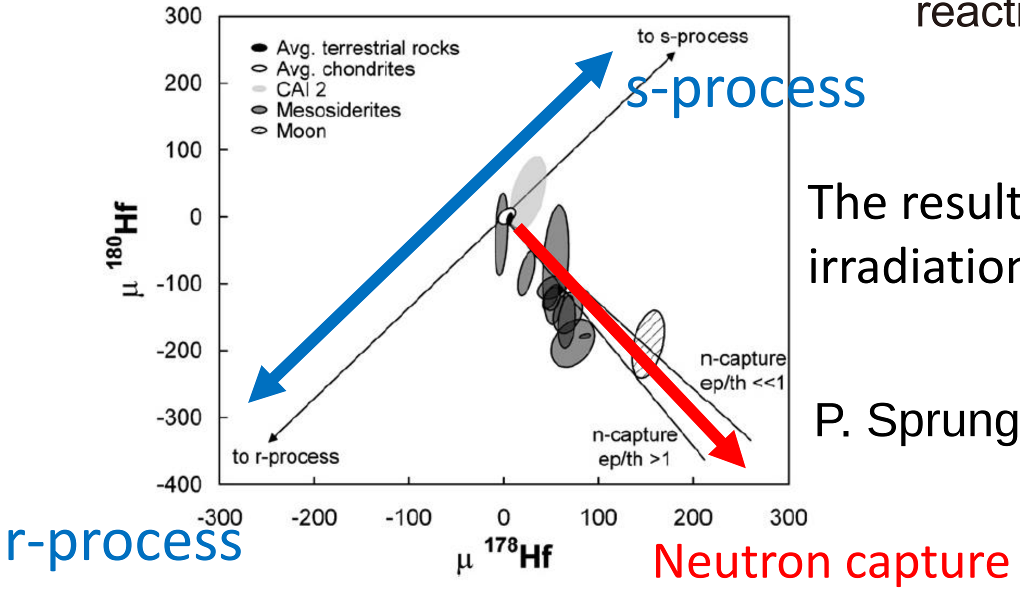
Mesosiderite, HED metorites

Another asteroid

Impact

Meteorites went to earth

Isotopic abundances of Hf



s-process

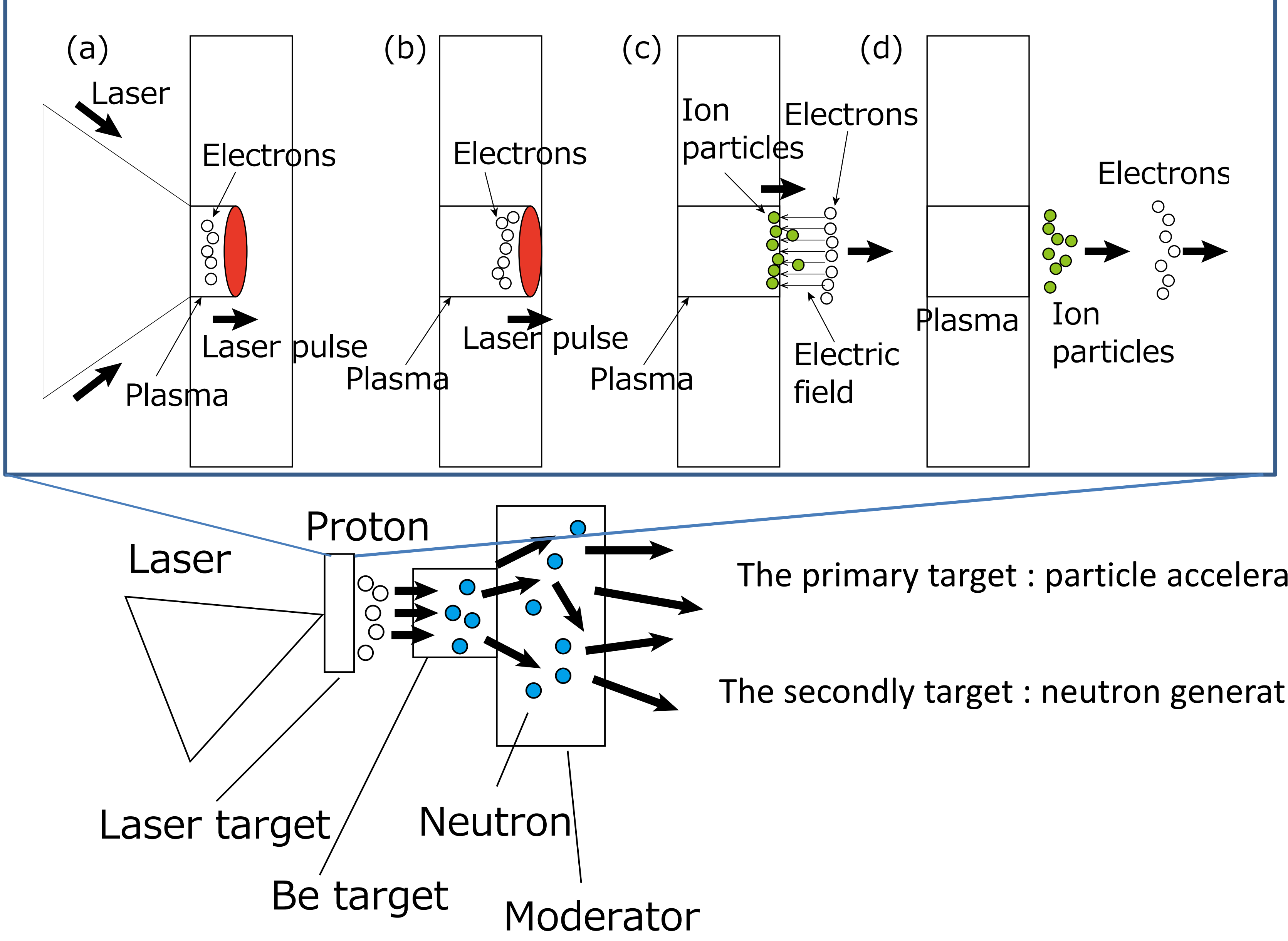
r-process

Neutron capture

The result shows that the strong neutron irradiation occurred at Vesta.

