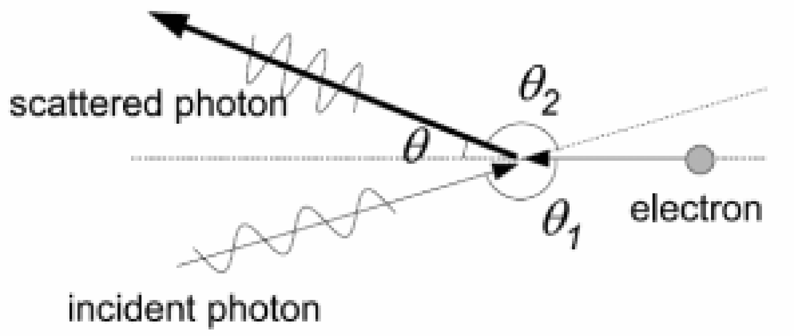
Applications of high-brightness gamma-rays from ERLs

Gamma-ray NDA research Group

T. Hayakawa (JAEA)

The 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

Laser Compton Scattering gamma-rays



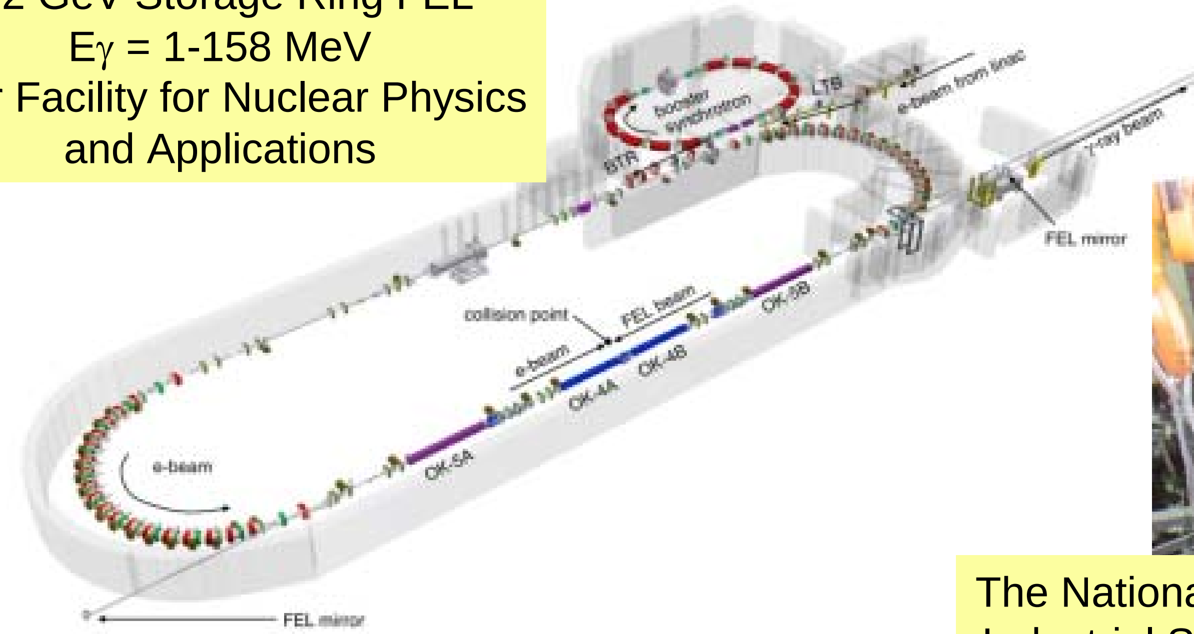
$$E_\gamma = \frac{E_L(1-\beta\cos\theta_1)}{1-\beta\cos\theta + (E_L/E_e)(1-\cos\theta_2)}$$

Narrow-band γ-ray is obtained by collimating the scattering angle θ.

However, inhomogeneous broadening exists – emittance, energy spread.

LCS γ-ray Sources in the world

HIγS @ Duke Univ.
1.2 GeV Storage Ring FEL
Eγ = 1-158 MeV
User Facility for Nuclear Physics and Applications

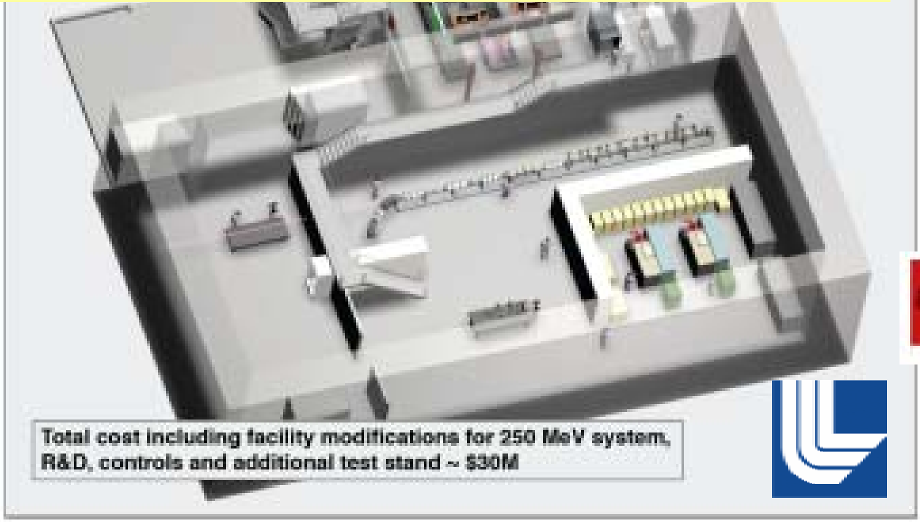


The National Institute of Advanced Industrial Science and Technology In Japan (AIST)
300-700 MeV Storage Ring
Eγ = 4-40 MeV
User Facility

NewSUBARU in SPring-8: 1-1.5 GeV Storage Ring
Eγ = 1.7-40 MeV
User Facility

Next generation of LCS γ-ray Sources

T-REX @ Lawrence Livermore Natl. Lab.
250 MeV Linac
Eγ = 1-2 MeV
Test Facility for Nuclear Security Applications

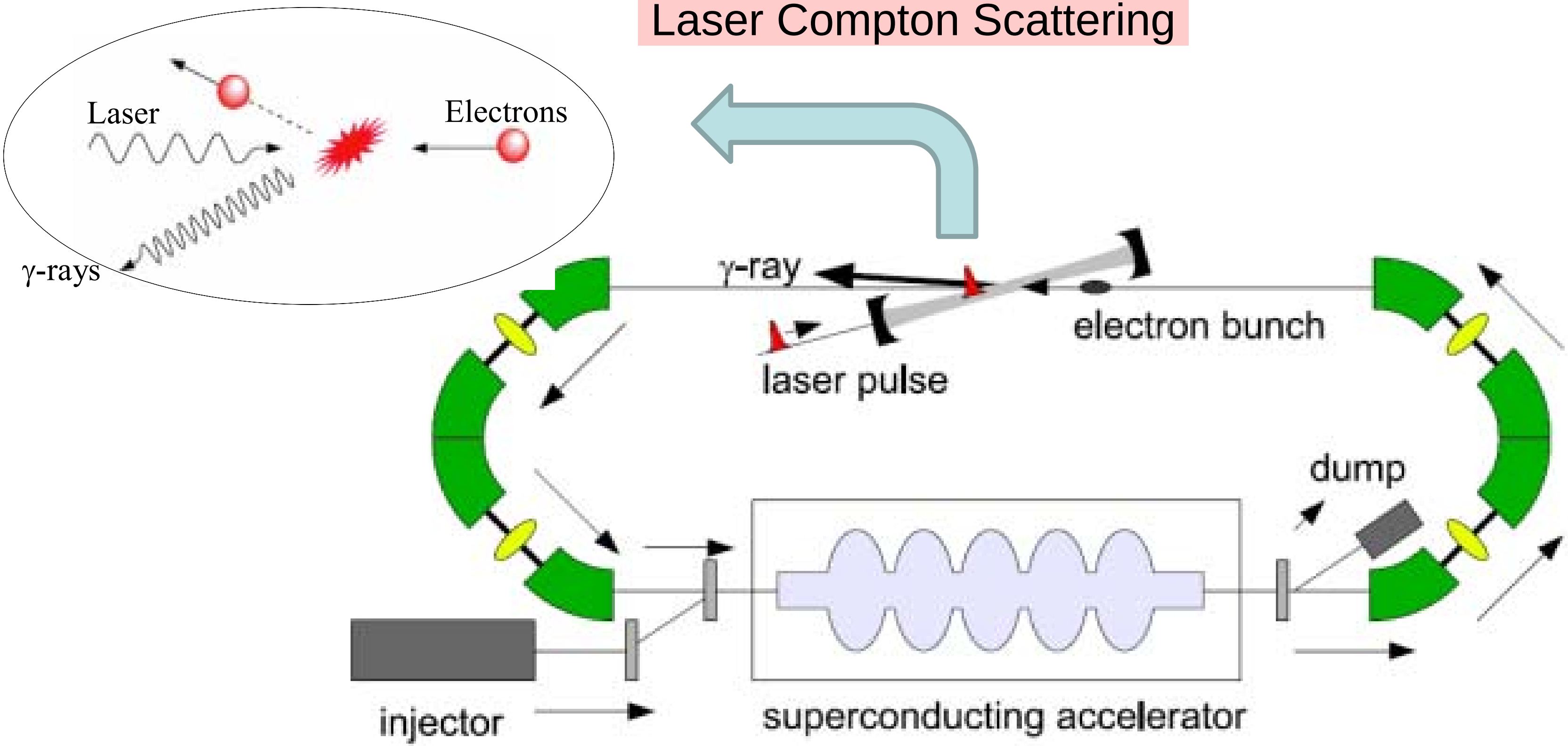


ELI-NP : Complex of PW lasers and LCS

ERL-based LCS gamma-ray @ KEK-JAEA
Test Facility for Nuclear Material Safegurds Applications

Energy-Recovery Linac as a γ-ray Source

Laser Compton Scattering

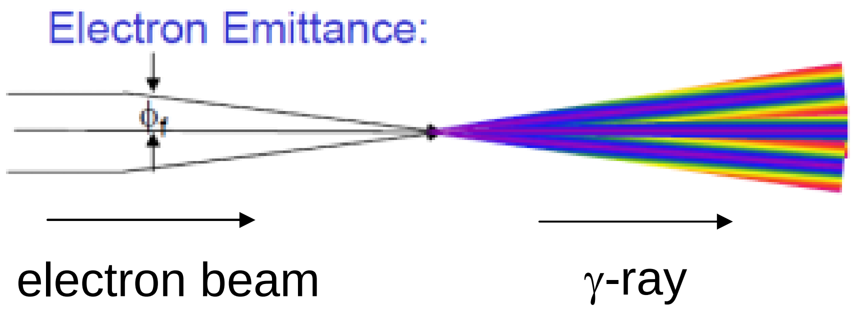


R. Hajima et al., AccApp'07 (2007).

- ✓ energy-recovery for high-average current beams
- ✓ always fresh electron beam

γ-ray beam with high-flux and narrow bandwidth

Small emittance for narrow-band γ-ray



emittance smears "angle-energy correlation" of γ-ray

from a detail analysis:

