The Fifth Blaise Pascal Lecture
Wednesday, March 10, 2010
Ecole Polytechnique

Photonuclear Physics

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Fondation Ecole Normale Supérieure
Institut de Lumière Extrême
and
LMU,MPQ, Garching

Mountain of Radioactive Wastes of JAEA

Cleanup of the nuclear legacy
by γrays, we see and control nuclei

Nuclear Waste Unidentified

Handled by hand individually at this time
→ estimated cost $20B for JAEA, $200B
    for Japan

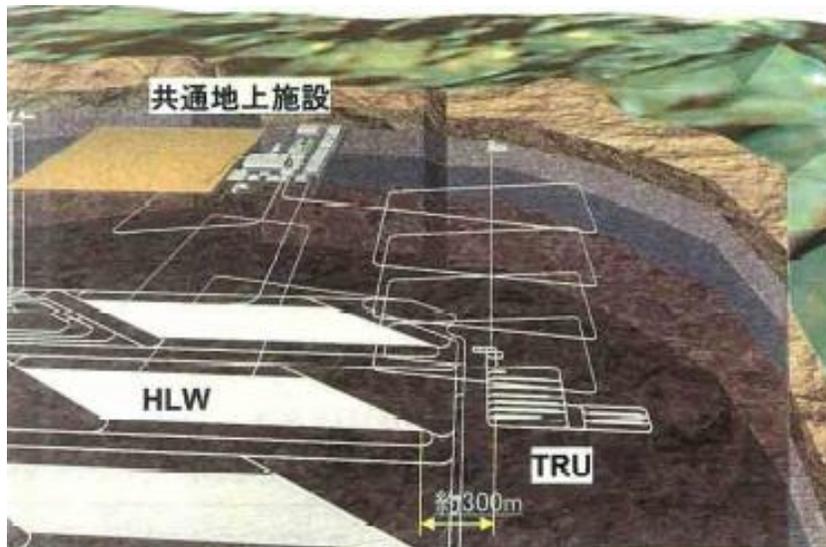(JAEA)

2

Germans move radioactive barrels

Long neglected 'toilet side' of nuclear energy, in contrast to its production ('kitchen side')

We need science (brain) of how to handle this; not just management (muscle)
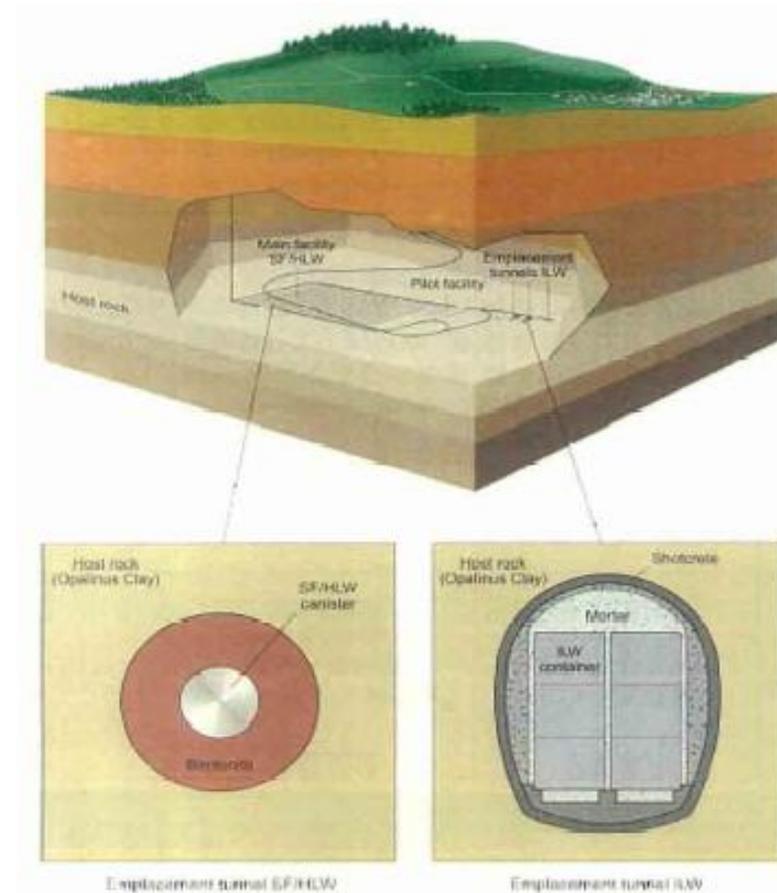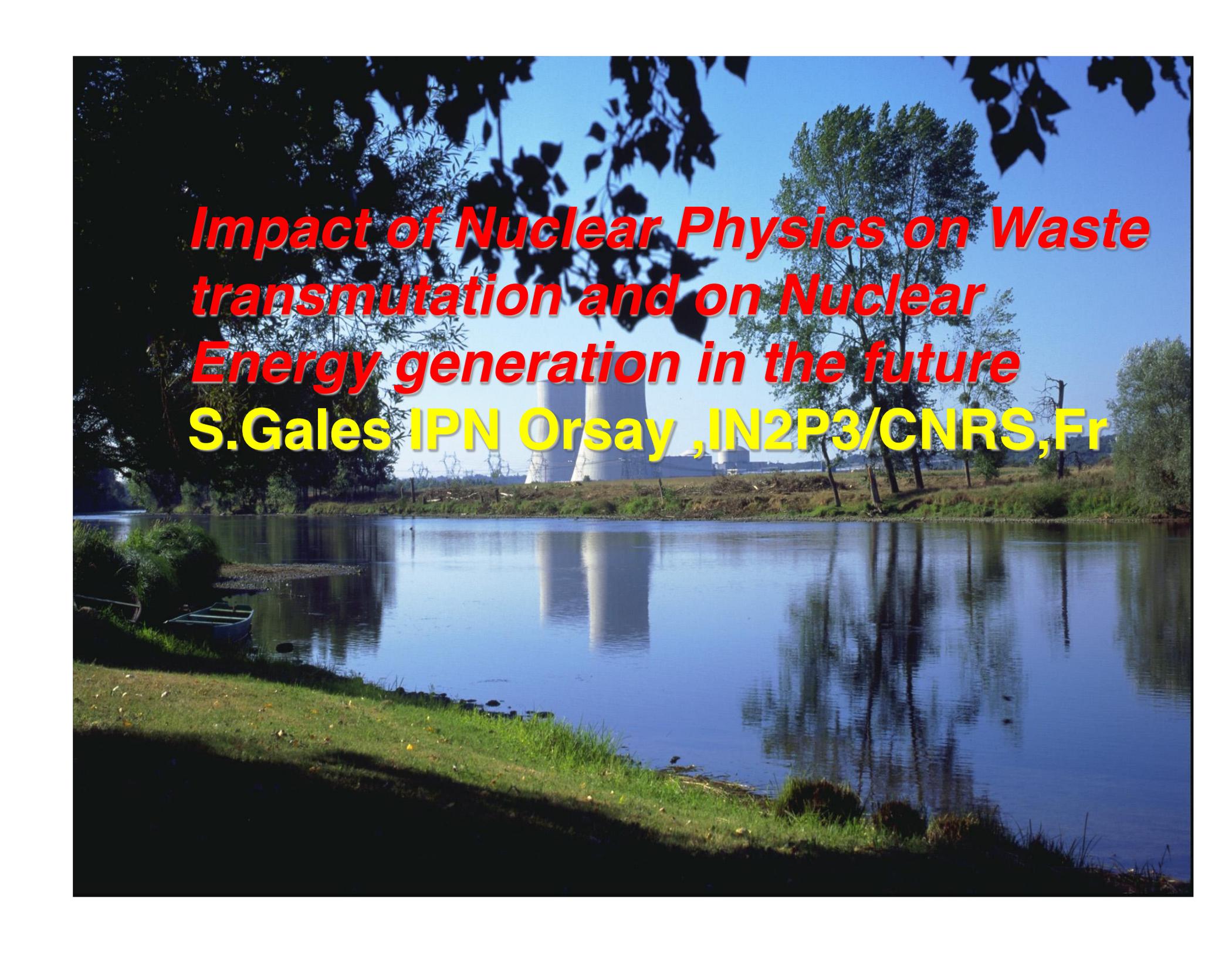
Disposal of Nuclear Waste

Underground burying

(Japan)

(Switzerland)

Impact of Nuclear Physics on Waste transmutation and on Nuclear Energy generation in the future
S.Gales IPN Orsay ,IN2P3/CNRS,Fr

Management of Nuclear waste: Nuclear Data for Hybrid Reactors

Subcritical reactors:

(Gales)

- specific data, reactions induced by n or p,Fission,capture,residues,..
- Innovative fuels (Th,Am, Cm, …)

0.1 eV   20 MeV   1 GeV
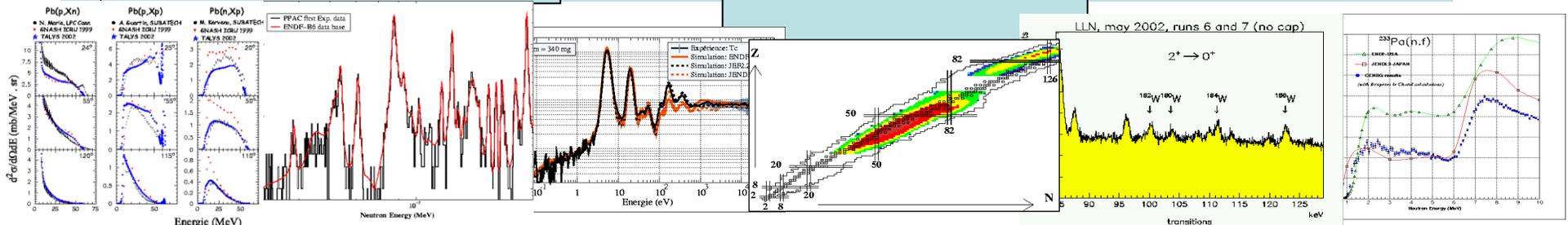
Critical reactors

Subcritical reactors

n-ToF CERN, thorium cycle, (n,fission), (n,xn)