P. Sprung, Earth Planet. Sci. Lett. 295, 1, (2010)

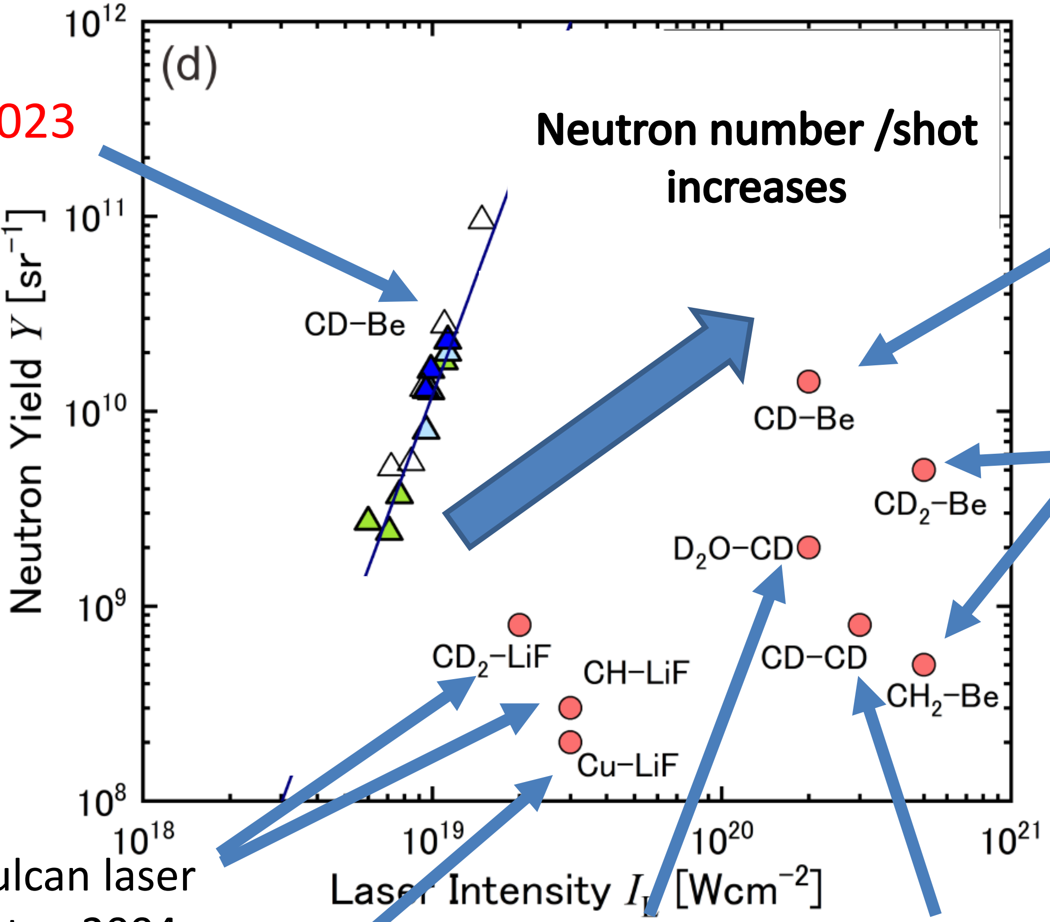
Mechanism of laser neutron generation



The primary target : particle acceleration

The secondly target : neutron generation

Laser neutron generation in the world



Neutron number /shot increases

LFEX laser
Osaka Uni., 2023

A. Yogo, Phy. Rev. X, 13, 011011 (2023)