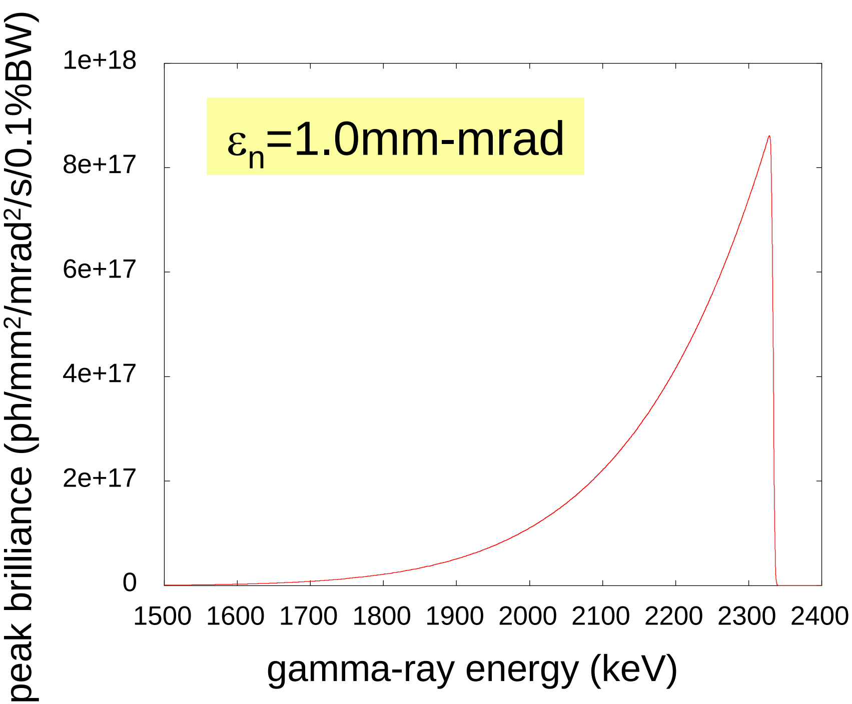
$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)_{rms} = 2\left(\frac{\varepsilon_n}{\sigma_x}\right)^2$$

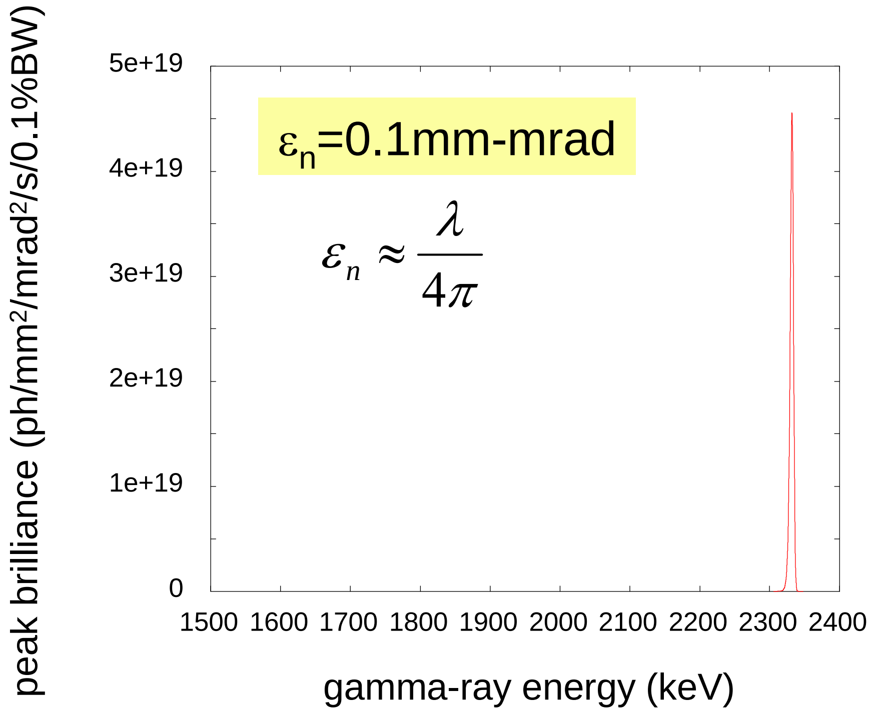
normalized emittance ε_n = 1mm-mrad, collision spot σ_x = 10μm → ΔEγ/Eγ = 2%

normalized emittance ε_n = 0.1mm-mrad, collision spot σ_x = 10μm → ΔEγ/Eγ = 0.02%

normalized emittance of 0.1mm-mrad is the key parameter.

On-axis Spectral Brightness (analytical estimation)





$$\hat{B}_z = \frac{4\times 10^{-15}}{\pi^2}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\exp\left\{\frac{\chi-1}{2\chi\Delta u_\perp^2}\left[2+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\left[1-\Phi\left\{\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\right]$$
$$\times\frac{\eta e^{1/\eta^2}[\Phi(1/\eta)-1]-\mu e^{1/\mu^2}[\Phi(1/\mu)-1]}{\mu^2-\eta^2}, \qquad (50)$$

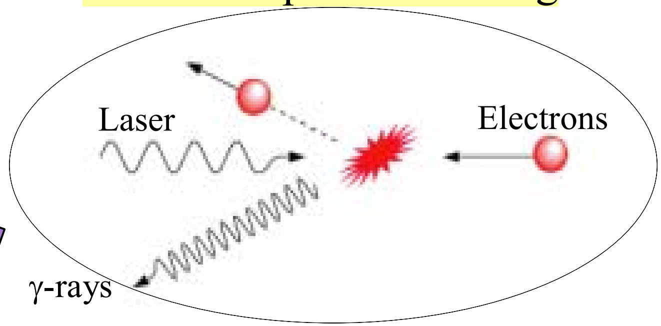
calculation by using a formula in [1].

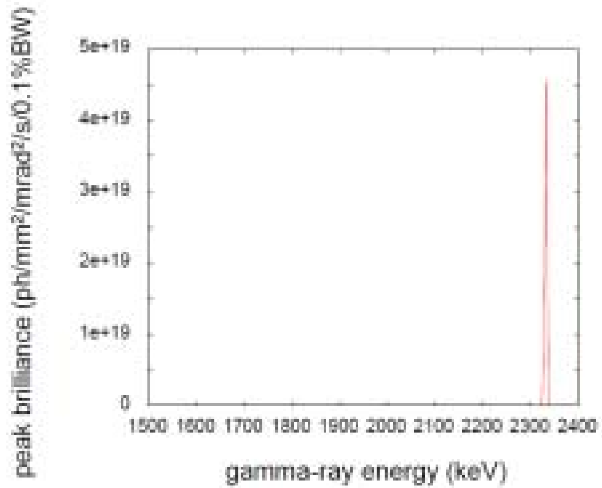
[1] F.V. Hartemann et at. Phys. Rev. ST AB 8, 100702 (2005).

Nuclear Engineering

Measurement of Nuclear Material by γ-rays

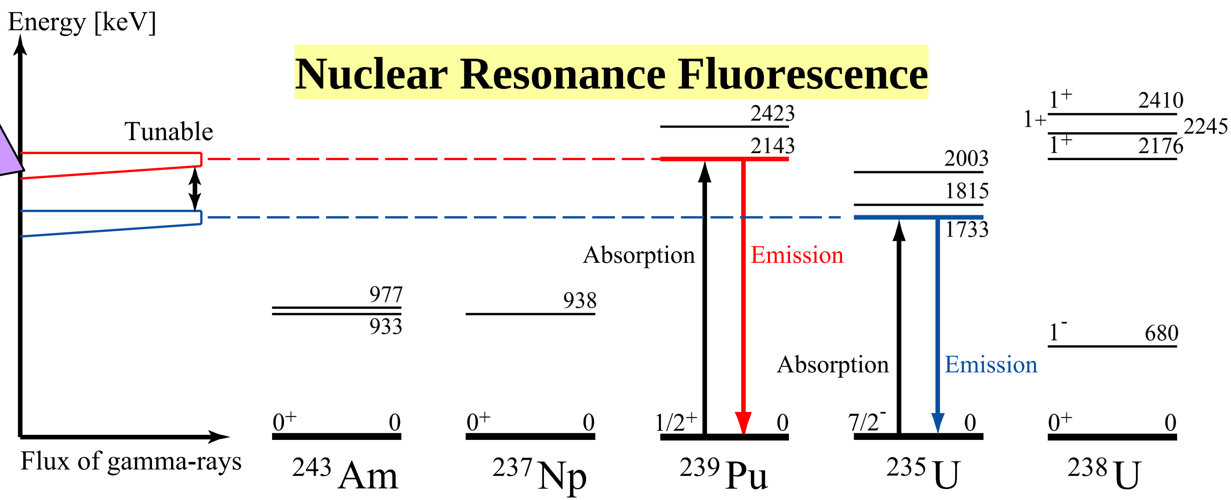
Laser Compton Scattering





Mono-energetic & tunable g-ray beam
(not like bremsstrahlung)

Nuclear Resonance Fluorescence



R. Hajima et al., J. Nuclear Science and Technology, 45, 441-451 (2008).

What is advantage ?

•Detection of isotopes of all the elements of Z>2

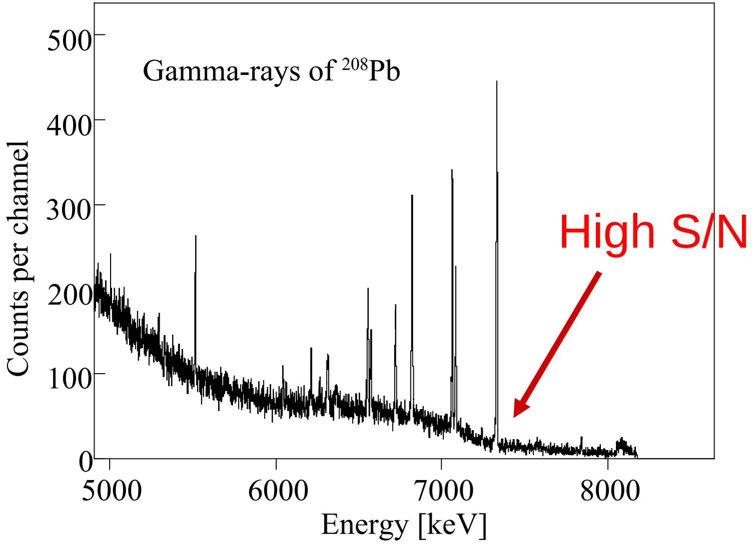
• We can identify unstable isotope.

• With about 2-MeV gamma-rays we can detect Pu through several centimeter thick shields.

• Gamma-rays at 2 MeV penetrates water of several ten centimeters.

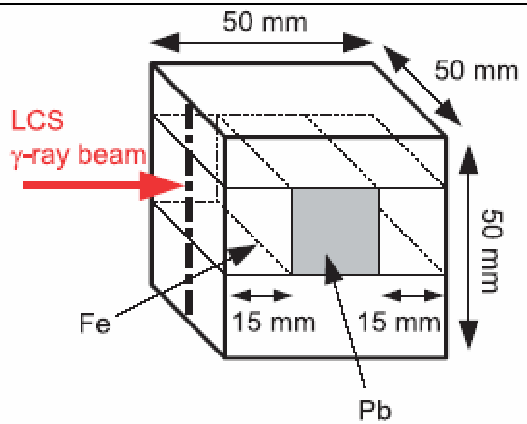
• High S/N ratio at peak

Example of detection of Pb-208 with a LCS gamma-rays in Japan.