VDG CENBG,
Tandem ORSAY,
thorium cycle,
(n,fission), (n,

GSI Darmstadt,
spallation residues,
inverse kinematics,
p + Fe, Xe, Pb, U

GELINA Geel
(n,γ), fission products
transmutation (^{129}I)
(n,xn) thorium cycle

Louvain-la-Neuve
Uppsala, Groningen,
(n,xclp), (p,xn),
(p,xclp), Fe, Pb, U

Some Conclusions
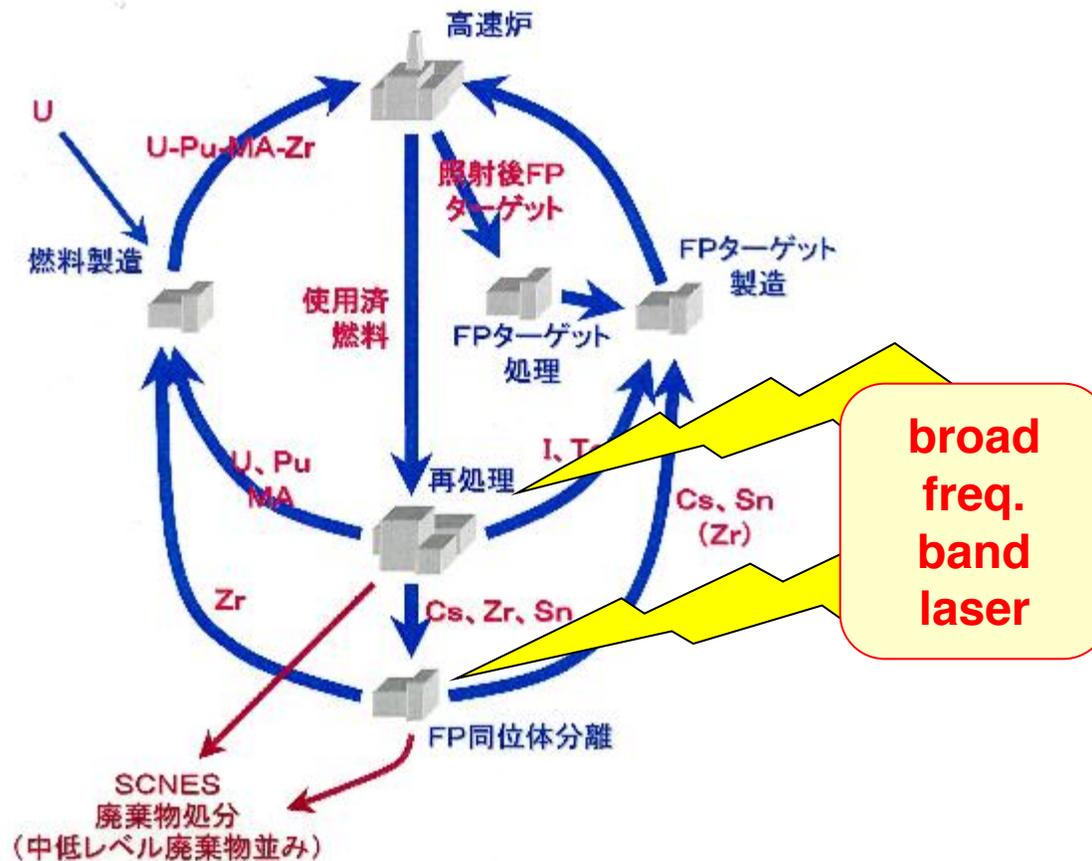
- *Nuclear energy does not appear any more to be a solved technical question*
  - *Overall (societal, economic) boundary conditions have evolved significantly since 1980 and will still do so in future*
  - *Innovation is and will be required . Evaluation of nuclear risk need more scientific input (not only though)!!*
  - **Basic research can contribute via :**
  - **Specific competences (improved data, accelerators, MC simulation)**
  - **More open approach to nuclear science (less short-term economically and technologically driven) ,multidiscip....**
  - **Basic training and formation**
- **Synergies exist with some basic science goals**
  - **Ex : Japan Joint Project, NSS,RIBF,ν beams , Accelerator target, Simulation.....**
- *Academia via its competence and its independence can provide a unique contribution to the future of nuclear energy.*

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Atomic Energy System Cyclable with Little Waste

<u>Yoichi Fujiie</u> (former Commissar, AEC of Japan: 'Self-Contained Nuclear Energy System （ＳＣＮＥＳ）'
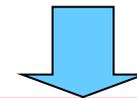
Introduction of short-pulsed laser

U
U-Pu-MA-Zr
燃料製造
高速炉
照射後FP ターゲット
FPターゲット 製造
使用済 燃料
FPターゲット 処理
再処理
U、Pu MA
Zr
I, T
Cs、Sn (Zr)
Cs、Zr、Sn
FP同位体分離
SCNES 廃棄物処分 （中低レベル廃棄物並み）

broad freq. band laser

laser quantum control

Invention of new time-domain separation/extraction of radioisotopes

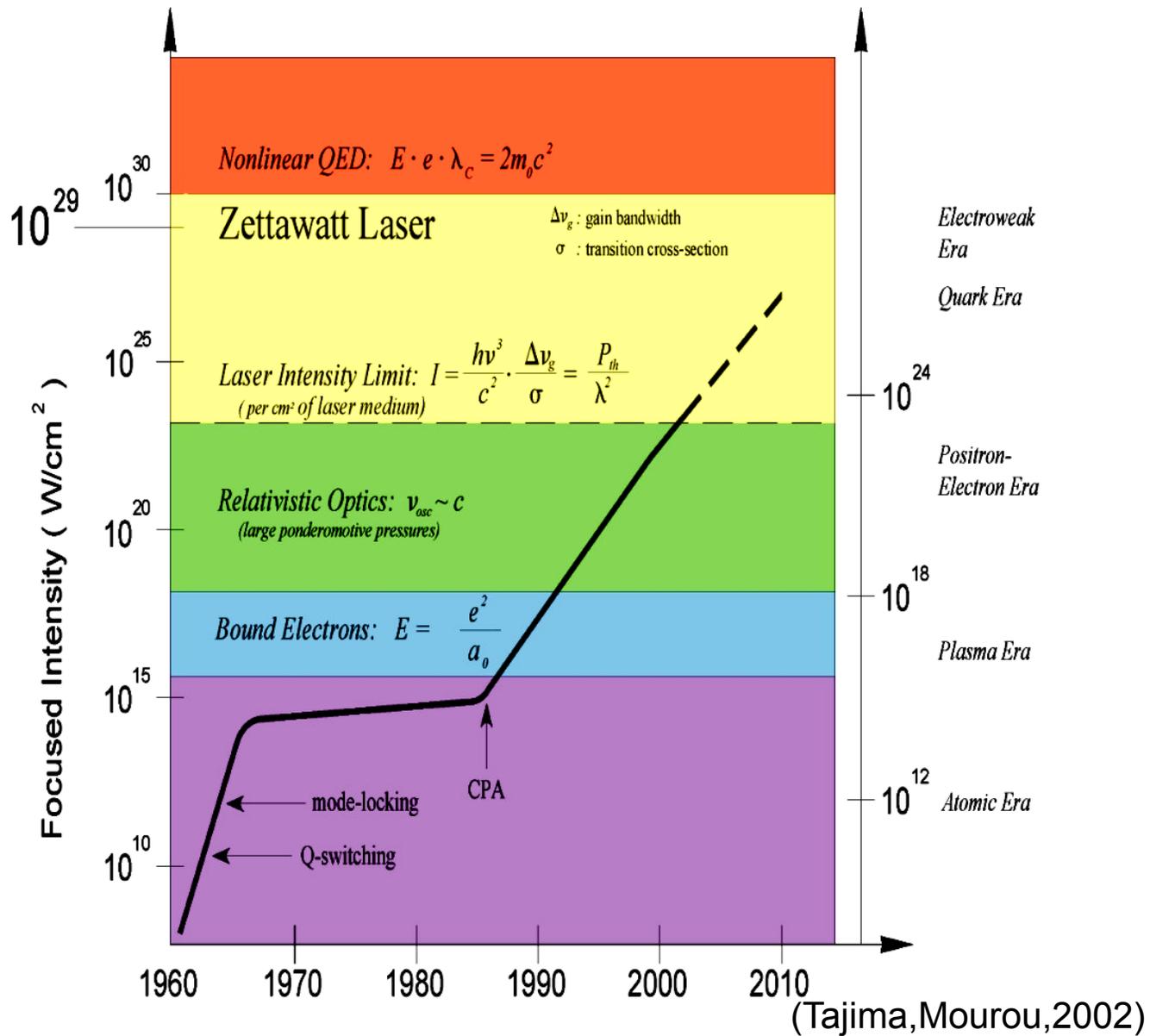H. Yamada, K. Yokoyama, et al, Phy. Rev. A 72, 063404(2005)

・ reprocessing of spent fuel

・ treatment of **radioactive wastes**

large quantity of photons necessary

Atomic energy is 'alchemistry'
Energy extracted through the 'alchemistry' process
We wish to put out only cyclable elements thru 'alchemistry'

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Lasers

(Tajima,Mourou,2002)

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First Nonlinear Optics Work after Laser Invention

1961
by Franken et al.

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan
(Received July 21, 1961)

The development of pulsed ruby optical masers[1,2] has made possible the production of monochromatic (6943 A) light beams which, when focussed, exhibit electric fields of the order of 10^5 volts/cm. The possibility of exploiting this extraordinary intensity for the production of optical harmonics from suitable nonlinear materials is most appealing. In this Letter we present a brief discussion of the requisite analysis and a description of experiments in which we have observed the second harmonic (at ~3472 A) produced upon projection of an intense beam of 6943A light through crystalline quartz.

A suitable material for the production of optical harmonics must have a nonlinear dielectric coefficient and be transparent to both the fundamental optical frequency and the desired overtones. Since all dielectrics are nonlinear in high enough fields, this suggests the feasibility of utilizing materials such as quartz and glass. The dependence of polarization of a dielectric upon electric field E may be expressed schematically by

$$P = \chi E\left(1 + \frac{E}{E_1} + \frac{E^2}{E_2} + \cdots\right), \qquad (1)$$

where E_1, E_2 ... are of the order of magnitude of atomic electric fields (~10^8 esu). If E is sinusoidal in time, the presence in Eq. (1) of terms of quadratic or higher degree will result in P containing harmonics of the fundamental frequency. Direct-current polarizations should accompany the even harmonics.

Table I. The square of the total p perpendicular to the direction of propagation of light through crystalline quartz.

Direction of incident beam	The square of the total p perpendicular to direction of propagation
x ($E_x = 0$)	$p_y^2 + p_z^2 = 0$
y ($E_y = 0$)	$p_z^2 + p_x^2 = \alpha^2 E_x^4$
z ($E_z = 0$)	$p_x^2 + p_y^2 = \alpha^2(E_x^2 + E_y^2)^2$

(z is the threefold, or optic, axis; x a twofold axis). If a light beam traverses quartz in one of the three principal directions, Eqs. (2) predict the results summarized in Table I. The second-harmonic light should be absent in the first case, dependent upon incident polarization in the second case, and independent of this polarization in the third.

If an intense beam of monochromatic light is focussed into a region of volume V, there should occur an intensity I of second harmonic given (in Gaussian units) by

$$I \sim (\omega^4/c^3)(pv)^2(V/v), \qquad (3)$$

where ω is the angular frequency of the second harmonic, c the velocity of light, and v an effective "volume of coherence"; that is, the size of a region within the sample in which there is

First textbook on Nonlinear optics by Bloembergen in 1965

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What γ beam brings in to nuclear physics

- Rutherford approach (collider and particle beam)

  high momentum penetrates deep interior of matter and scatters,

  sees smallest detail of matter

  $\lambda/a \leq 1$ (λ, a are probe and target sizes)

- 'laser' (and γ beam) approach

  photon beam penetrates, but

   not local real space structure,

  excites the structure, induces

   dynamics and spectroscopy,

  possibly controls

  $\lambda/a \sim 10^4$ (both for atoms and nuclei)

γ beam revolution of *nuclear physics*:
   similar to laser revolution of *atomic physics* in'60s

γrays: opens new nuclear physics

-measurement of neutron cross section of rare nuclei by inverse
      process of (γ,n)

-*nuclear resonance fluorescence* and *spectroscopy*

-particular excitation

      *nuclear electroweak excitation such as parity measurement

      *isomer creation

      *particular excitation and interaction with inner-shell electrons

-manipulation of nuclei by more than one gamma pulse

      *consecutive excitation to higher levels

      *exploration of exotic nuclear states?

      *quantum control of nuclear states

 -polarized positrons

-non-contact and fast detection of nuclear materials

-monitoring of nuclear reprocessing

-transmutation of nuclei with small neutron cross section

-materials research with nuclear resonance, Moessbauer

-cold neutron beam generation, etc. etc.