The PHELIX laser,
GSI in Darmstadt
Kleinschmidt, 2018

The Trident laser, LANL
Roth, 2013

The Vulcan laser
Lancaster, 2004

The Jupiter Laser, LLNL
Higginson, 2011

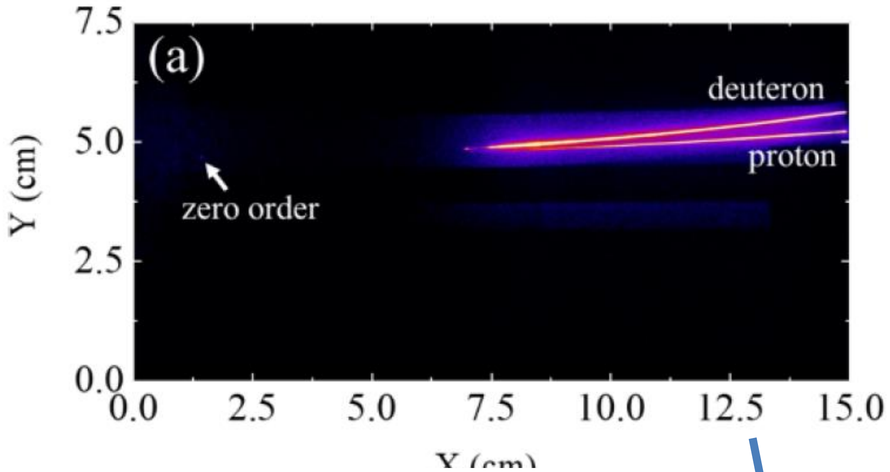
The Vulcan laser
Alejo, 2017

The Vulcan laser
Kar, 2016

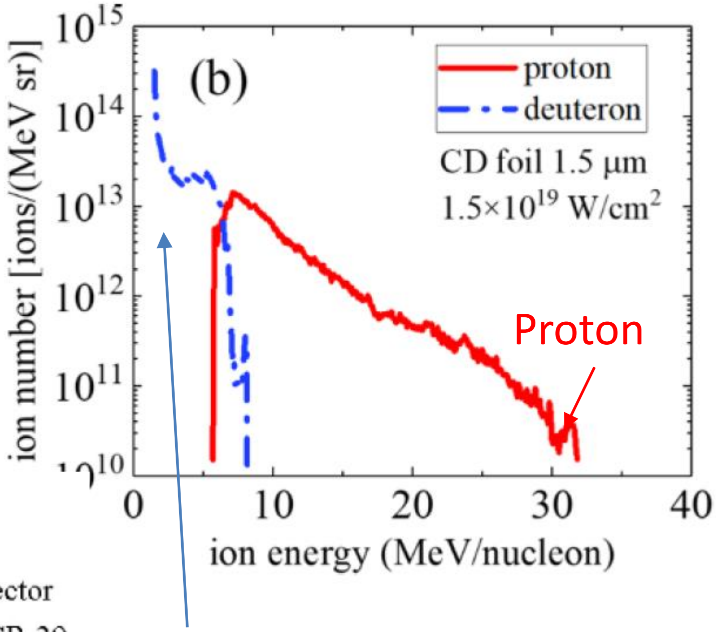
Rutherford Appleton
Laboratory

Ion energy by LFEX at Osaka Uni.