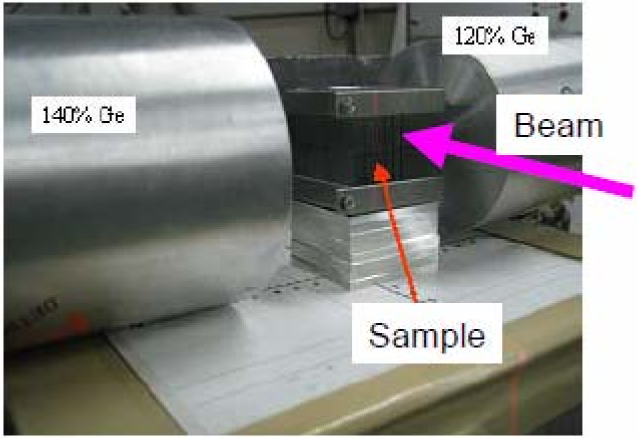


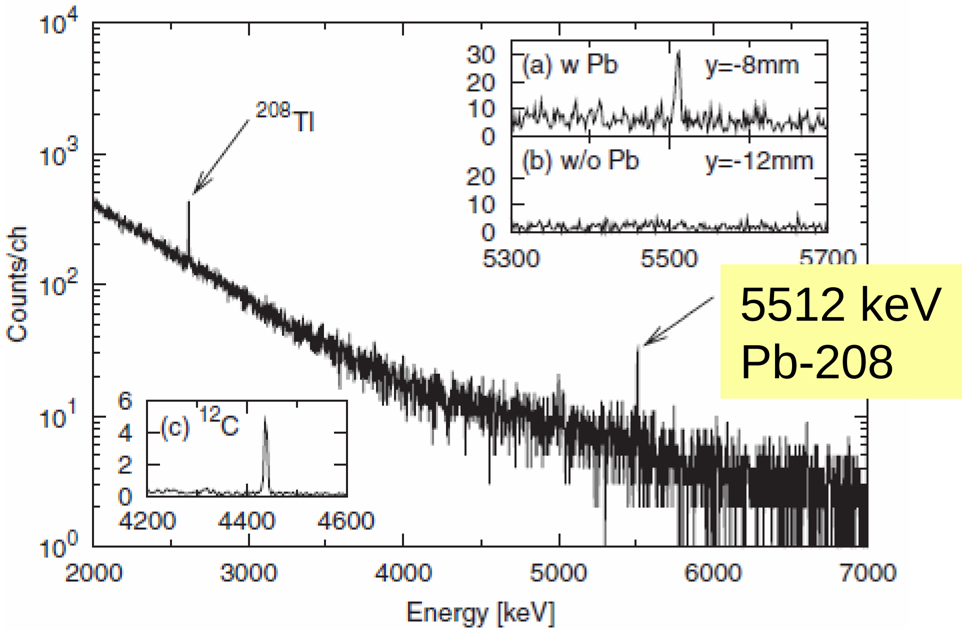
T.Shizuma,et al., Phys. Rev. C 78, 061303(R) (2008)

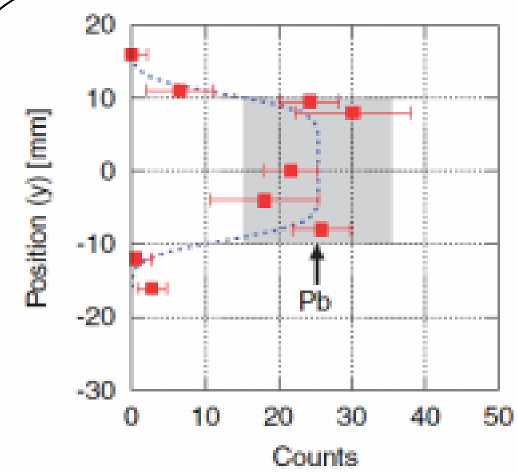
Experimental Demonstration at AIST (Tsukuba)



Pb block shielded by 15mm-thick iron box



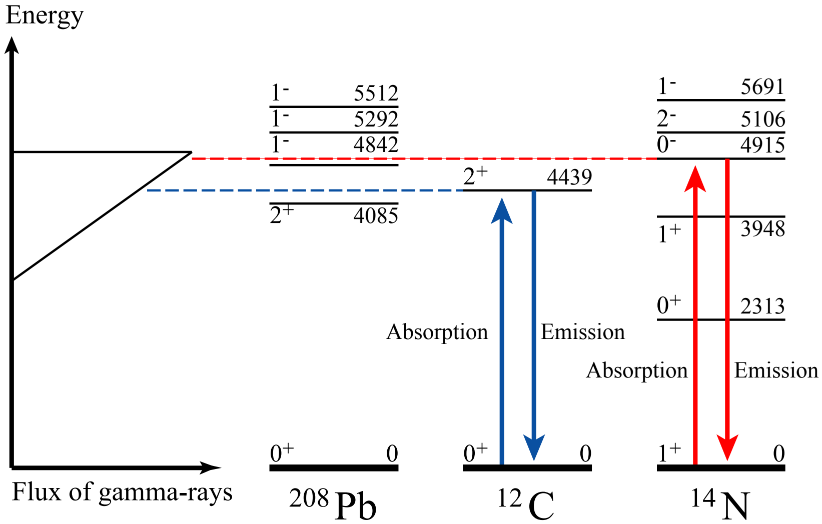




Position and shape of the Pb block were clearly identified.

N. Kikuzawa et al., Applied Physics Express 2, 036502 (2009).

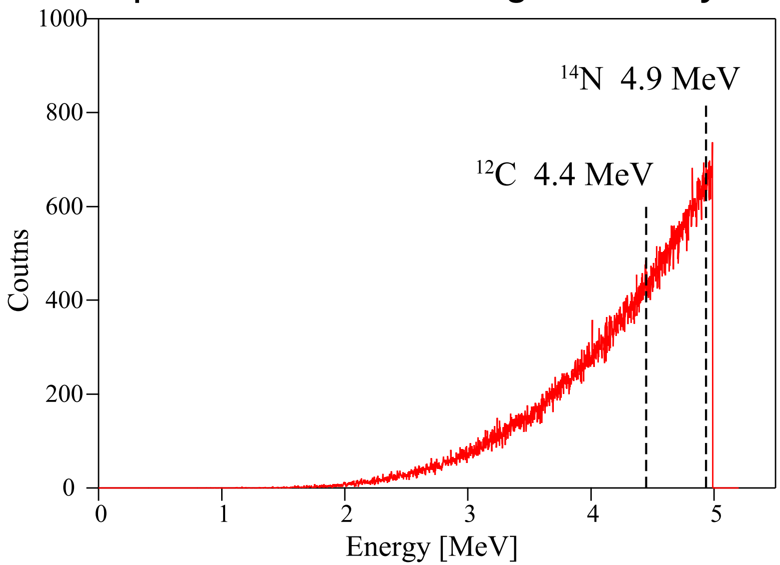
Demonstration of detection of two isotopes at AIST (Tsukuba)



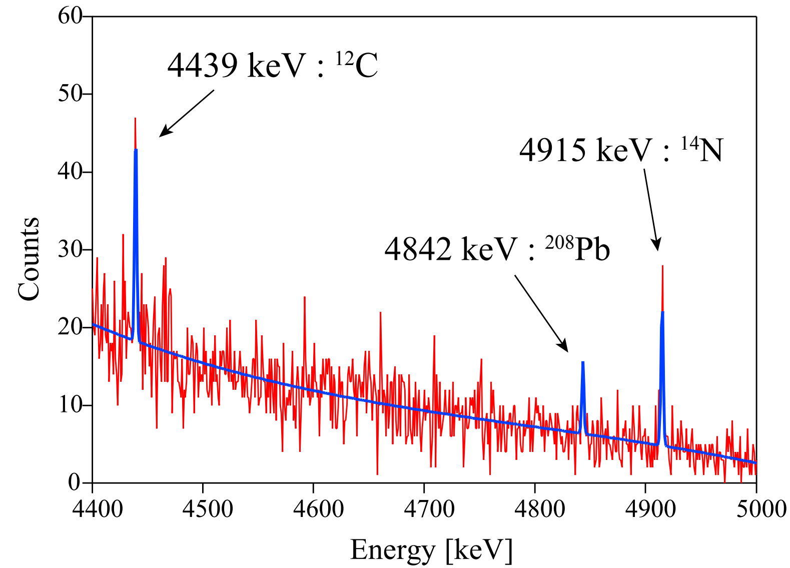
The NRF method can be extended to detect several isotopes at the same time with a selected energy width gamma-rays

We have demonstrated to detect ^{12}C and ^{14}N of the melamine hidden by 15-mm thickness iron plate.

Spectrum of incident gamma-rays



Spectrum of NRF gamma-rays

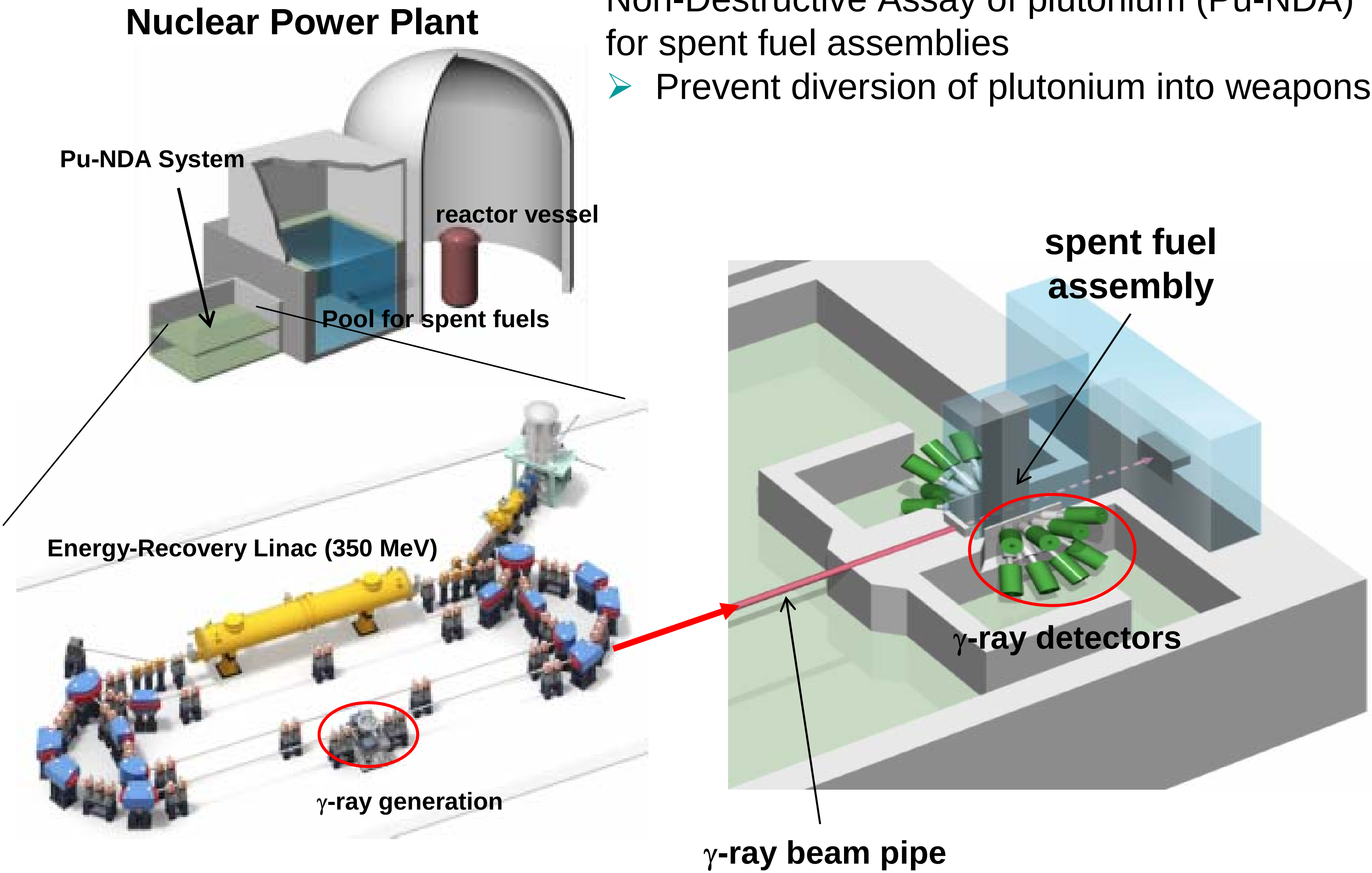


T. Hayakawa et al., Review of Scientific Instrument, 80, 045110 (2009)

A Proposal of a Spent Fuel Pu-NDA System

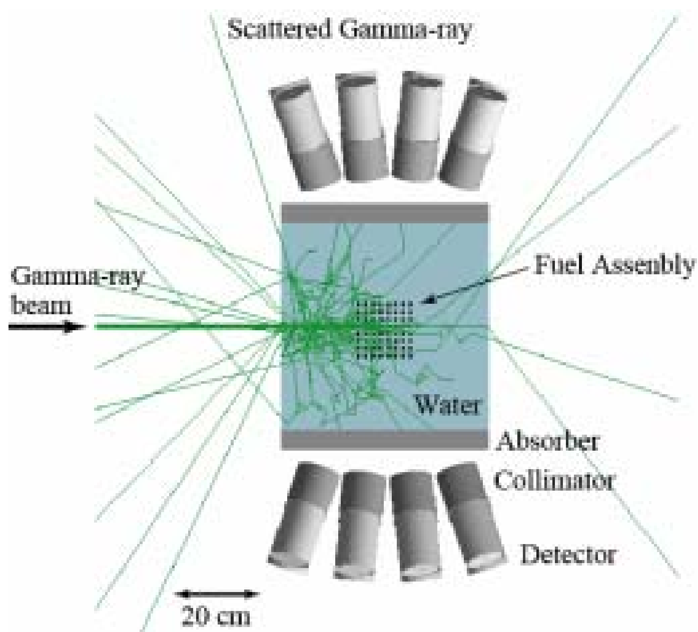
Non-Destructive Assay of plutonium (Pu-NDA) for spent fuel assemblies