Dawn of Photonuclear Physics:

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      similar to the eve of the laser invention, spawning new atomic physics

Beginning of <u>Photonuclear Physics International Work</u> (Kizu,2006,-)

"2nd US-Japan Nuclear Photo-Science Workshop

Purple Orchid Inn, Livermore, July 26-27, 2007

- Opening Remarks, C.P.J. Barty (LLNL)

Presentations

- Nonlinear Thomson and JAEA interest, T. Tajima (JAEA)
- Energy Recovery Linacs (ERLs), N. Nishimori (JAEA)
- T-REX Status, C. Barty (LLNL)
- **"**
- …..

Now, -US-Japan governments seriously considering research on this subject

-IAEA

-ELI Nuclear Pillar

Can Laser Save (Help) Nuclear Energy?

- Challenge: to *safely* and *economically* identify and reduce nuclear waste
- Efficient Generation of <u>High-Fluence Gamma Rays</u>
- Accurate and safe detection and identification of isotopes
- <u>Efficient Separation</u> of bad nuclei
- <u>Nuclear Transmutation</u> of selected nuclei, e.g. I
- Is there a niche for laser?

NUCLEAR ENERGY :GLOBAL FACTS

A rather Young form of energy, of limited importance at the world level (7%),economically viable source of electricity (320GWe.y,16%)

Production concentrated in a few countries

(USA+FR+J)= 2/3 of the world

A passionately contested energy for

Its origin related to defense,

Its cost structure (high investments ,delayed returns)

Questions insufficiently dealt with in the past

Proliferation (Pu mostly)

Nuclear waste management

These questions generate social concerns for the future

S. Gales

LEPS facility @Spring-8

Collision

8 GeV electron

E_e P_0 electron beam θ ω γ rays

E_e' p ω_0 laser

Recoil electron

Electron tagging

a) SPring-8 SR ring

laser hutch

Laser light

Inverse Compton γ-ray

c) experimental hutch
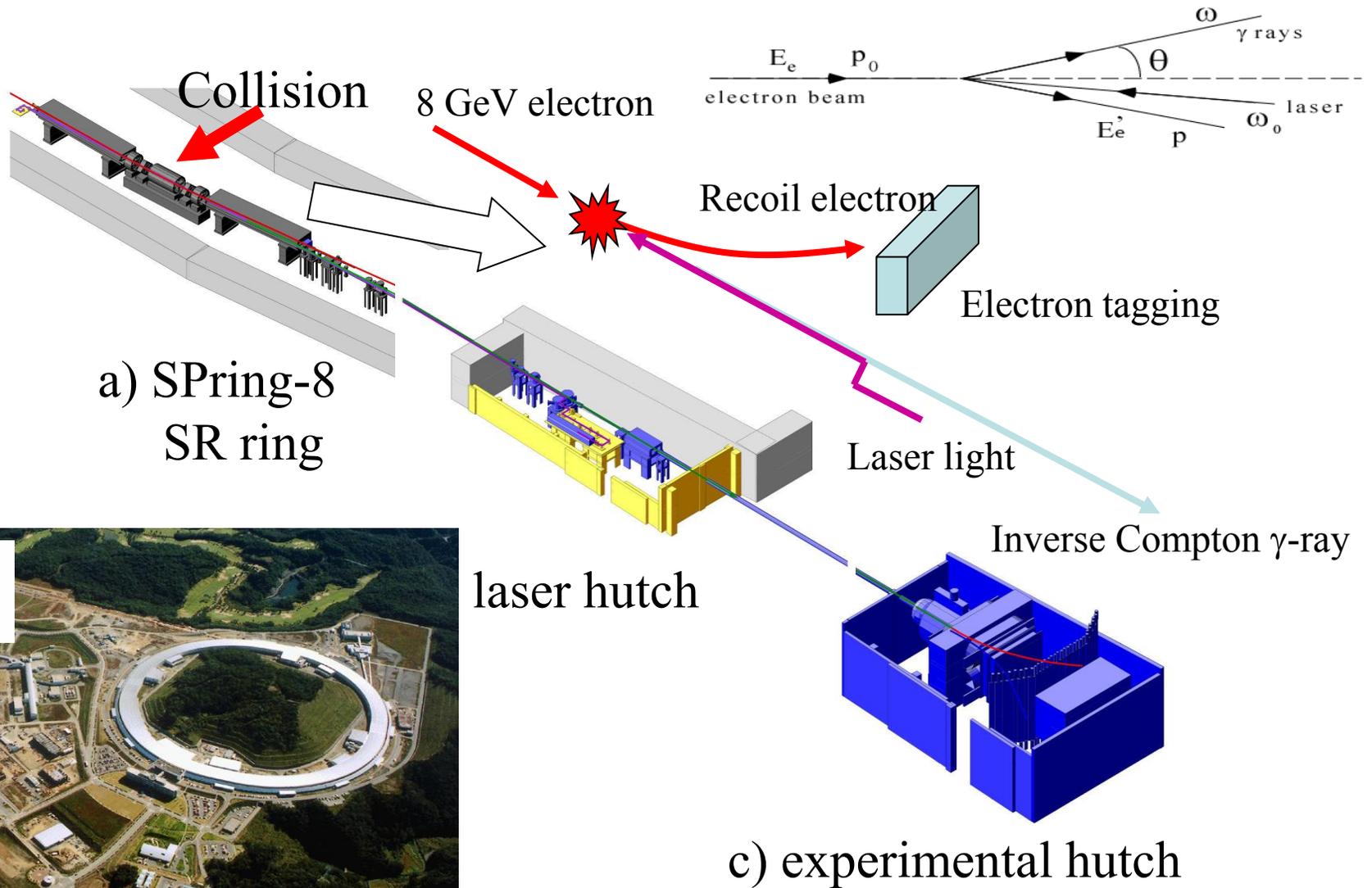
RCNP、 JAERI、 JASRI collaboration

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LLNL MEGAray Compton Source

Mono-energetic Gamma rays
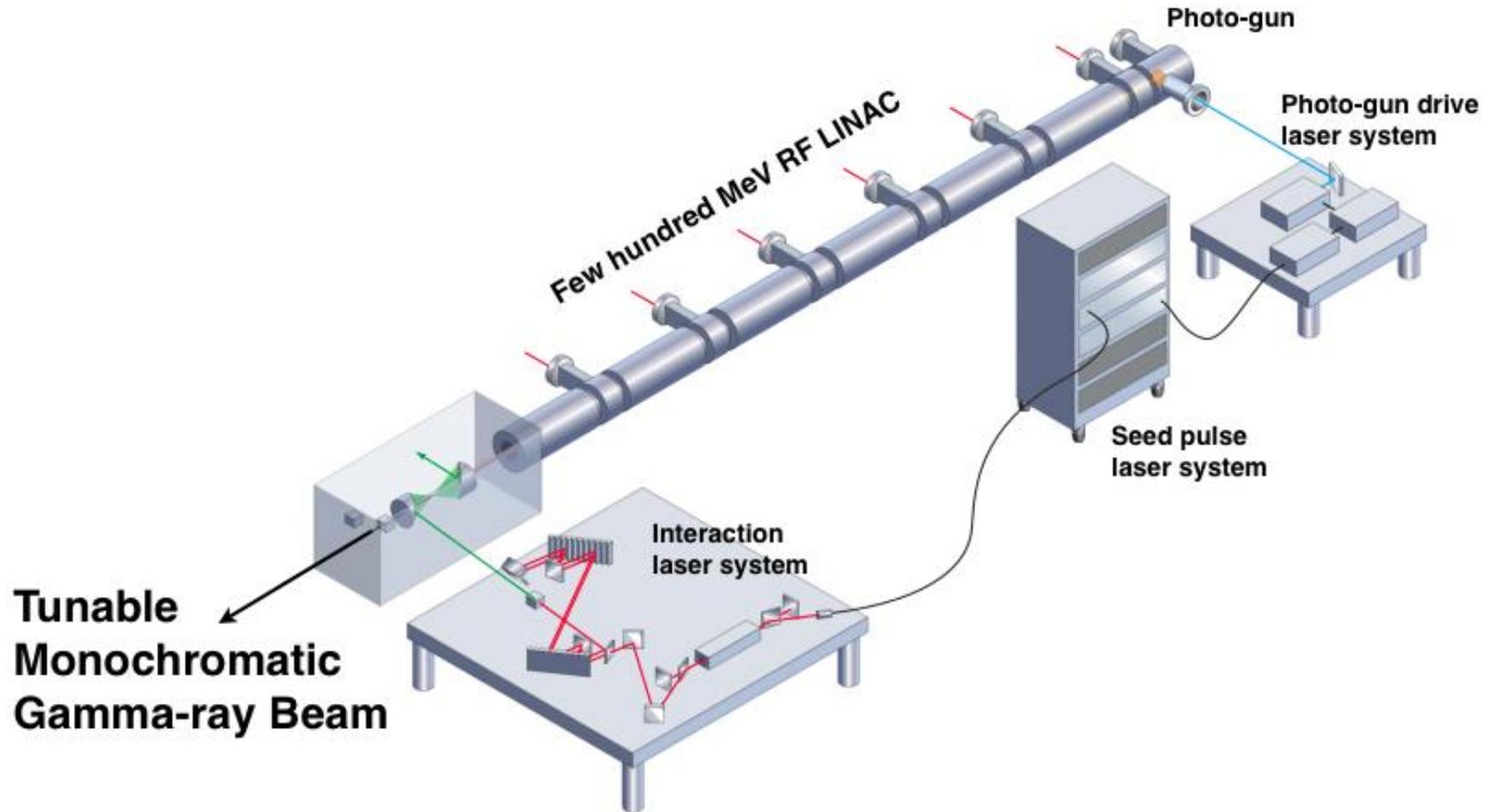
Table-top Synchrotron Laser Compton Source

Lyncean(Professor Ron Ruth,SLAC)

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MeV LCS Facilities

HIGGS facility, Duke University (US)
FEL+electrons
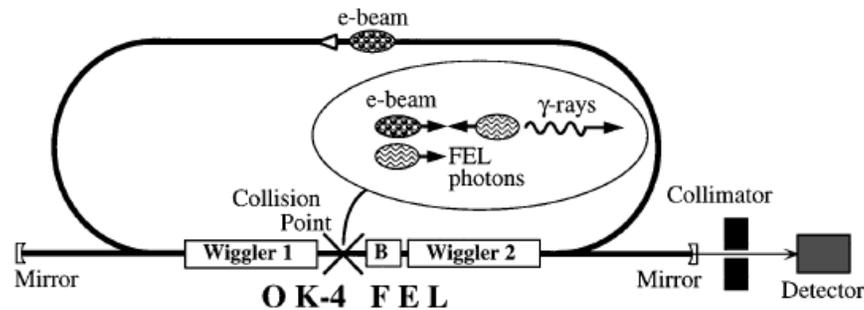
V. N. Litvinenko, PRL, 1997

AIST TERAS (Japan)

- Energy 5~20MeV ?
- 10^7 photons/s: high flux
- dE/E is very sharp
- Good S/N ratio
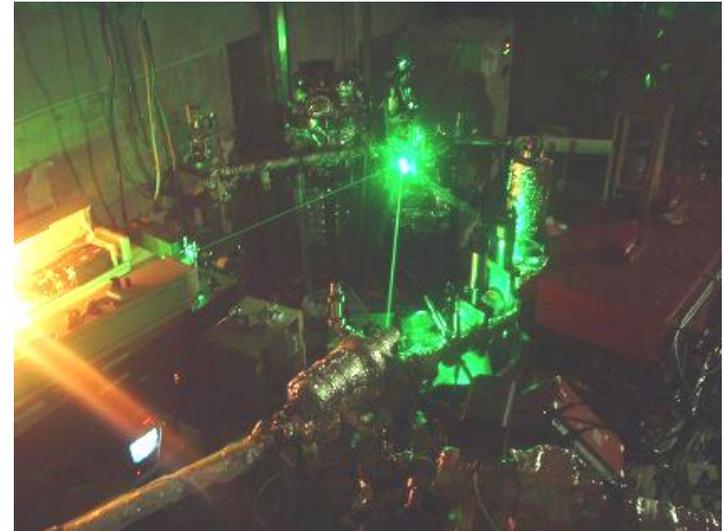
Nd/YVO$_4$ Laser + electrons in storage ring
- Energy 5~50 MeV
- 10^4 photons/MeV/s

However, the flux is too small to be used as the NRF assay method.