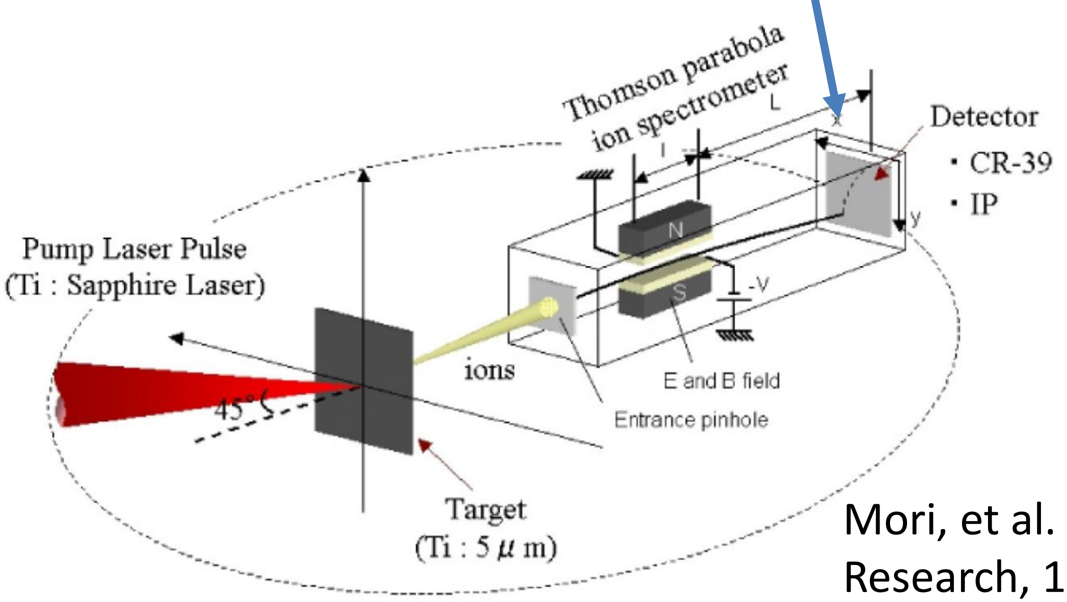
Observed image of ions



Energy spectrum of proton and deuterons

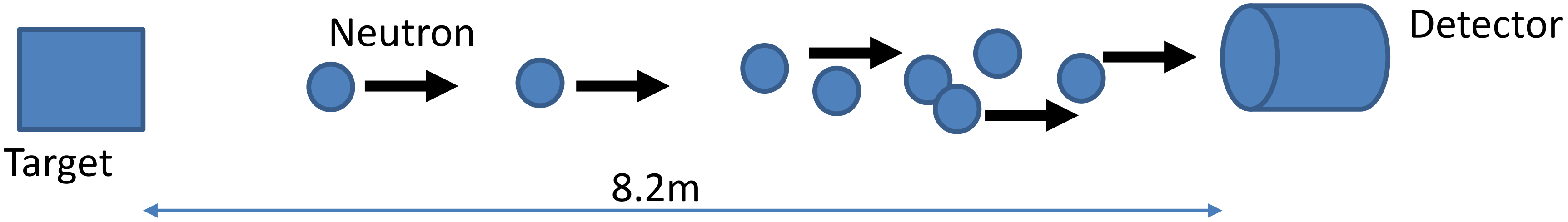


Deuteron



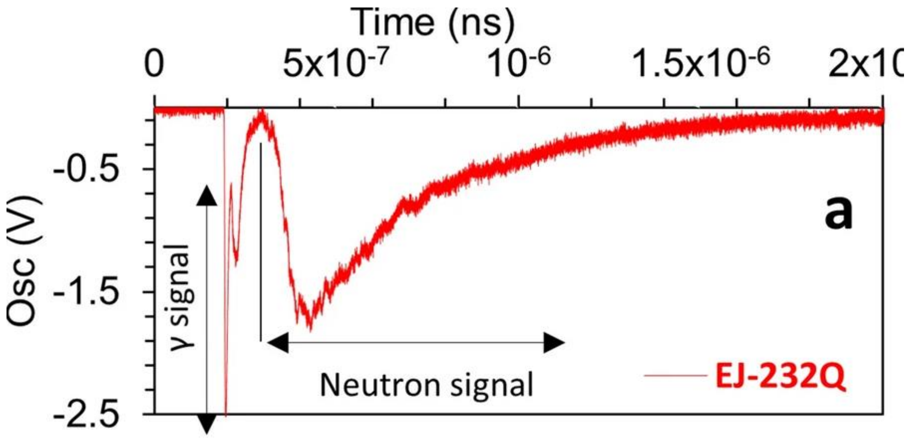
Mori, et al. Plasma and Fusion Research, 1, 042 (2006)