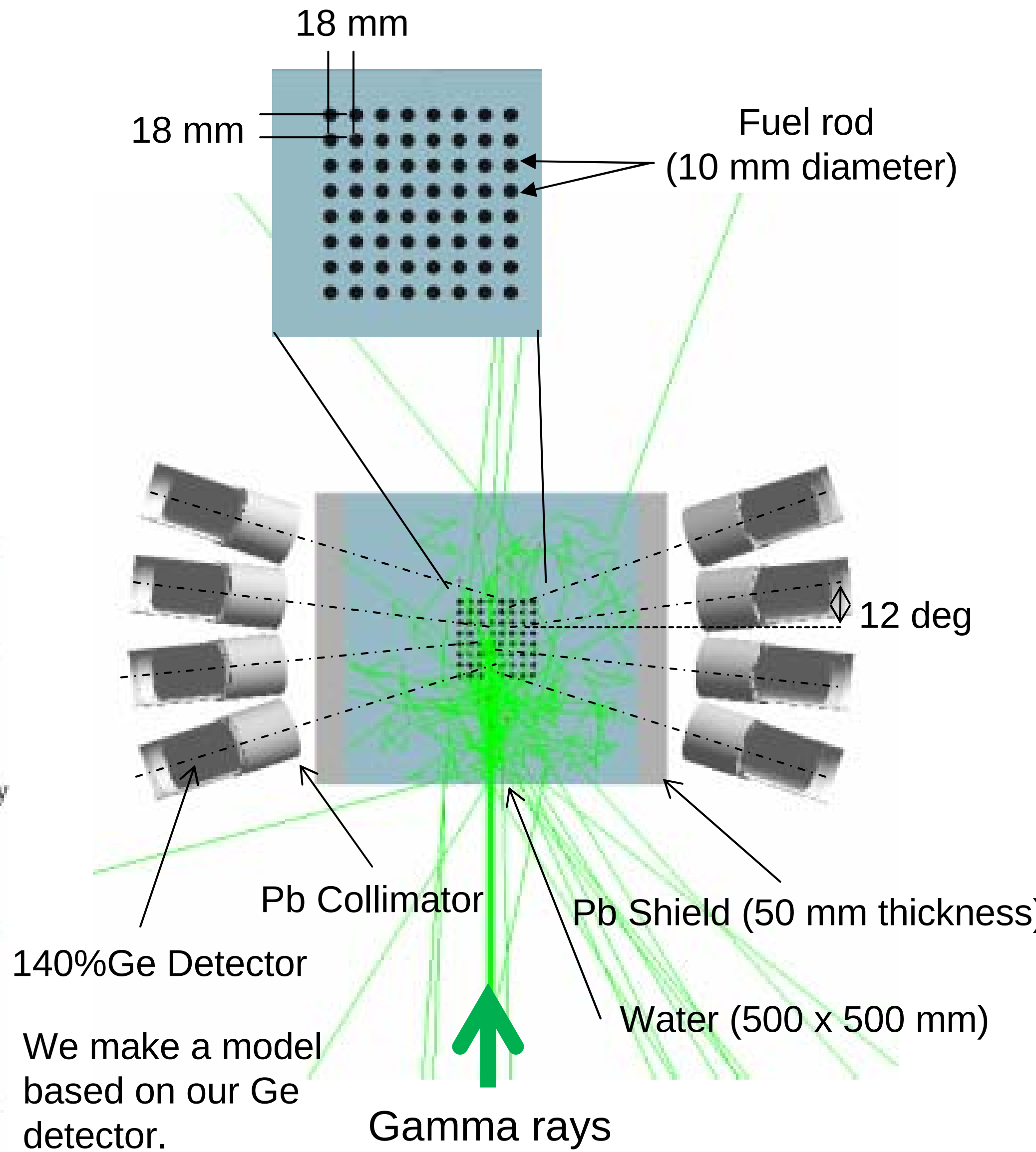
- Prevent diversion of plutonium into weapons



Model for simulation

Composition	
Density	11.0g/cm³
UO_2	90 % (U-238 100 %)
PuO_2	10 % (Pu-239 52 %) (Pu-240 48 %)

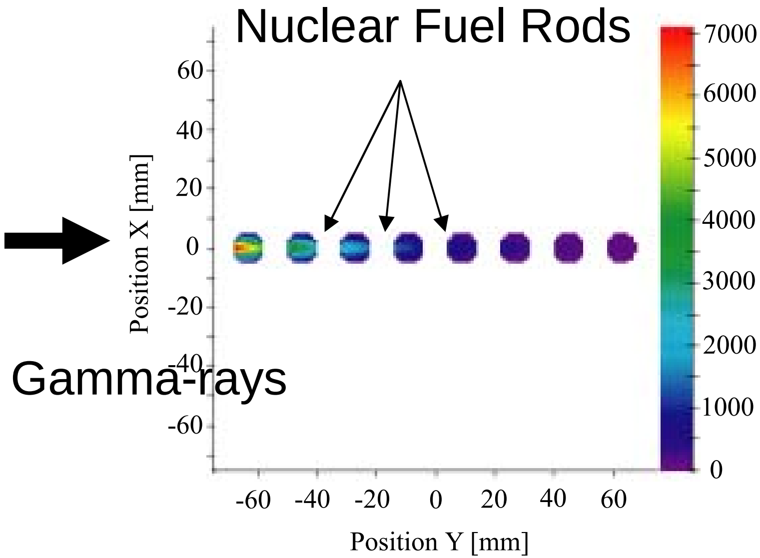




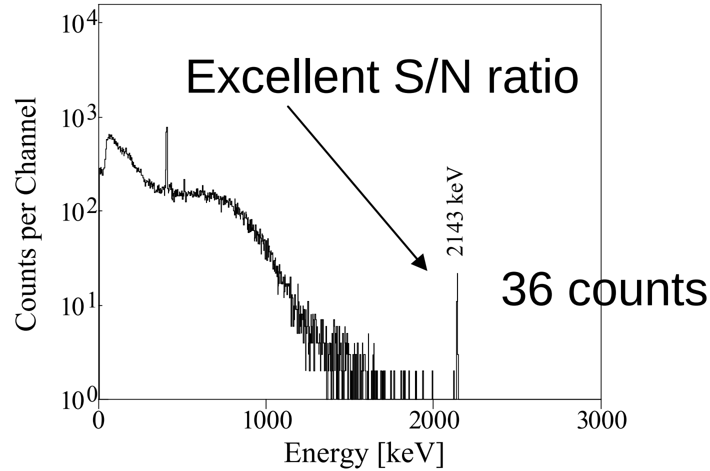
We make a model based on our Ge detector.

Expected spectrum

NRF event rates



A sum spectrum for 5 seconds



Our designed system can observe ^{239}Pu in all rods.

For 10% PuO_2 with 4000 s,
We can obtain 2.8×10^4 events for ^{239}Pu.

For 1% PuO_2 with 4000 s,
We can obtain 2.8×10^3 events for ^{239}Pu.

Statistical Error is 2%.

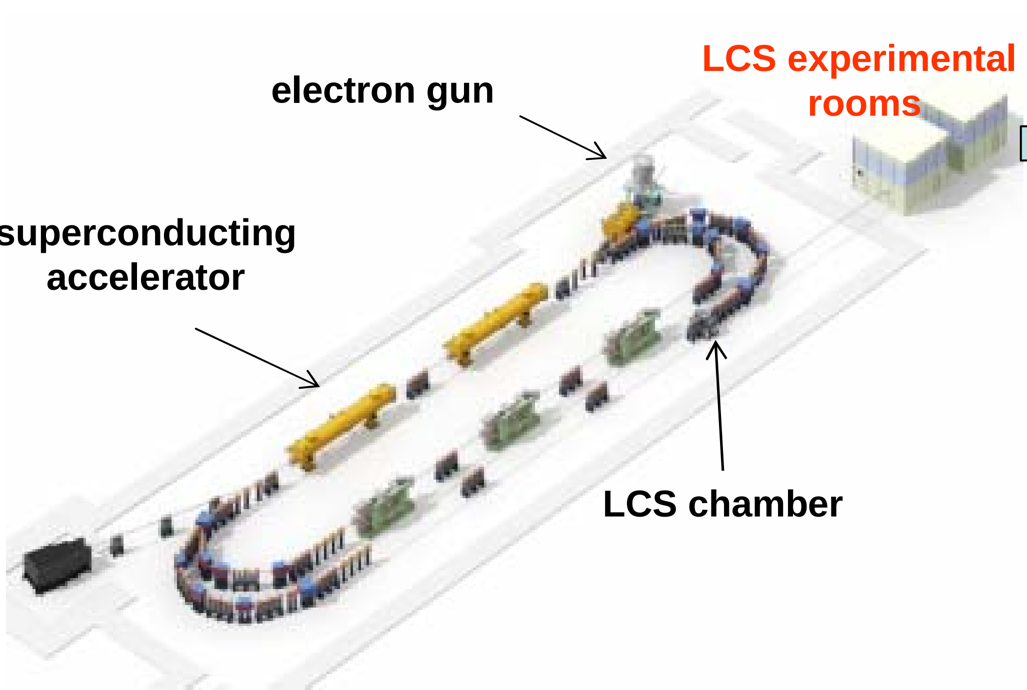
We can measure with statistical error of 2%.

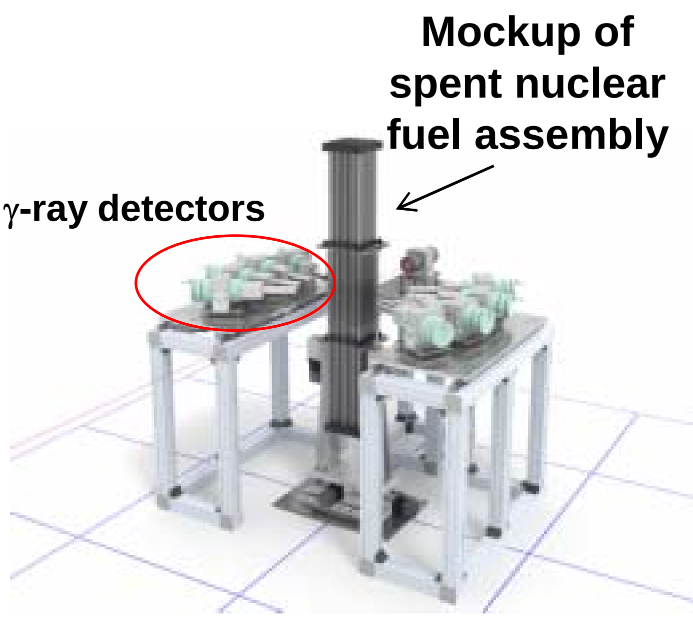
T. Hayakawa, et al. NIMA, 621, 695 (2010).