Detailed layout of the **THomX** machine

High brillianc e Photogun

LINAC 3 GHz – 500 / 700 MeV

Electrons

Waist

Compton X-ray

Bellows

X,Y Motorised table

Laser and cavity

10**13 γ/s

Zone d interaction Compton

0.5

Vertical Height (mm)

X-ray Photon

2σ

0

Electron Bunch

Laser Pulse

−0.5

−20   0   30

10-2001
8621A1

Distance Along Trajectory (mm)

Anneau de stockage

15 m

Users

30m

20
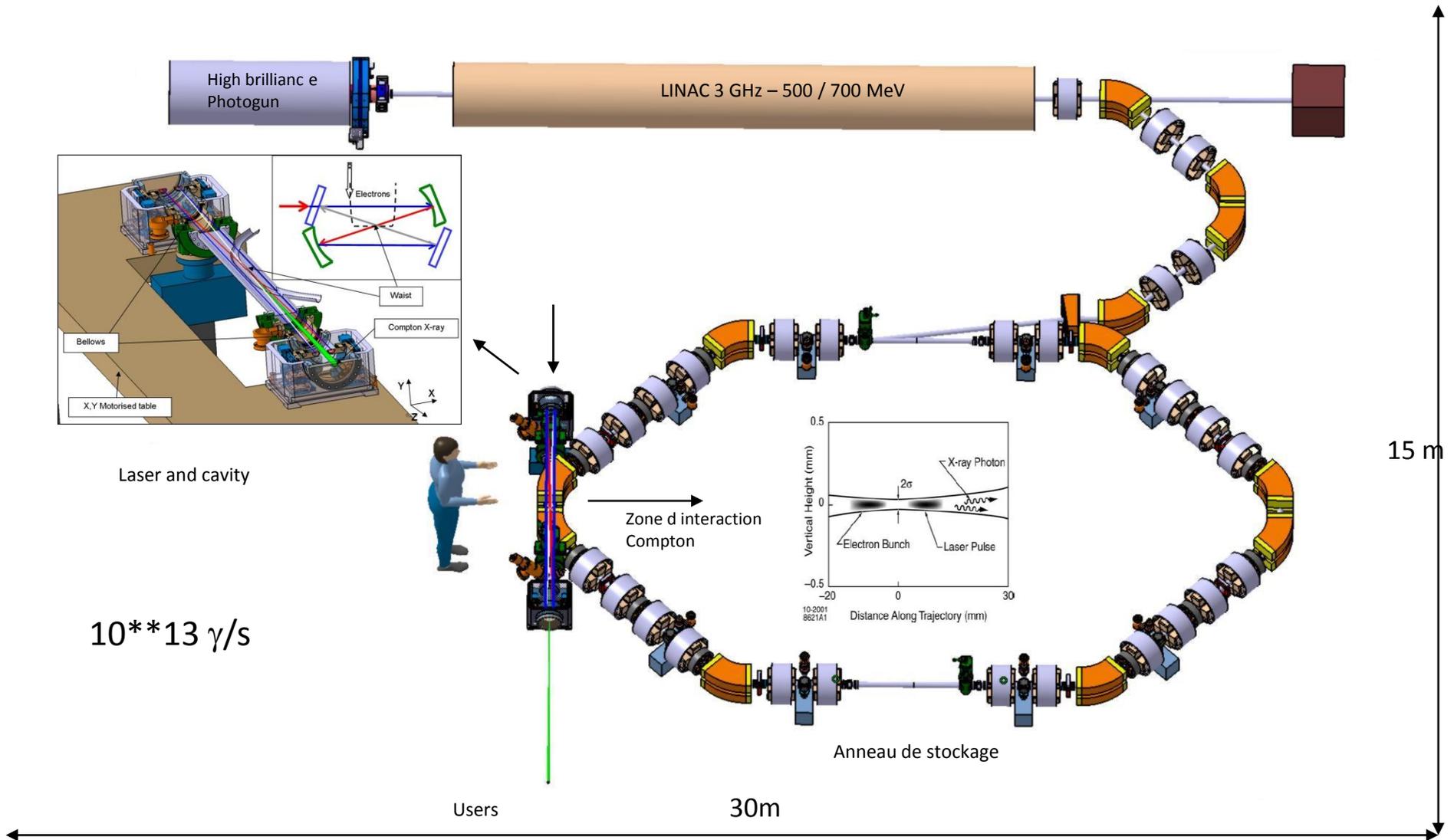
(G. Wormser)

JAEA concept of a high-flux γ-ray source

flux of LC γ-ray

$$F = \frac{fN_e N_L \sigma_C}{A}$$

f collision frequency

N_e number of electrons

N_L number of laser photons

σ_C scattering cross-section

A effective sectional area

we need high repetition, tightly focused, high power, high current beams.

laser super cavity

Supercavity

γ-ray

Laser
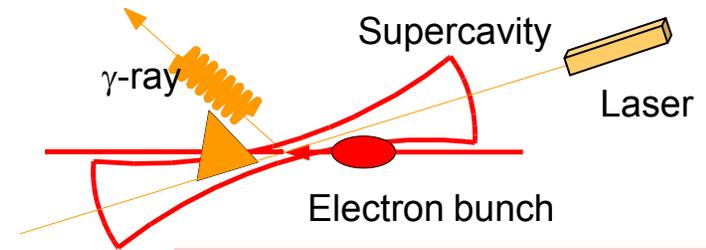
Electron bunch

laser photons are recycled

high-flux γ-ray is available.
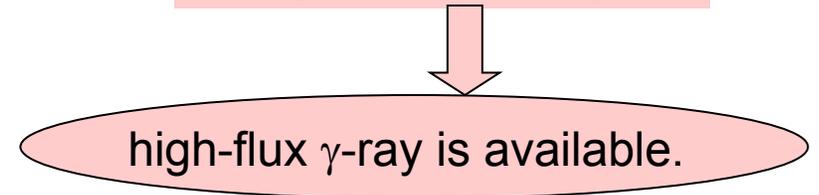
electron energy is recycled

Pb collimator

Laser Compton Scattering

γ-ray

linac

electron injector

Energy Recovery Linac

Acceleration

Deceleratio

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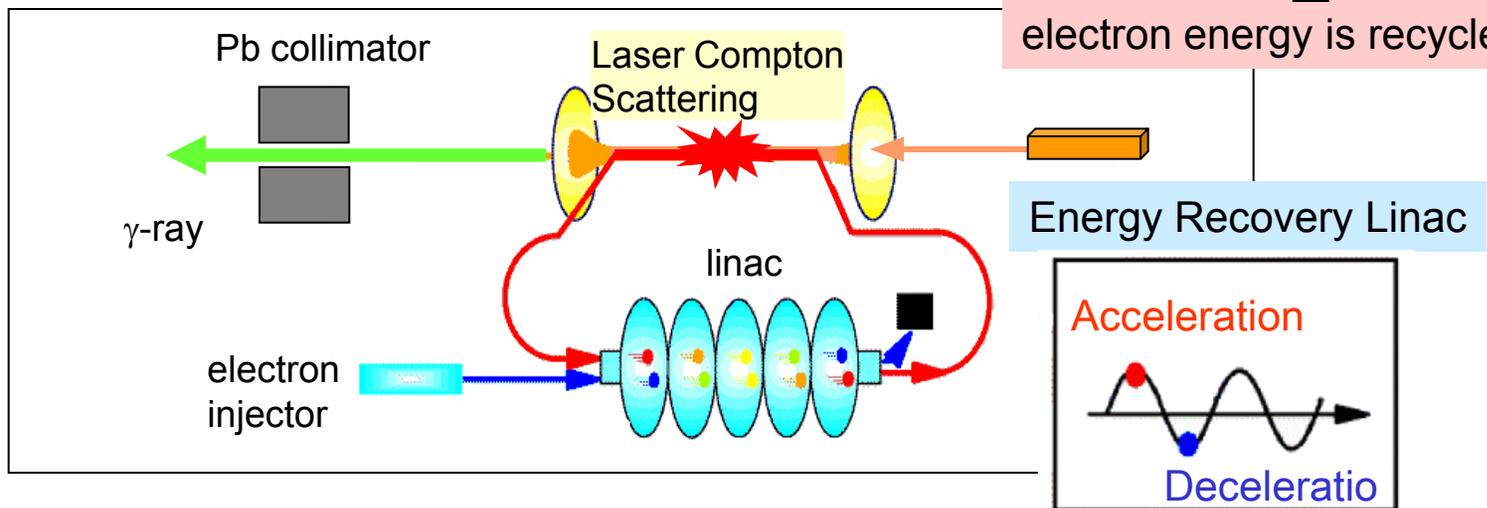
Proposal of a High-flux γ-ray source with a 3-loop ERL
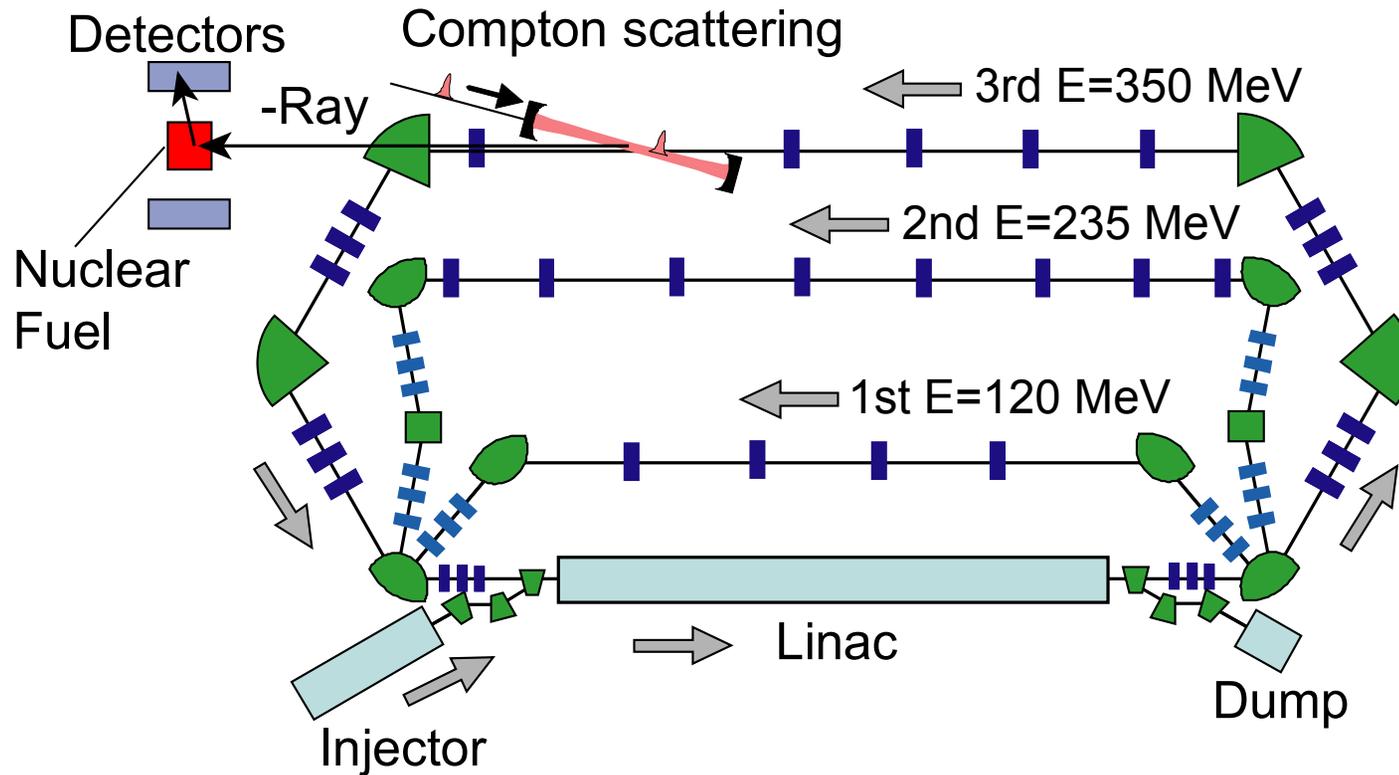
The electron beam is accelerated three times and decelerated three times.