Neutron energy measurement



Time-of-flight method: flight time is converted to particle energy

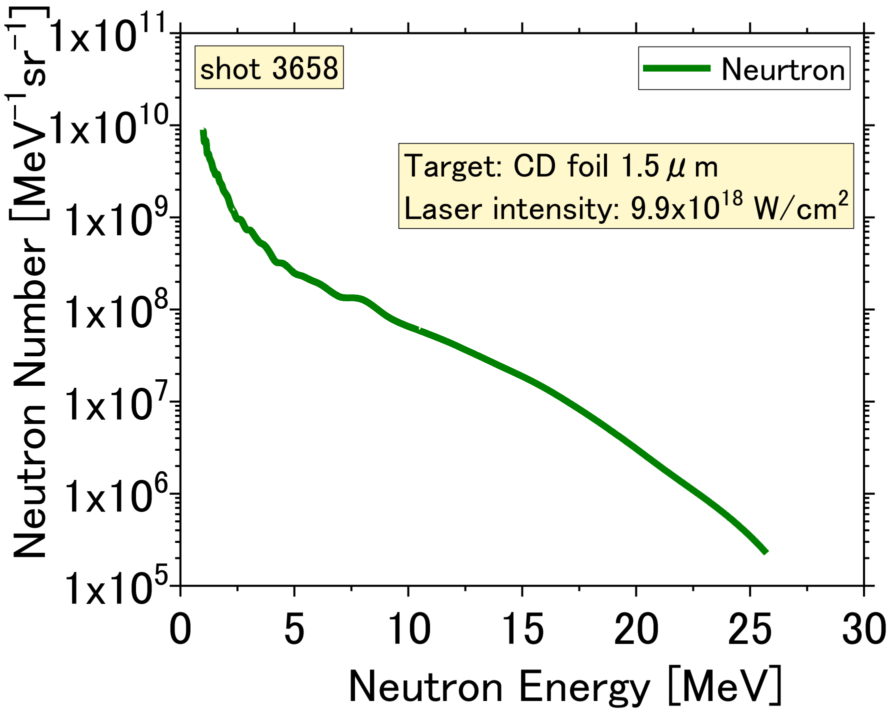
Output of detector



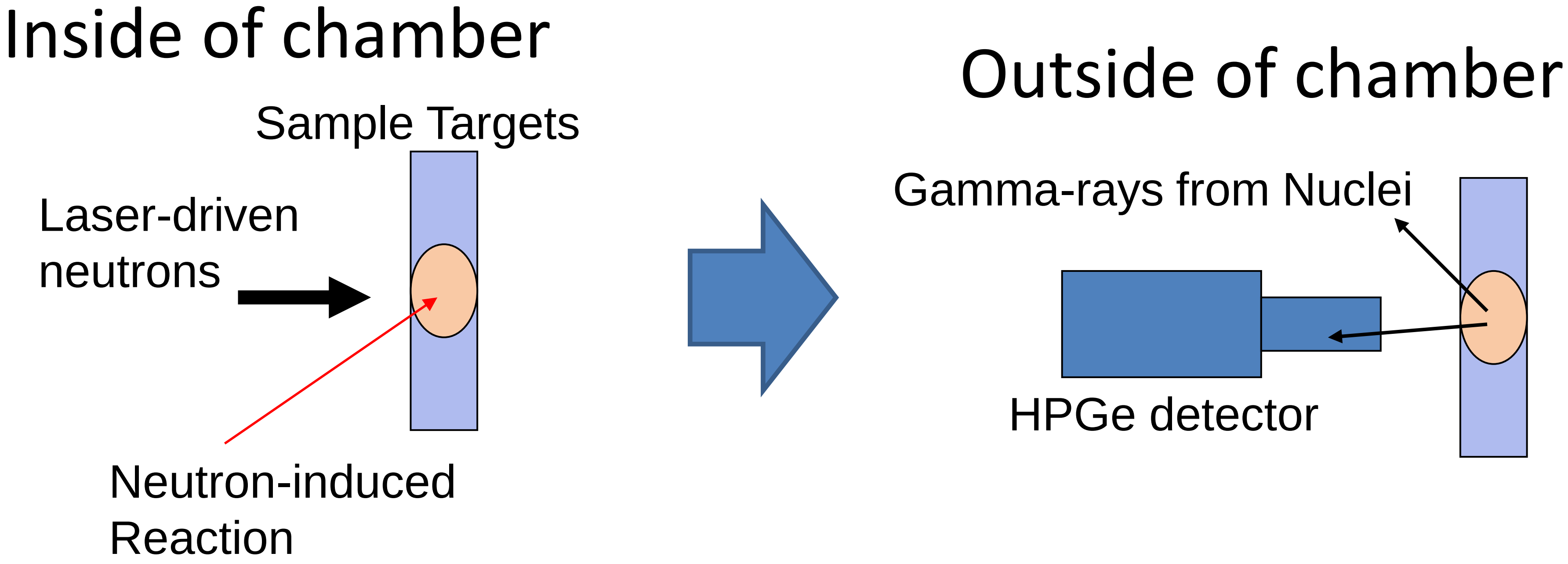
S. R. Mirfayzi, et al. Sci. Rep. 10, 20157 (2020).