LCS-γ experiment at the Compact ERL

3-year R&D program funded from MEXT (2011-2013)

- Installation of a LCS chamber
- Generation of LCS γ-rays
- Demo-Experiment of NRF measurement





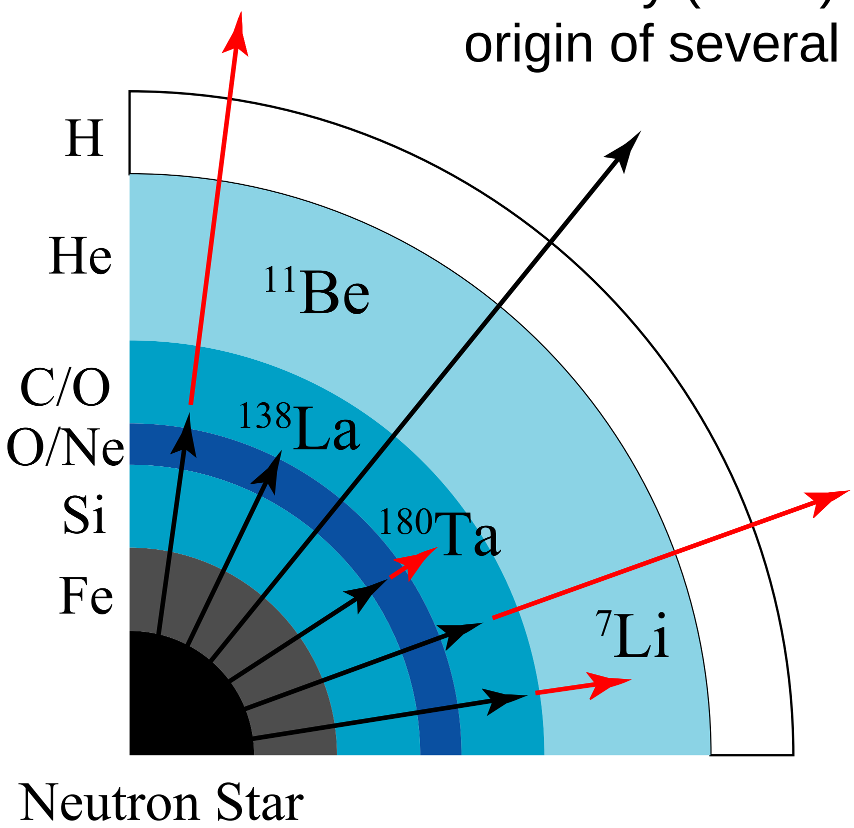
Non-destructive measurement of isotope

Nuclear Astrophysics

1. Neutrino-induced reaction nucleosynthesis in supernovae
2. Neutrino oscillation in supernova neutrino-process
3. Transition probability between the isomer and the ground state in supernovae.

Supernova Neutrino process

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



T. Yoshida, PRL (2005)

Synthesis of Light elements ^{7}Li and ^{11}Be constrains the energy spectrum of the neutrino.

T. Yoshida, PRL (2006)

Neutrino-process can constrains the mixing parameter for neutrino ocsillation.

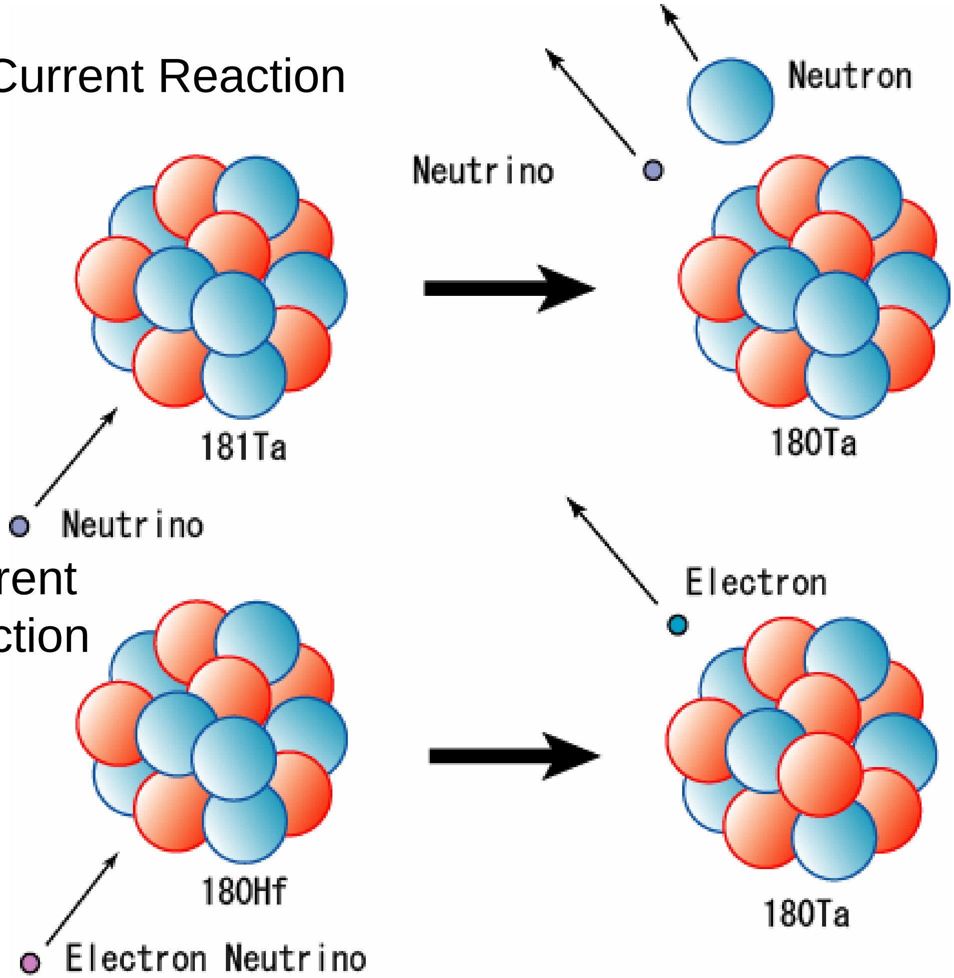
Core collapse supernova explosions

Neutrino wind originates from Neutron star

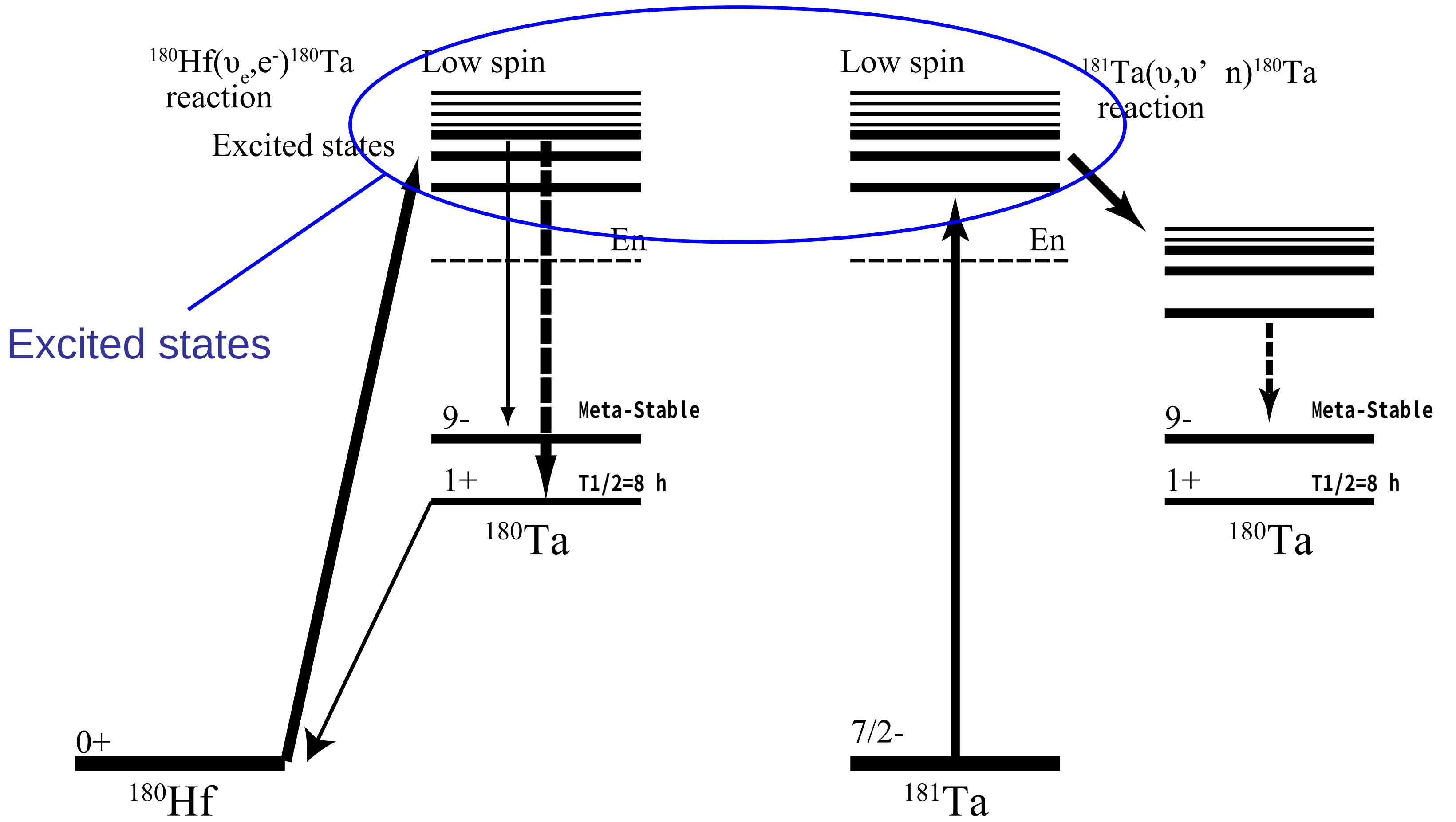
Neutrino Induced-Reactions

Neutral Current Reaction

Charged Current Reaction



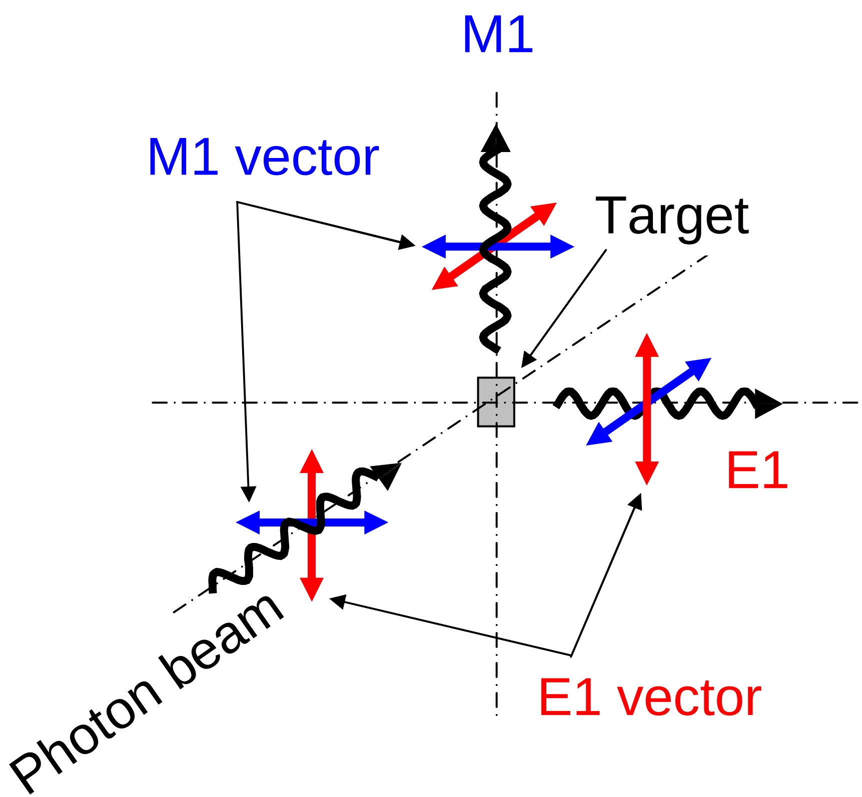
Measurements of M1 strength



M1 strength is a key parameter for neutrino reaction because neutrino has no charge.