(Hajima)

Isotope detection by γ

Nuclear resonance fluorescence excitations near 2 MeV in ^{235}U and ^{239}Pu

W. Bertozzi,[1] J. A. Caggiano,[2] W. K. Hensley,[2] M. S. Johnson,[3] S. E. Korbly,[1] R. J. Ledoux,[1] D. P. McNabb,[3] E. B. Norman,[3] W. H. Park,[1] and G. A. Warren[2]

[1]*Passport Systems Incorporated, Acton, Massachusetts 01720, USA*
[2]*Pacific Northwest National Laboratory, Richland, Washington 99352, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
(Received 30 June 2008; published 8 October 2008)

A search for nuclear resonance fluorescence excitations in ^{235}U and ^{239}Pu within the energy range of 1.0-to 2.5-MeV was performed using a 4-MeV continuous bremsstrahlung source at the High Voltage Research Laboratory at the Massachusetts Institute of Technology. Measurements utilizing high purity Ge detectors at backward angles identified nine photopeaks in ^{235}U and 12 photopeaks in ^{239}Pu in this energy range. These resonances provide unique signatures that allow the materials to be nonintrusively detected in a variety of environments including fuel cells, waste drums, vehicles, and containers. The presence and properties of these states may prove useful in understanding the mechanisms for mixing low-lying collective dipole excitations with other states at low excitations in heavy nuclei.

Introduction. In the current geopolitical environment, proliferation of nuclear and radiological materials is a major concern. Many efforts are underway to develop a system that

mode is an electric dipole excitation. Other modes are possible but these are the major ones that have been identified in the literature.

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Proposal of Nondestructive Assay of Radionuclides

using nuclear resonant fluorescence technique

There are many minor actinoid (MA) and long-lived fission products (LLFP) in the nuclear waste drum.

How do detect such the MA and LLFP ?

A new Method

Energy

4618keV

3948keV

Energy Tunable LCS gamma-rays

2312keV

1779keV

1322keV

1257keV

Excitation   De-excitation

強度(log)   14N   28Si   79Se

Only Nucleus of interest can be detected
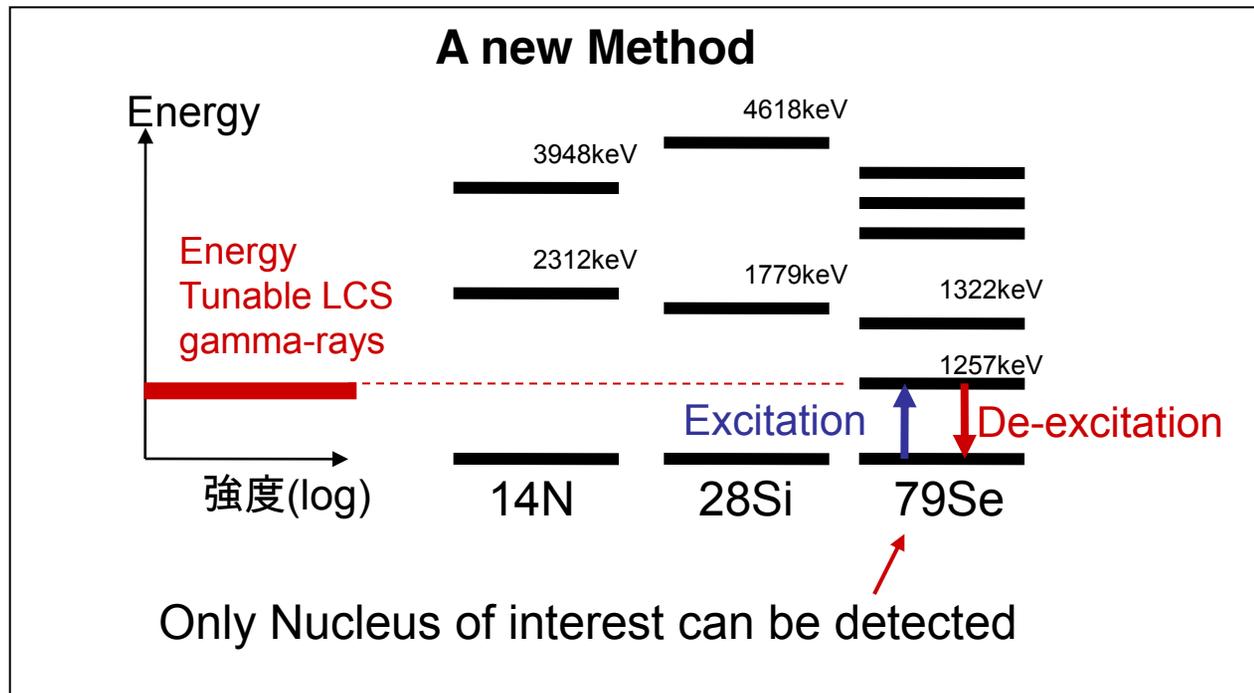
(Hajima)

•**This method can detect all radioactivities except ^{3}H**
•**However, this method require a very high-flux gamma-ray source.**

NRF experiment using Synchrotron Radiation at SPring-8 for Parity Mixing Measurement
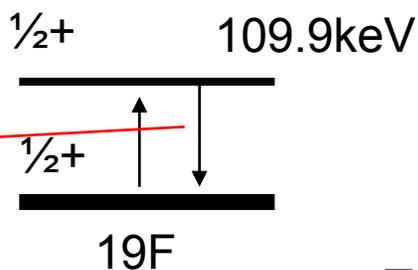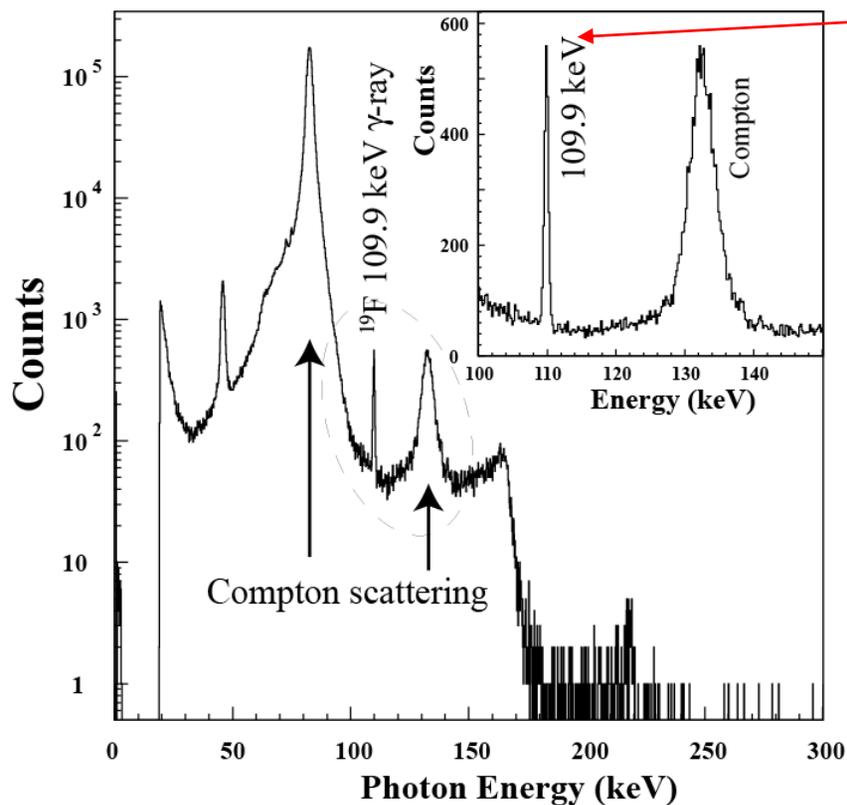
(K.Kawase).

½+   109.9keV

½+

19F

Target and detector

(Fujiwara, Kawase et al.)

Advantages of Nuclear Resonance Fluorescence detection

2.176 MeV for U-238

ΔE/E ~ 1%

2.0   2.1   2.2
Photon Energy (MeV)

detector   target

γ-ray beam

NRF signal
U-238
2.176 MeV

Photon energy (MeV)
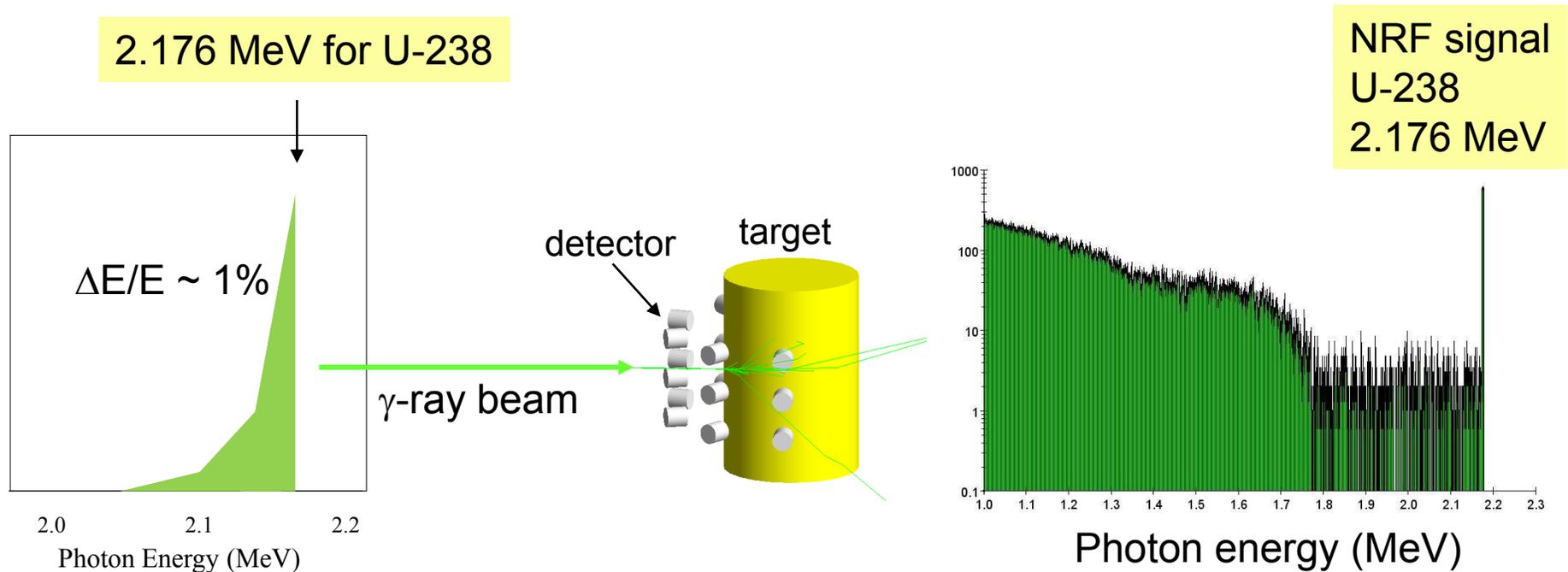
(1) Nondestructive detection of radioactive and stable nuclides