E>1 MeV is measured.

Primary neutron energy spectrum



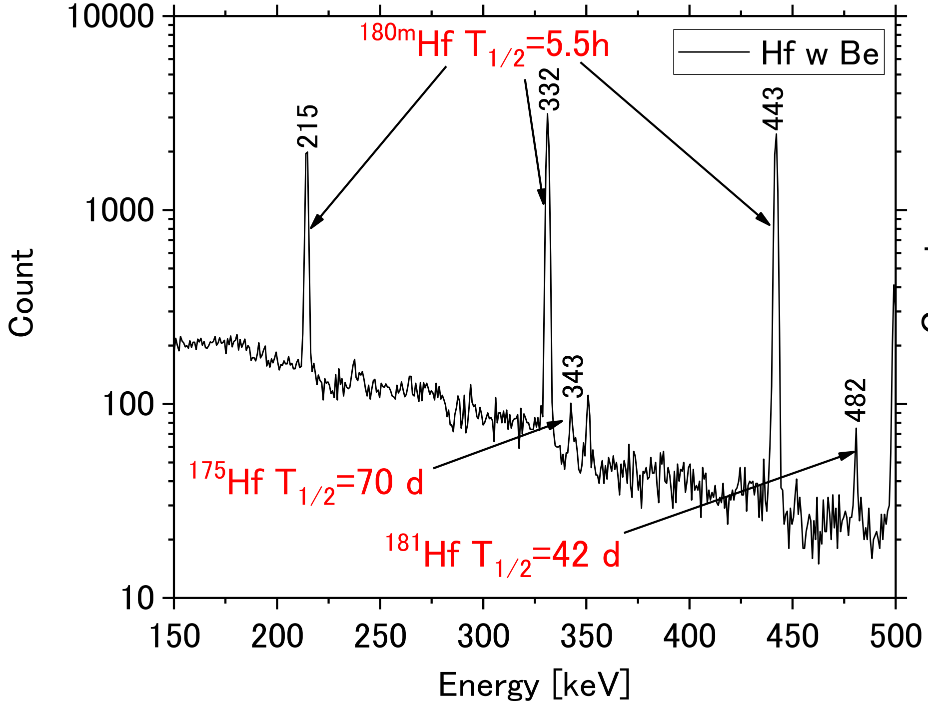
Activation method



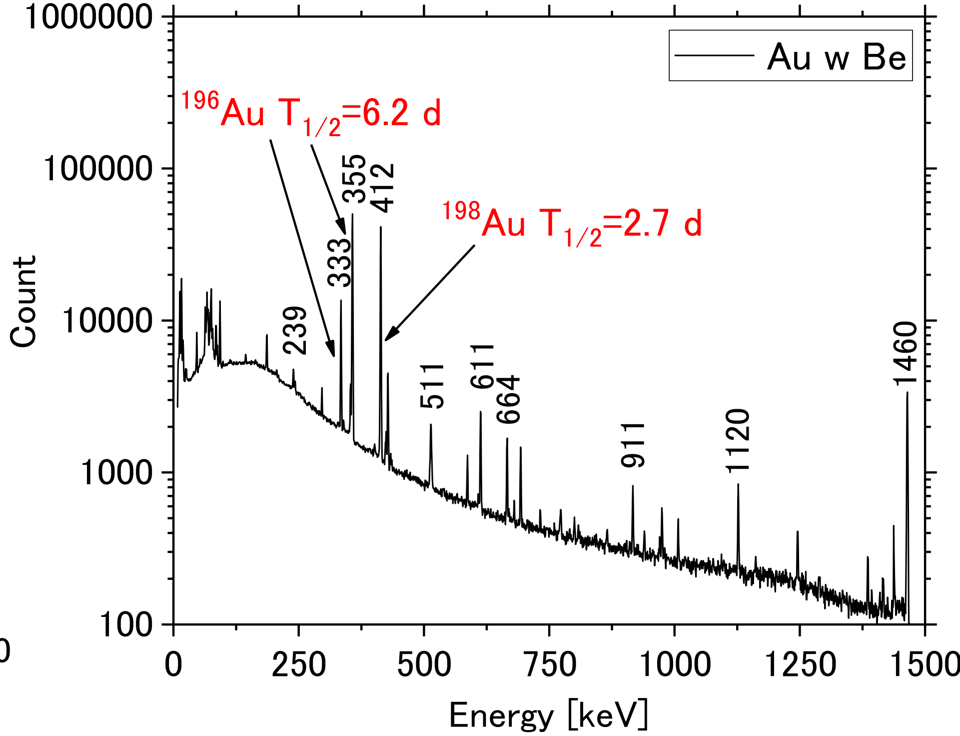
Activation method is known as one of the most precise measurement methods of the number of radioactive nuclei.