Principle of the Measurement

If the photon beam is vertically polarized;
E1 (M1) transitions are scattered into the horizontal (vertical) plane
at the scattering angle of 90 ° .



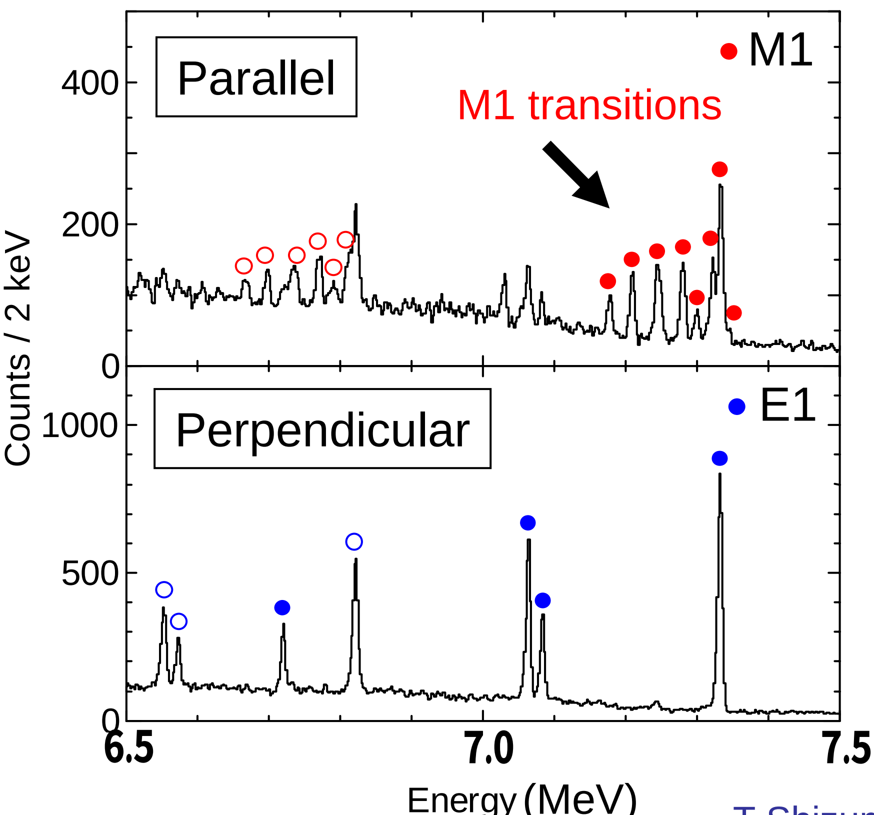
Asymmetry

$$A = \frac{\sigma(90^\circ,0^\circ) - \sigma(90^\circ,90^\circ)}{\sigma(90^\circ,0^\circ) + \sigma(90^\circ,90^\circ)}$$

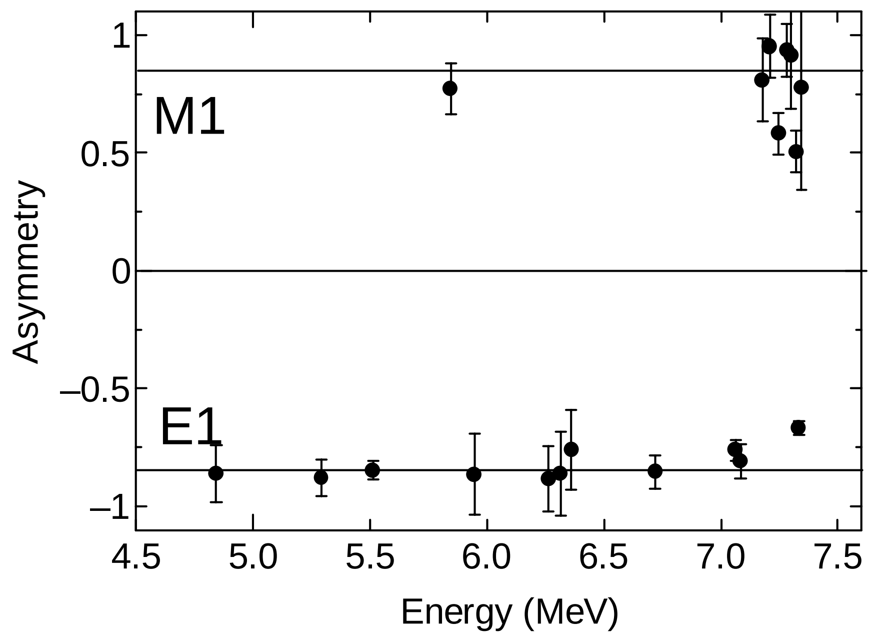
$$= \begin{matrix} +1 \text{ for } M1 \text{ transiton} \\ -1 \text{ for } E1 \text{ transition} \end{matrix}$$

Experimental Results

- Clear difference between different polarization measurements
- Multipole (E1/M1) determination
- Observation of the detailed M1 structure in ^{208}Pb



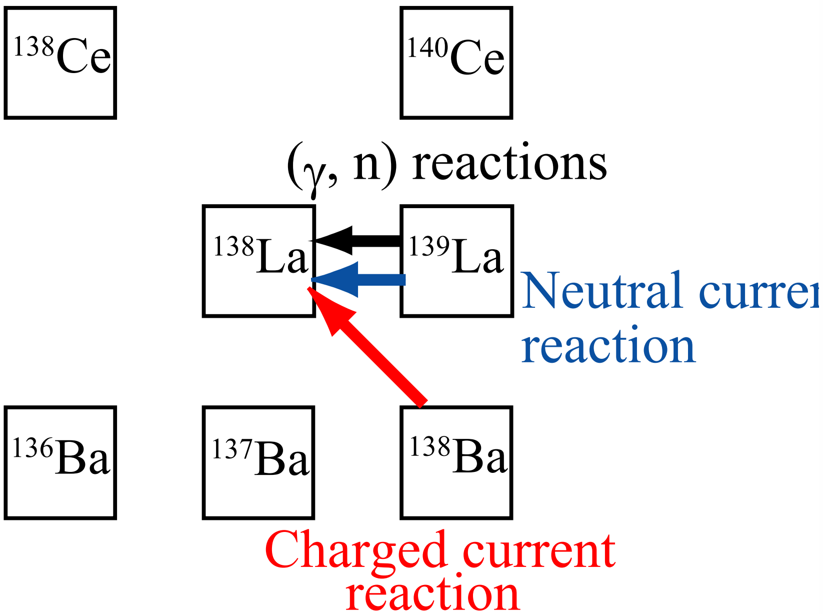
$$Asym. = \begin{cases} +0.85 & \text{for } M1 \text{ transiton} \\ -0.85 & \text{for } E1 \text{ transition} \end{cases}$$



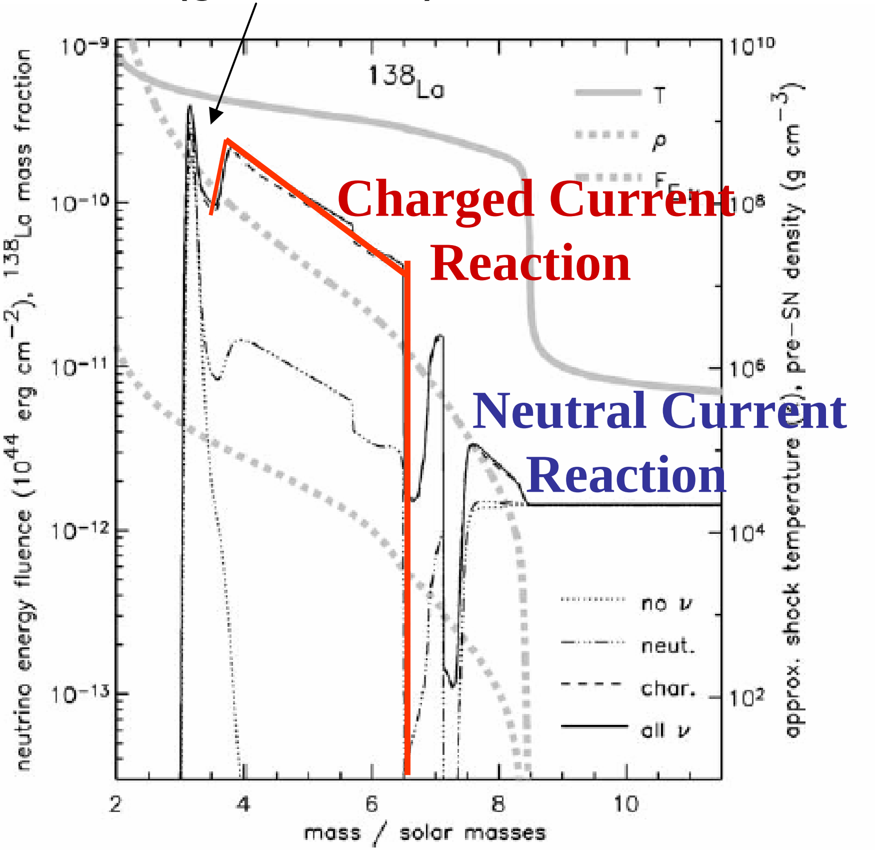
T.Shizuma,et al., Phys. Rev. C 78, 061303(R) (2008)

Nuclear Reactions in neutrino-process

A. Heger, Phys. Lett. B 606, 258 (2005)



(gamma, n) reactions



Charged Current Reaction (CC)
Is most important.

Neutrino-process production for ^{7}Li, ^{11}Be, ^{138}La, and ^{180}Ta were calculated.
Former three isotopes are reproduced (normalized ^{16}O)
BUT ^{180}Ta is overproduced.

Improvement of Charged Current Reaction Rate for ^{138}La and ^{180}Ta

A. Byelikov, Phys. Rev. Lett. 2007

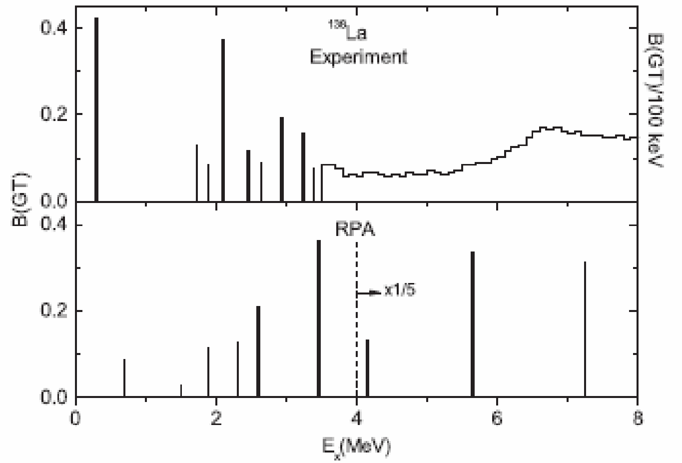
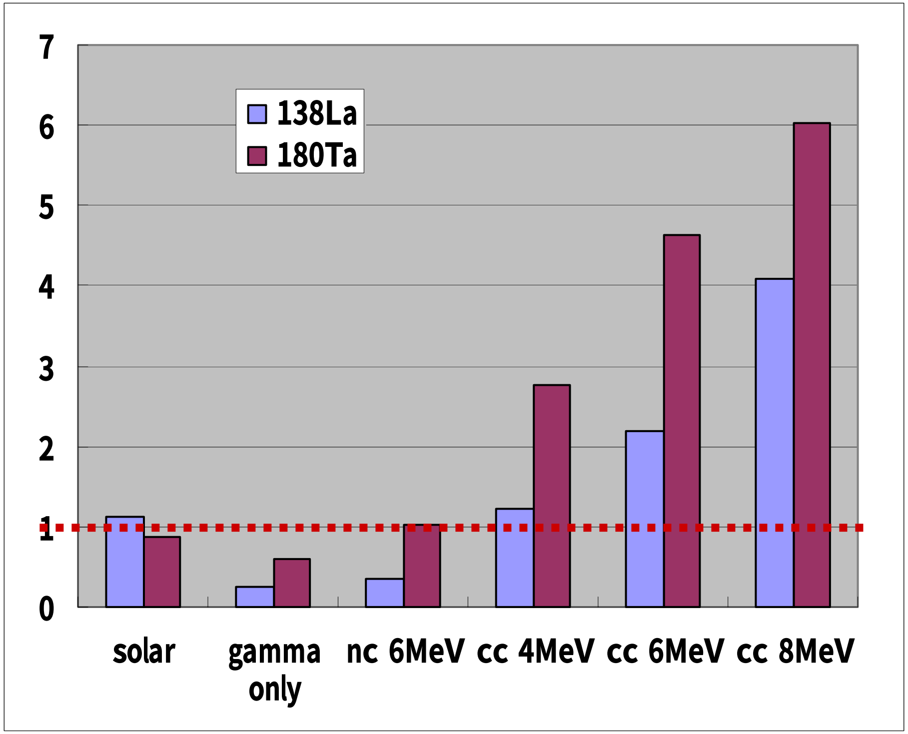


FIG. 3. GT strength distribution in ^{138}La. Top: present work. Bottom: RPA calculation used in Ref. [2].