(2) Excellent signal-to-noise ratio in the energy-resolved gamma-ray detection

(3) Detecting many kind of nuclides by scanning the γ-ray energy

(4) Detection through a thick shield

(5) Full utilization of modern laser and accelerator technologies

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(Hajima)

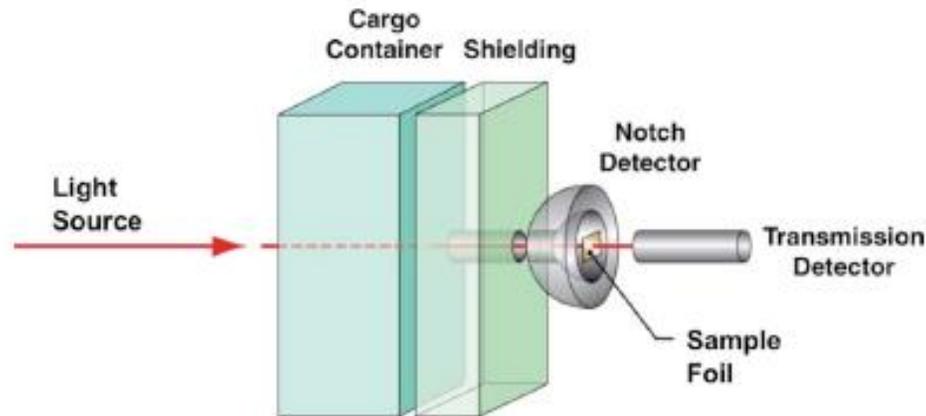# '**Notch Filter**': a method of fail-safe to detect specific nuclear matter

FIG. 2. (Color online) Schematic representation of the detection system studied here. A photon beam is sent to interrogation cargo. After passing through the container the flux of resonant and off-resonant photons is measured. Resonant flux is measured by "notch detectors" that observe NRF within a small sample foil made of the isotope that is being looked for. The flux of off-resonant photons is measured with a simple transmission or current detector.

(Pruet,…Barty,2006)

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Experiment of nondestructive detection of concealed isotope

Pb block shielded by 15mm-thick iron box

5512 keV
Pb-208

Position and shape of the Pb block were clearly identified.

[2] N. Kikuzawa et al., Applied Physics Express 2, 036502 (2009).
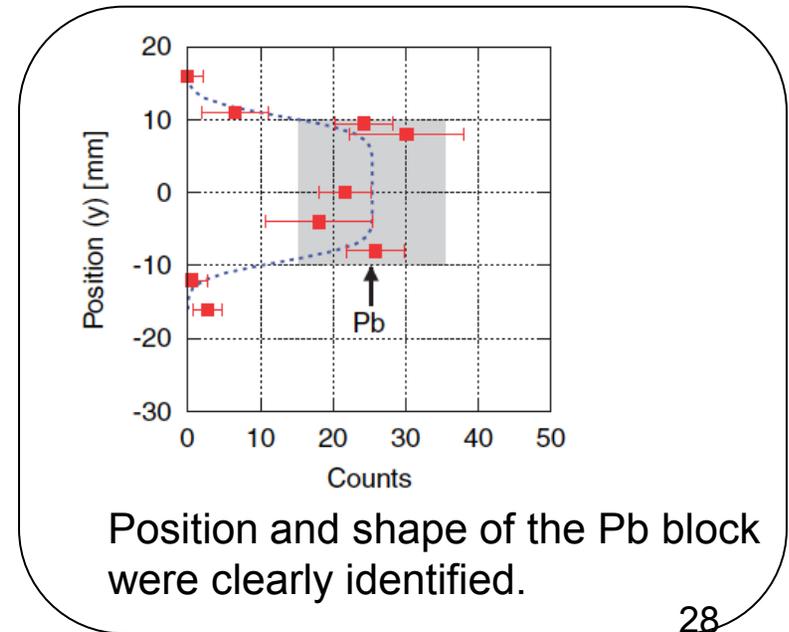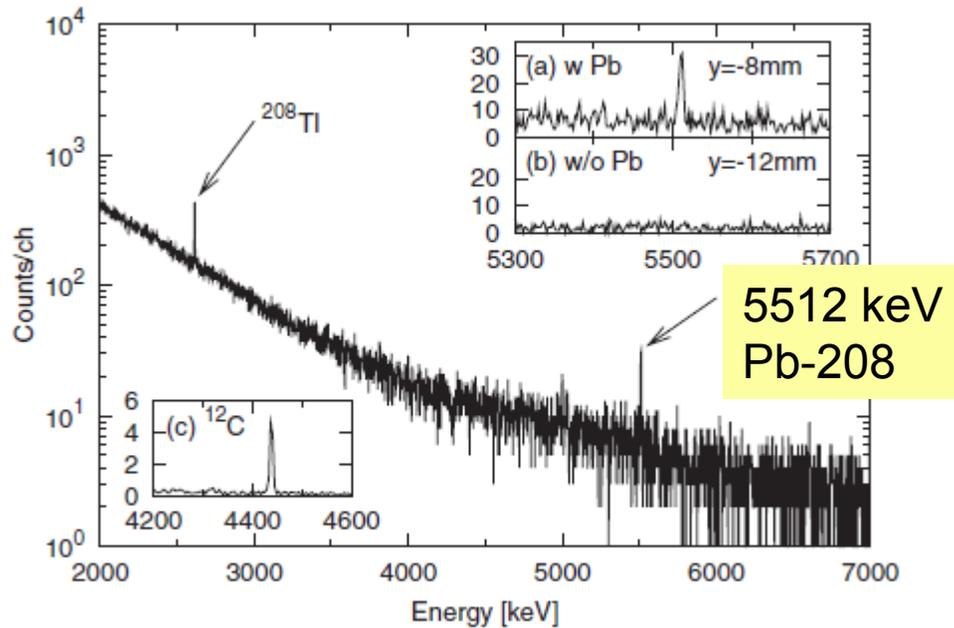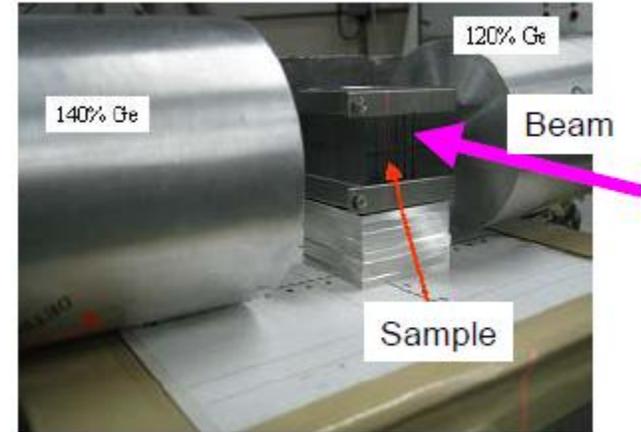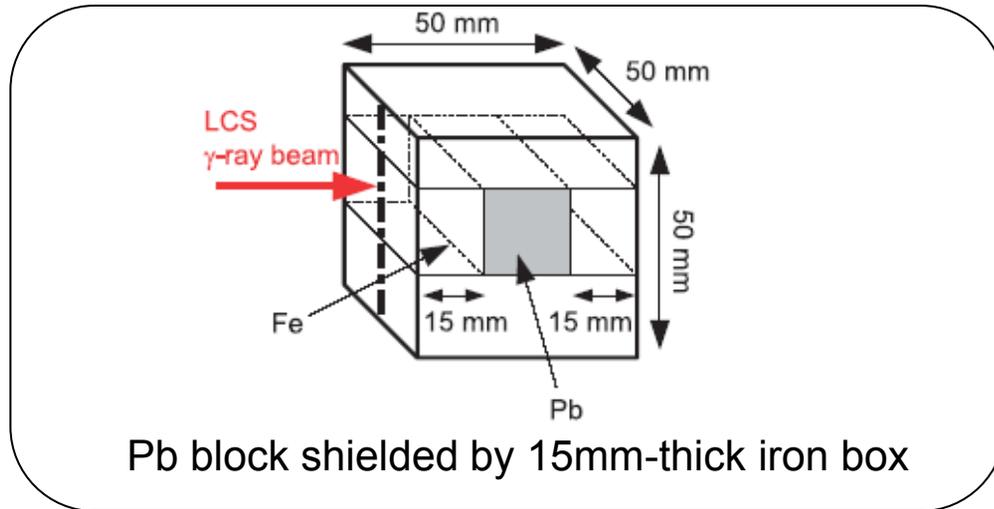
Safeguards technology based on mono-energetic γ-ray

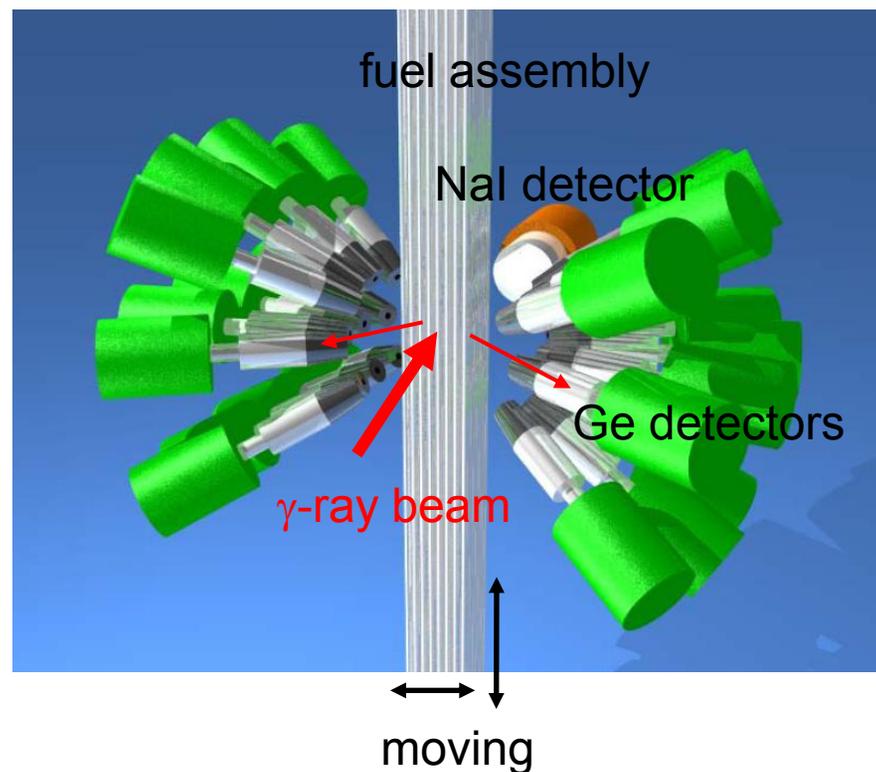Nuclear material accountability is an important issue for nuclear energy usage in the frame of Nuclear Non-Proliferation Treaty.