Gamma-ray spectrum from neutron irradiated targets.

Hf sample



Au sample

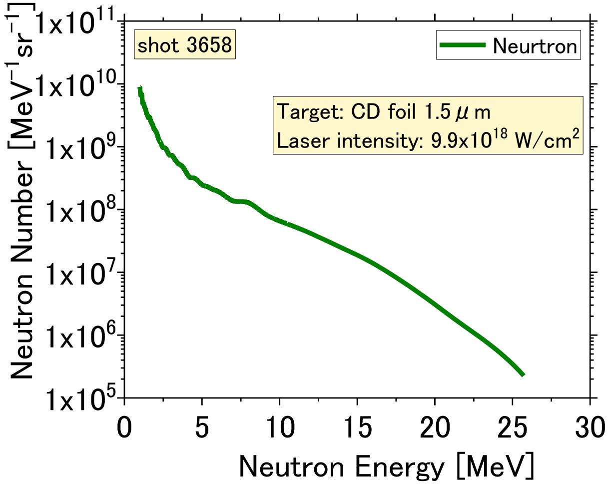


^{196}Au is produced by ^{97}Au(n,2n)^{196}Au reaction (E=8-20MeV)。

Measurement of high energy neutrons

From measured spectrum

1. Integrated neutron reaction cross section S can be calculated from Neutron spectrum $\phi(E)$ and the reaction cross section $\sigma(E)$



$$S = \int_{8\mathrm{MeV}}^{20\mathrm{MeV}} \sigma(E)\phi(E)\,dE$$

From the JENDL nuclear database.

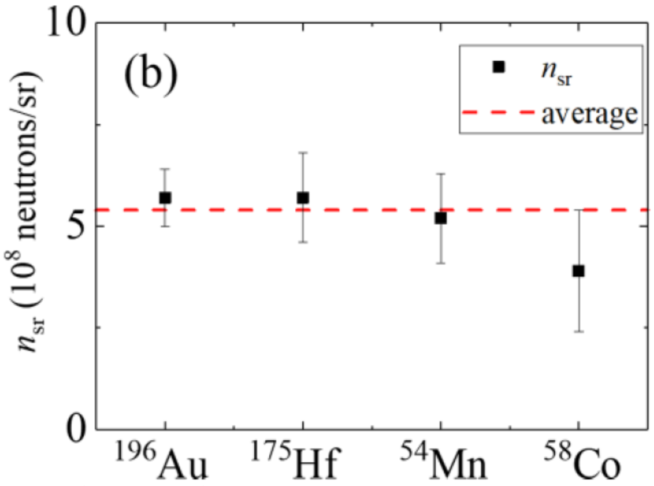
2. $n_{8\text{-}20\mathrm{MeV}}$ is calcualted from Measureed $r_{(n,2n)}$ and S

$$n_{8\text{-}20\mathrm{MeV}} = \frac{r_{(n,2n)}}{S} \times \frac{Area}{Solid\ angle} \times Scatterd\ effect$$

[neutrons/sr]

$r_{(n,2n)}$: Experimental (n, 2n) reaction rate per nucleus

Neutron fluences obtained from the four targets are consistent !