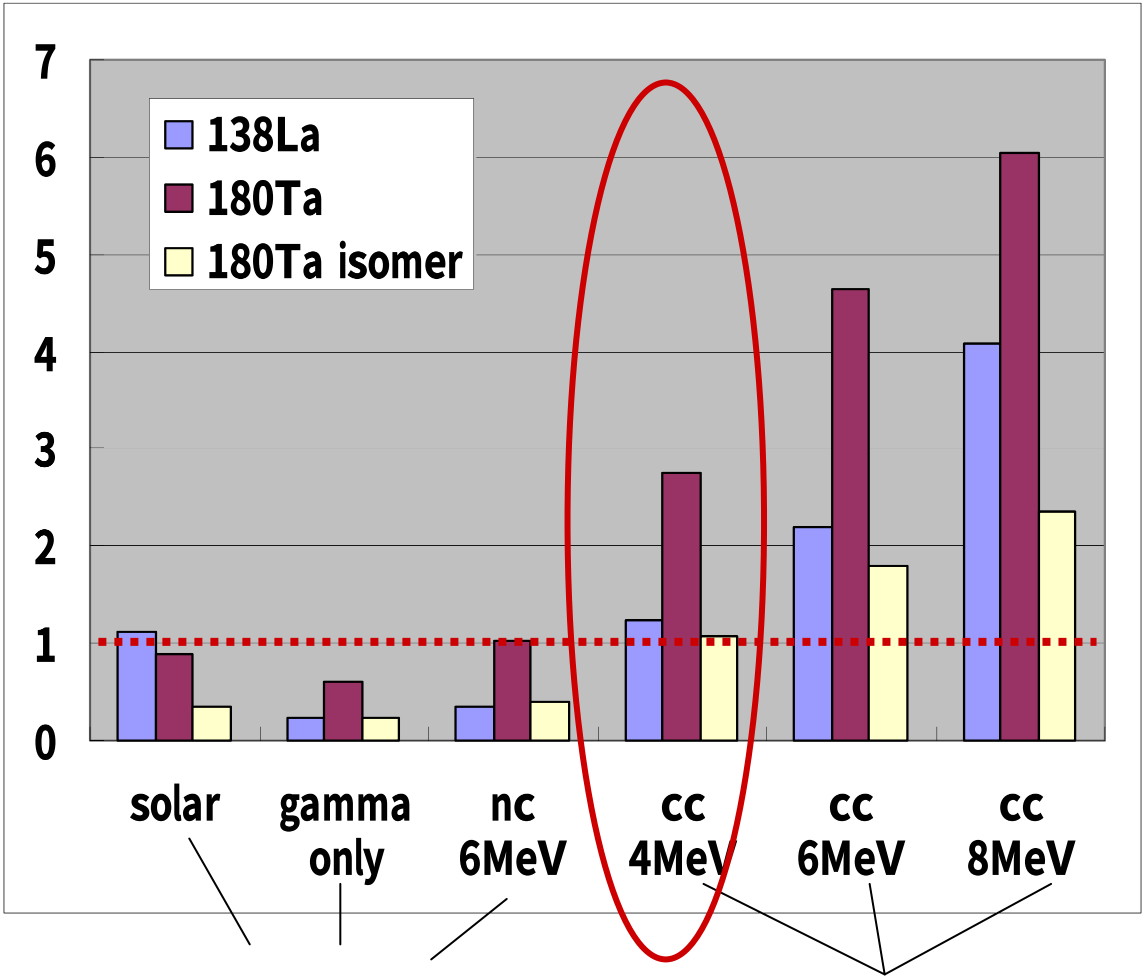
They measured the Gamow-Teller Strength at RCNP



- The abundance of ^{138}La can be reproduced by + CC at 4MeV but that of ^{180}Ta is overproduced.
- This magnitude depends on unknown branching ratio of the isomer.

New Result

Normalized to ^{16}O



We multiply the calculated abundance by the factor of Pi = 0.39

Both the nuclei can be reproduced consistently by +Charged Current Reactions at 4MeV.

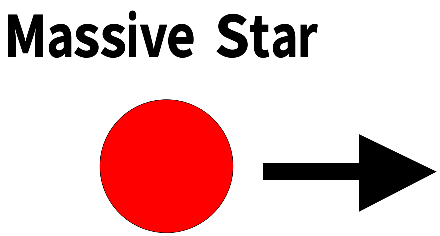
Heger, Phys. Lett. B, 2005

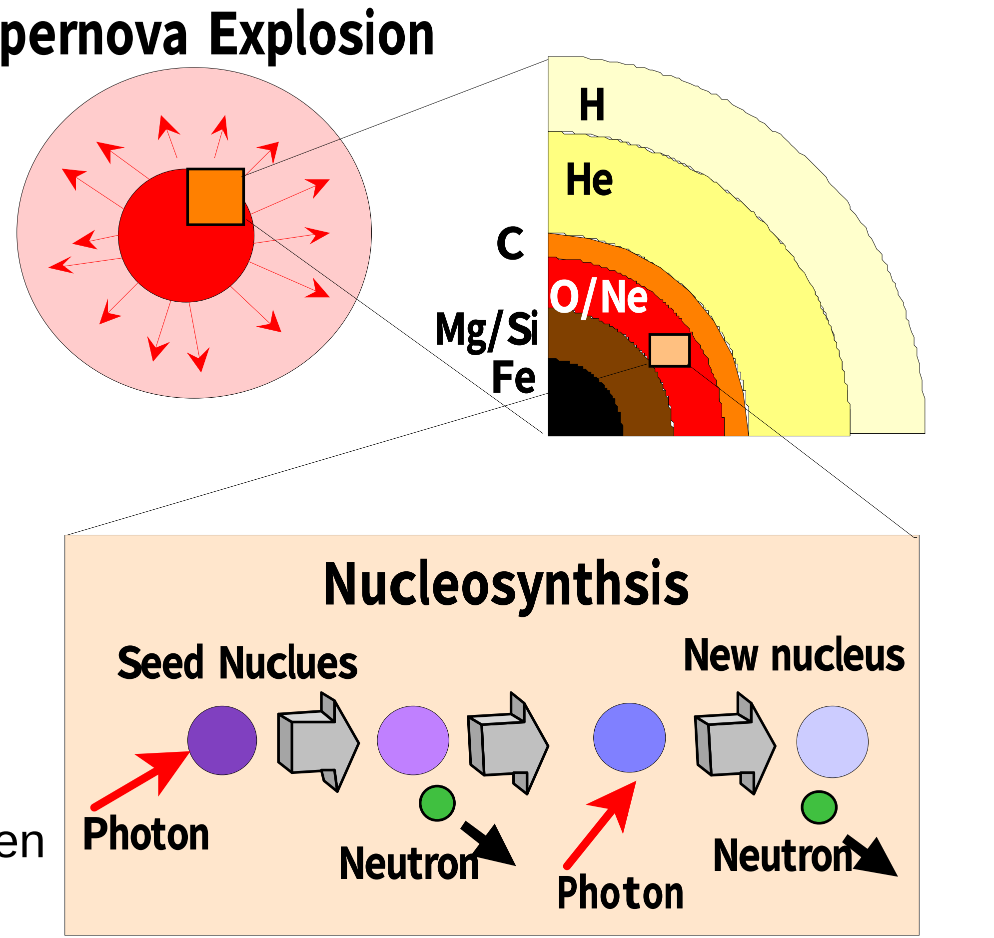
Byelikov, Phys. Rev. Lett, 2007

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

Nucleosynthesis in supernovae

Some rare isotopes are synthesized from preexisting elements by photon-induced-reactions such as (γ ,n) reactions.





The mass is 8 times heavier than our Sun.

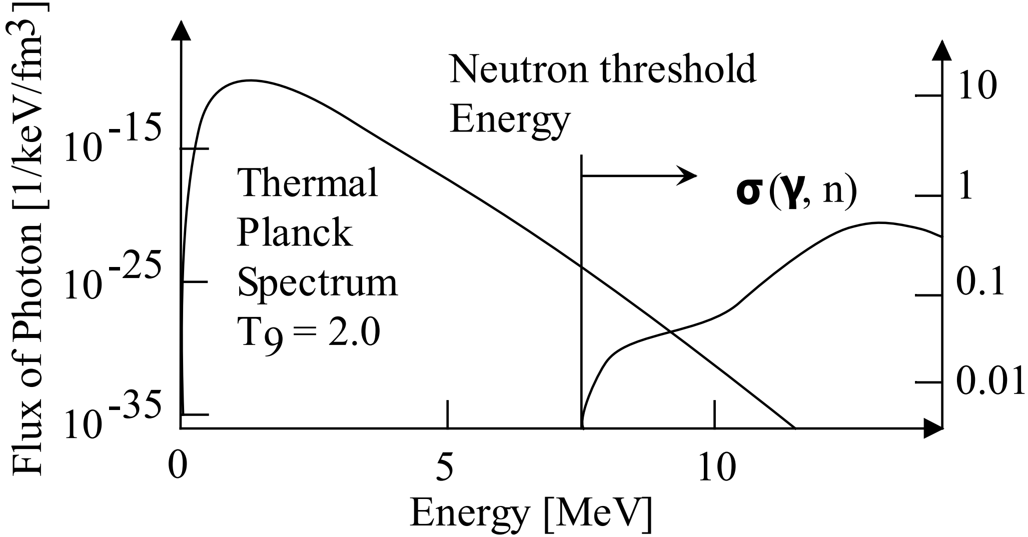
Woosley, Astrophys. J. 1978

Evidence for this process has been Found in the solar abundances

T.Hayakawa, Phys. Rev. Lett. (2004).

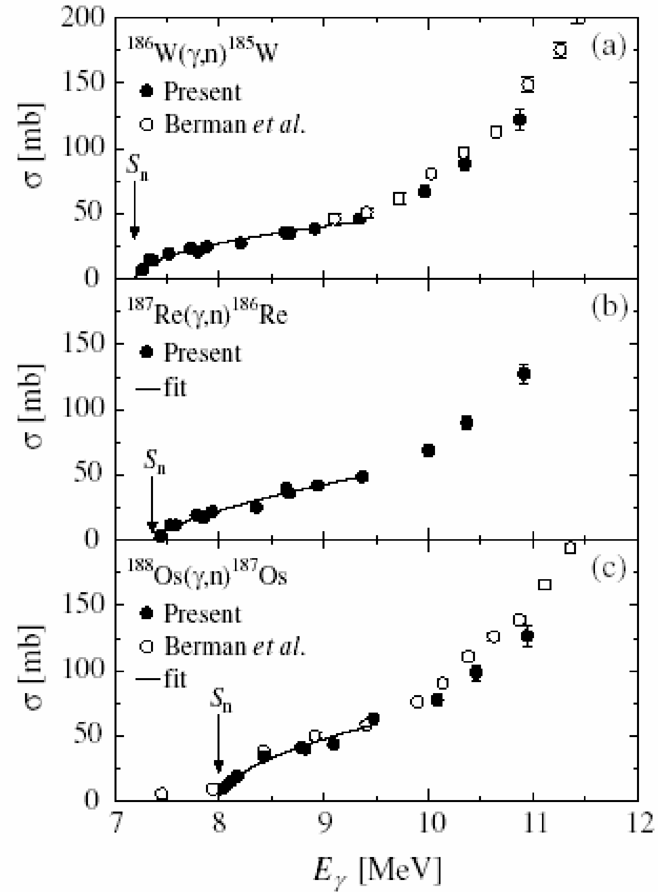
Two neutrons are picked off

Measurement of (gamma, n) reaction cross-sections at AIST



Measurements of (gamma,n) reaction rates are imporatant for nucleosynthesis calculations.