Nondestructive assay system of spent fuel assemblies – U, Pu and MA. → **Material accountability for operator & Safeguards verification for inspectorates**

fuel assembly

NaI detector

Ge detectors

γ-ray beam

(Hajima)

moving

Deep penetration of γ-rays in a fuel assembly

Ge detectors

density of NRF events from Pu-239
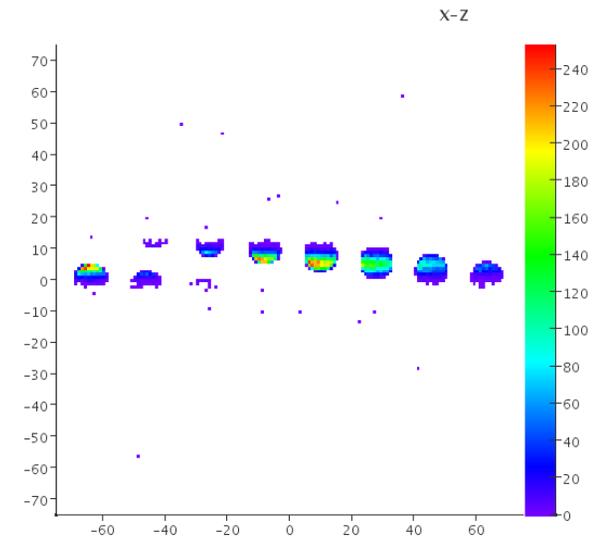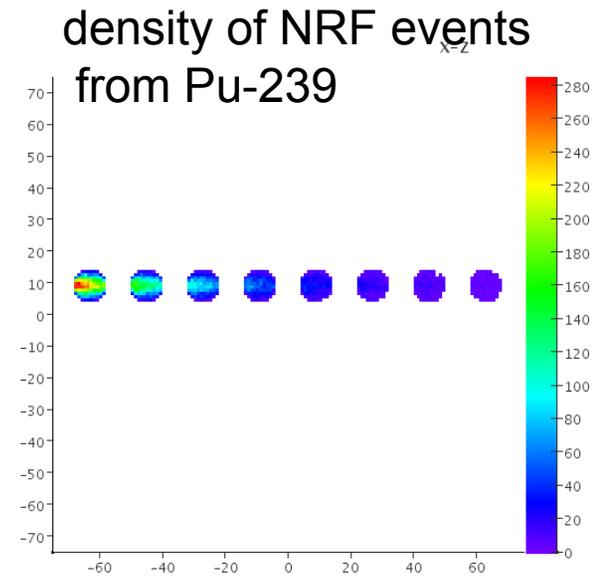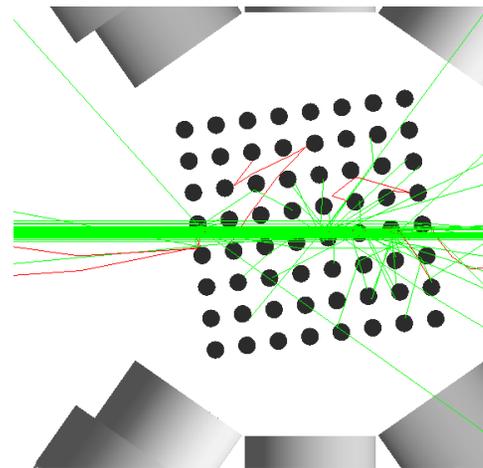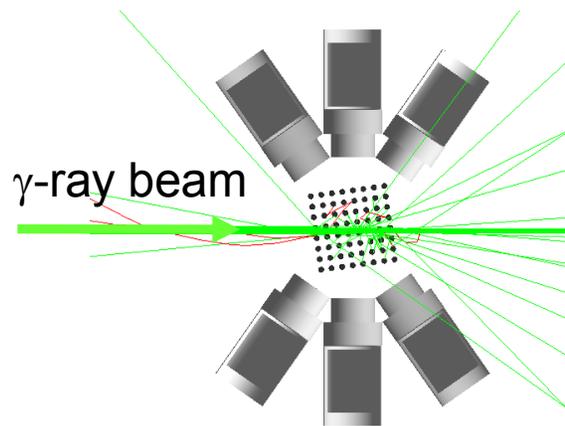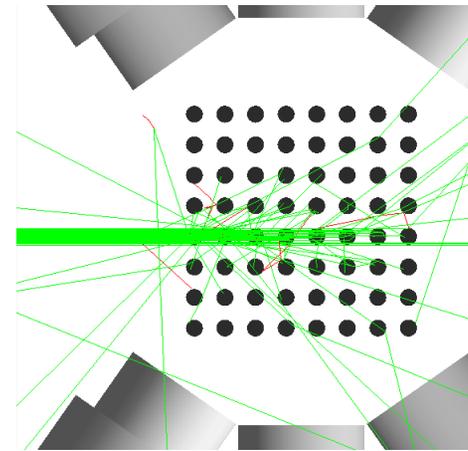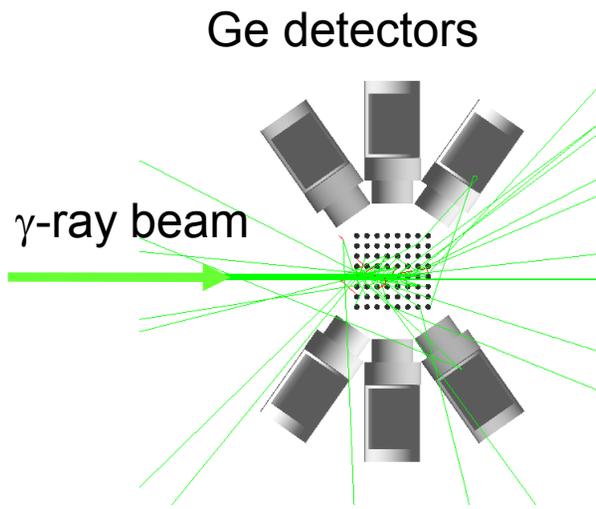
γ-ray beam

γ-ray beam

GEANT-4 based Monte Carlo code developed by Hajima's group.

Sharp discriminatory capability of monoenergetic γ rays

2 MeV e-Brem X-Ray image simulation
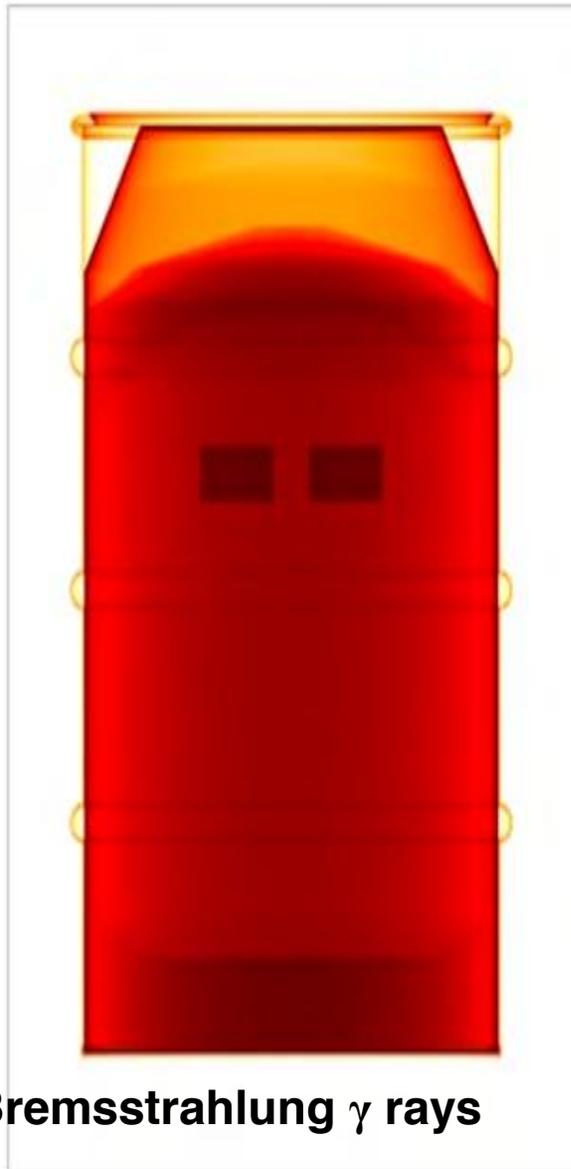
1.734 MeV NRF image simulation

Nuclear Resonance fluorescence signal

vs

Bremsstrahlung γ rays
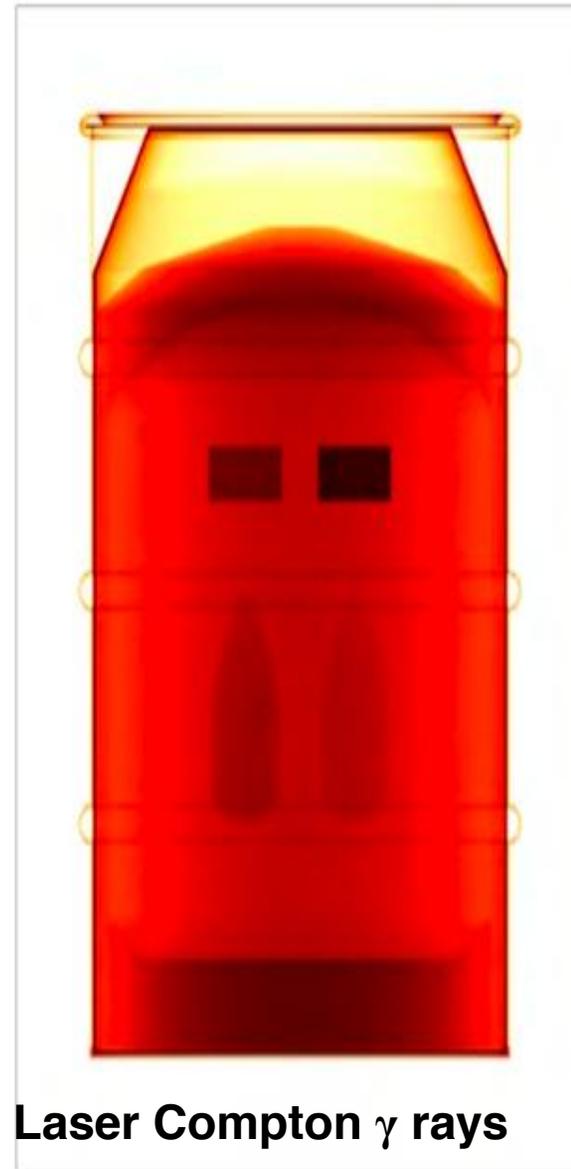
Laser Compton γ rays

C. Barty and T. Tajima (2008)

Present status of MeV g-ray beam :

ation in Japan :
pring-8 (8 GeV electron storage ring (SR))
ERAS of AIST (National Institute of
dvanced Industrial Science and Technology)
0 MeV—800 MeV SR
ew Subaru
EK SR
ga SR