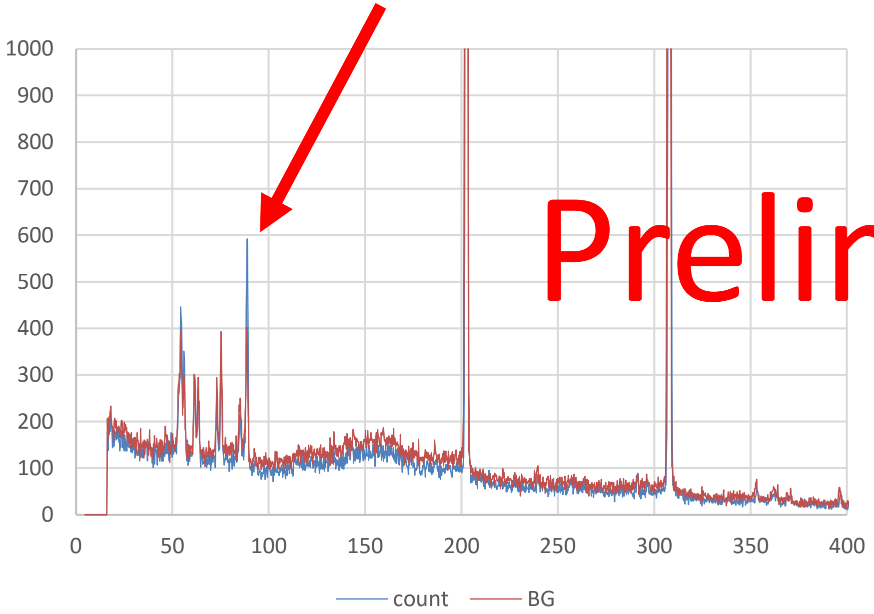
Mori, et al. Phys. Rev. C 104, 015808 (2021).

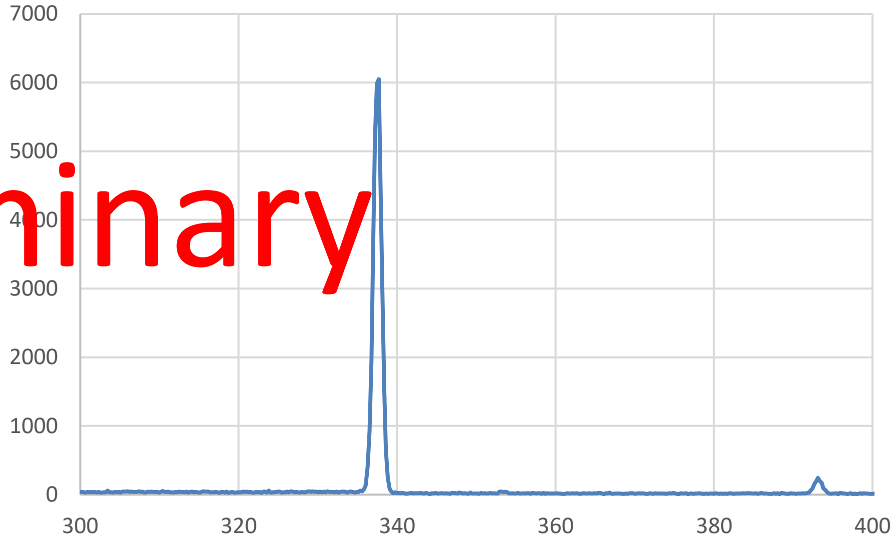
Measurement of decay acceleration of ^{176}Lu

Lu target

In target

Decay acceleration





Preliminary

We observed signals of decay acceleration by laser driven neutrons.

New data from Ryugu

An space explore "Hayabusa2" visited on an asteroid "Ryugu" and returned with its samples.

Ryugu was found that it was formed in the region outer the Jupiter orbit and moved to the inside.

Yokoyama, Science, 2022

Ryugu was located far from the other asteroids, which are the parent bodies of the meteorites.

It gives an important hint for decay acceleration.

Summary

Laser-driven pulsed neutron sources have remarkable advantages:

1. High flux for a single shot
2. Short pulse width
3. Continues energy spectrum

⇨ Nuclear Astrophysics

Proposals for nuclear astrophysics experiments using laser driven gamma-ray pulse.

T. Hayakawa, et al. Quantum Beam Science, 1(1), 3 (2017).

We verified high energy neutron fluence using activation method

Mori, et al. Phys. Rev. C 104, 015808 (2021).

We verified thermal neutron fluence using activation method.

Mori et al., J. Phys. G: Nucl. Part. Phys. 49 065103 (2022).

We demonstrate decay acceleration by cosmic-ray neutrons

Proposal for decay acceleration by neutron generated with cosmic rays.
T. Hayakawa, et al. Communications Physics 6, 299 (2023).