P. Mohr, Phys. Rev. C, 69, 032801(R) (2004)



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

Fundamental Physics

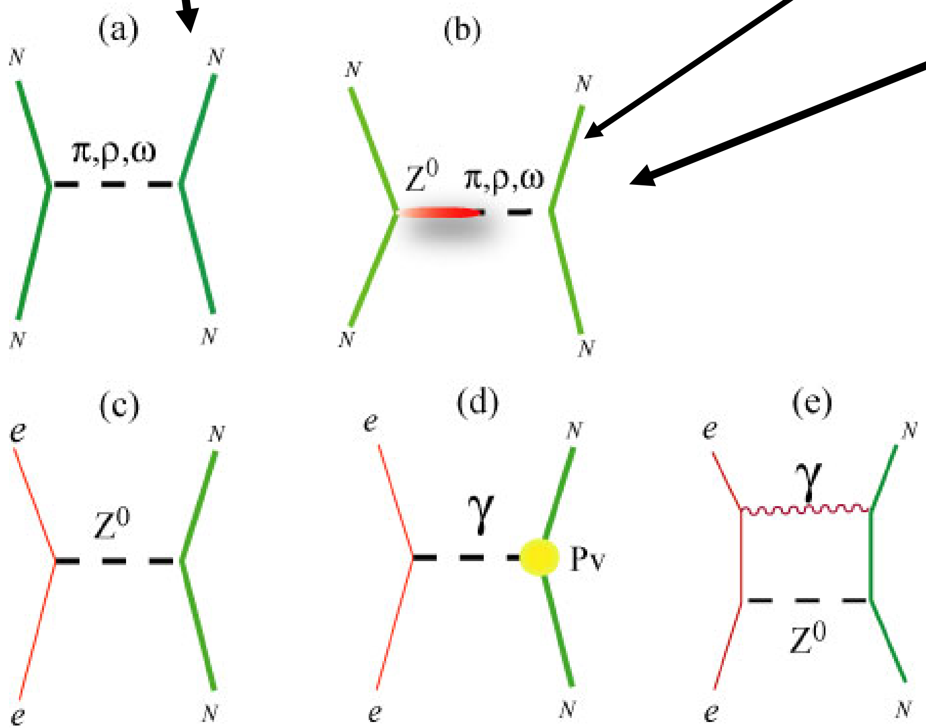
Parity Mixing in Nuclei

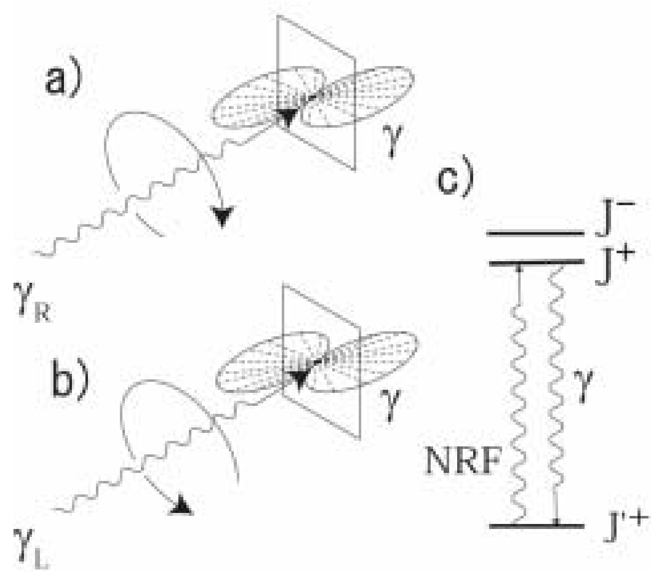
Interaction between Neutral Current Boson and Meson (Nucleon-Nucleon Interaction)

Z^0 : Neutral Current Boson

Standard Nucleon-Nucleon Interaction

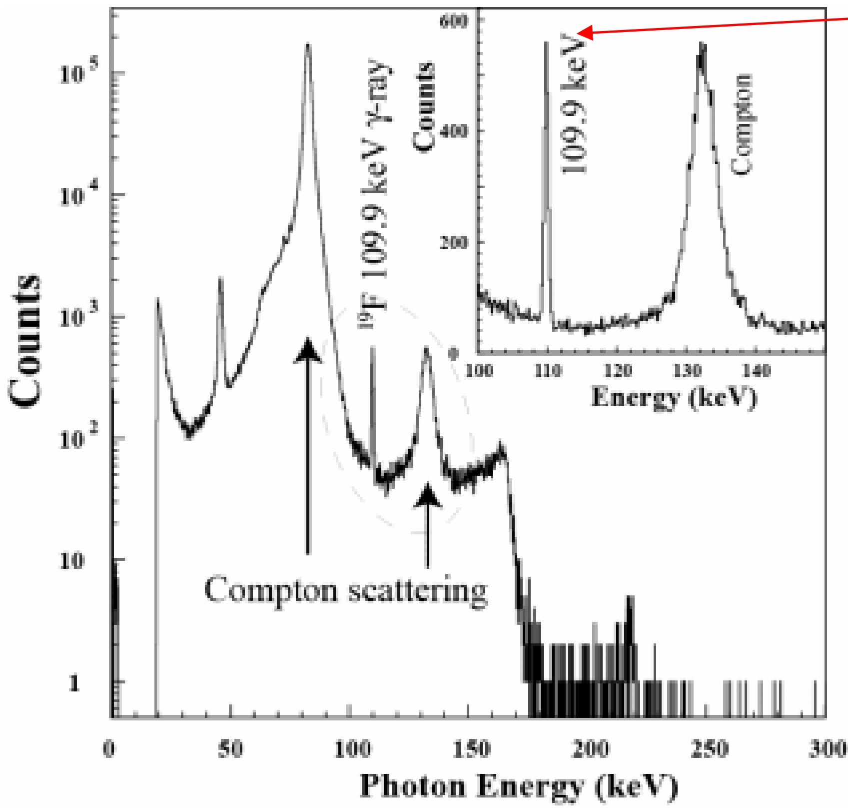
Interaction between Z^0 and Mesons.

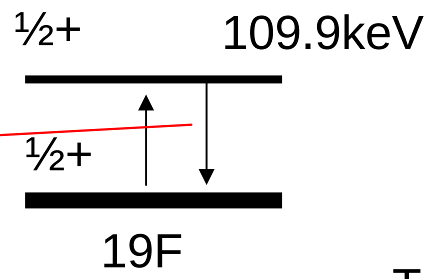




The interaction can be determined by polarized LCS gamma-rays. Fujiwara, J. Phys. G (2006).

NRF experiment using Synchrotron Radiation at SPring-8 for Parity Mixing Measurment

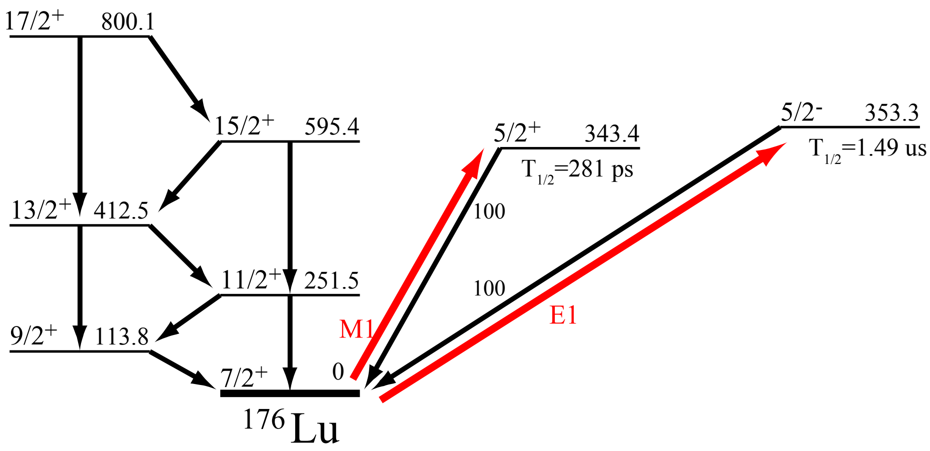




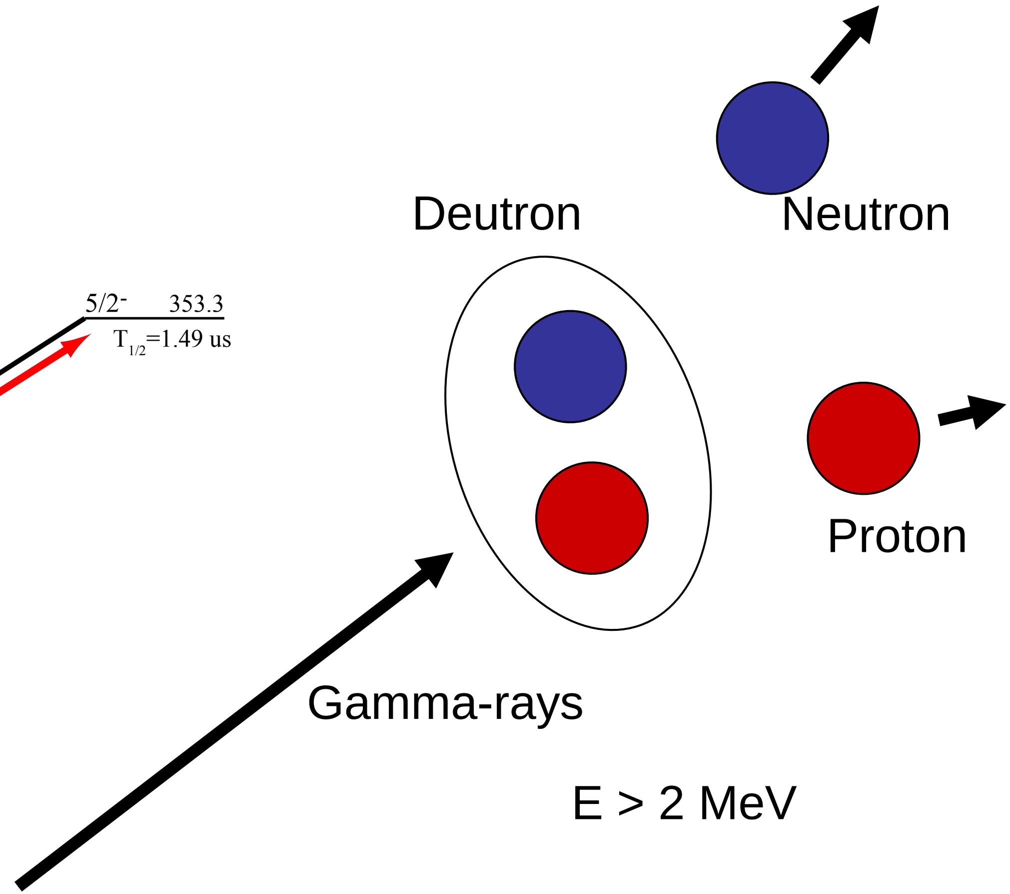
Target and detector

K.Kawase, submitted.

Other candidates and final goal



dE = 9.9 keV



E > 2 MeV

Measurement of Neutrons

M. Fujiwara, Private comm.

Present

10^7 photons/s → ERL 10^{13} photons/s

New Frontier !

Thank you very much