Collaboration between Nuclear physics
and Laser physics

er Technology developments
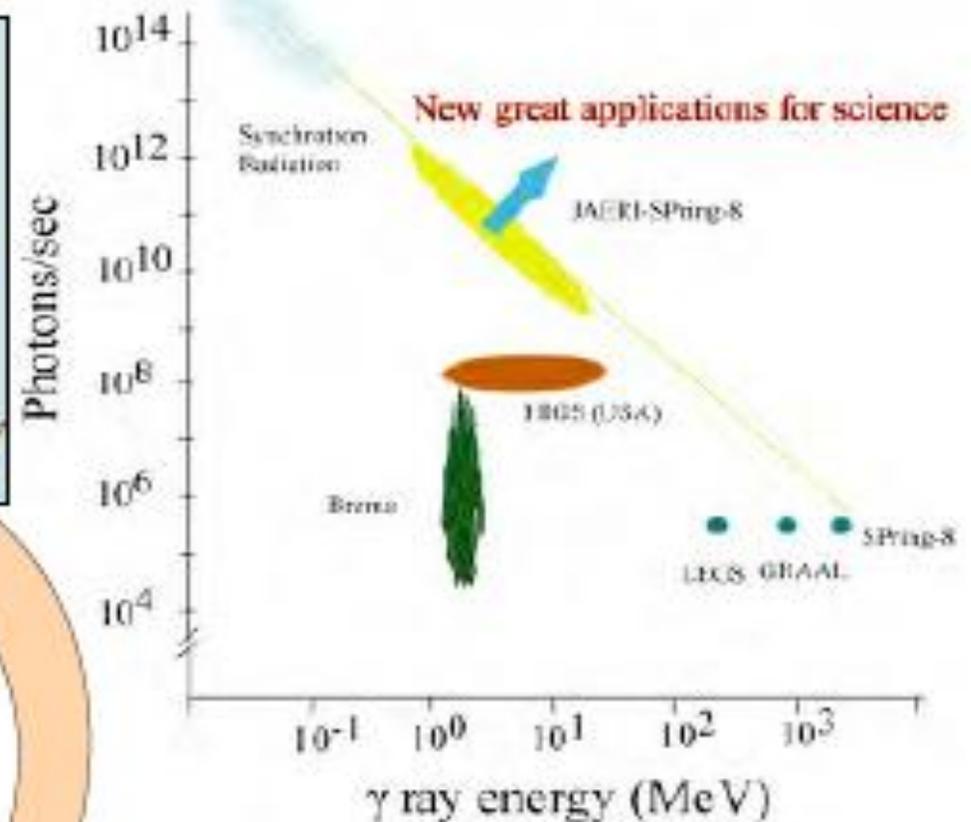
(M. Fujiwara)

Photonuclear processes

Nakano et al., PRL 91, 012002 (2003)

GeV Photon

K^-

neutron

Θ^+ particle
(Penta-quark particle)

K^+

neutron

Peak of Θ^+

uudd$\bar{s}$

Θ^+ (1530)

N(1710)

Σ(1890)

Ξ(2070)

ddss$\bar{u}$

uuss$\bar{d}$

(Spring-8)

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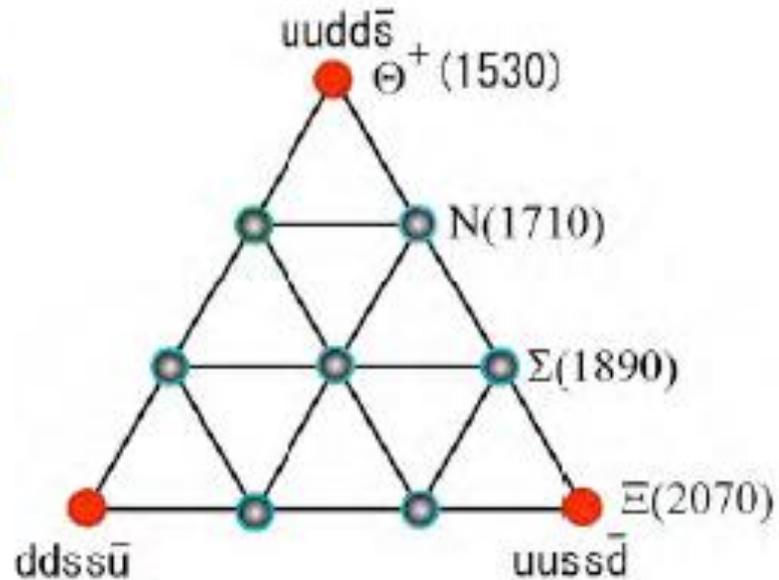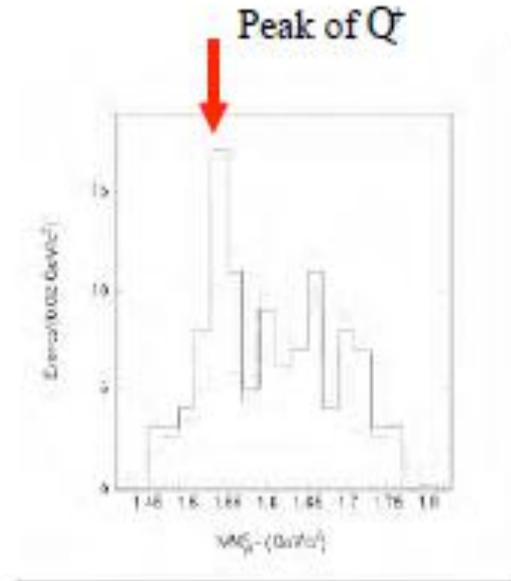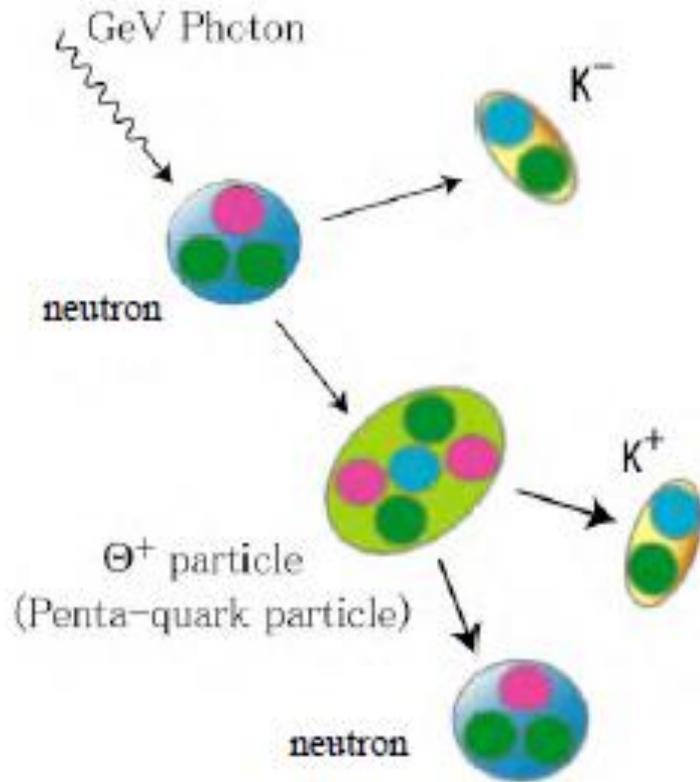
Parity Mixing in Nuclei

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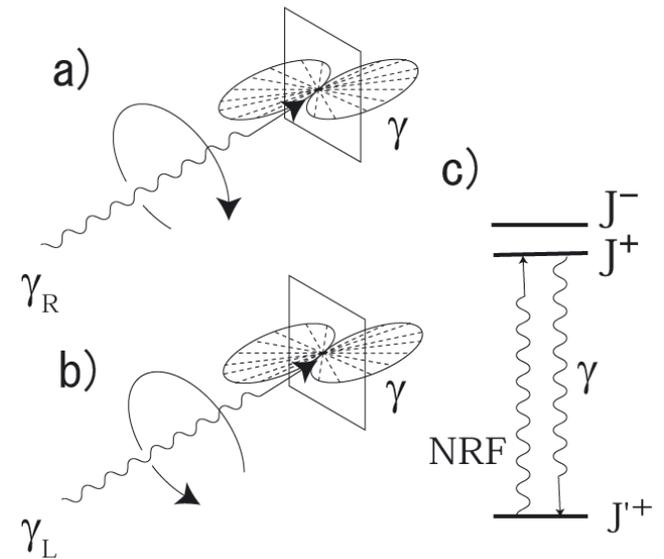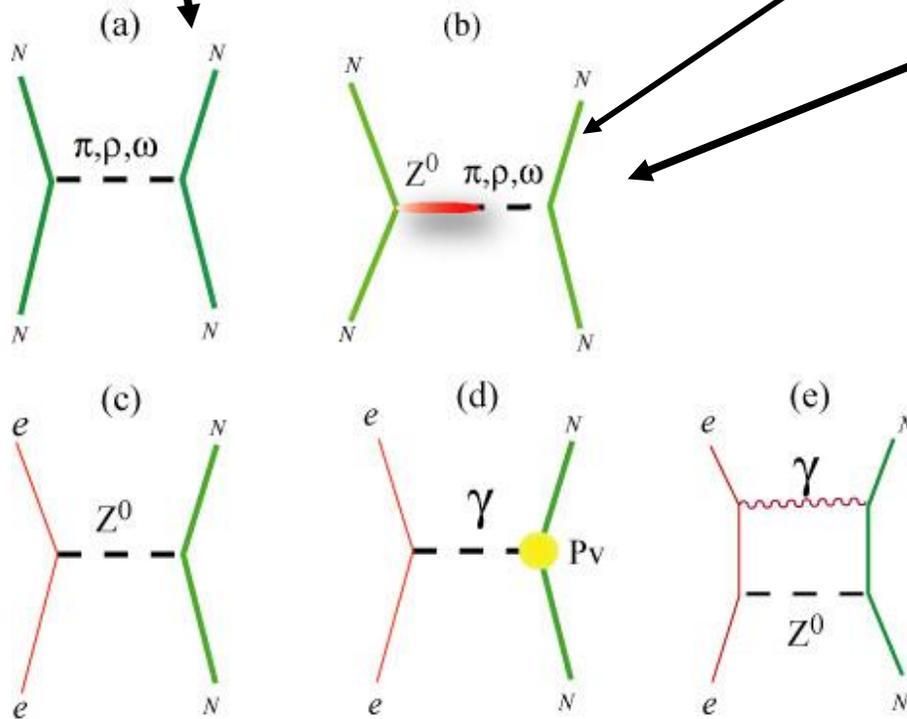
The interaction can be determined
by polarized LCS gamma-rays.
Fujiwara, J. Phys. G (2006).

Parity Assignment

Asymmetry at $q=90°$

$$A = \frac{1}{P_\gamma}\frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}$$

$P_g = 1$ $\Longrightarrow$

$$A = \begin{cases} +1 \text{ for } M1 \text{ transitons} \\ -1 \text{ for } E1 \text{ transitions} \end{cases}$$

P_g : Photon polarization

^{208}Pb(γ_{pol},γ), E$_\gamma$=7.8 MeV   *Ohgaki et al.*

Linearly polarized photons

$N_\parallel$

$q=90°$ M1

$E1$ $N_\perp$

$\vec{E}$ $\vec{H}$

LCS beam
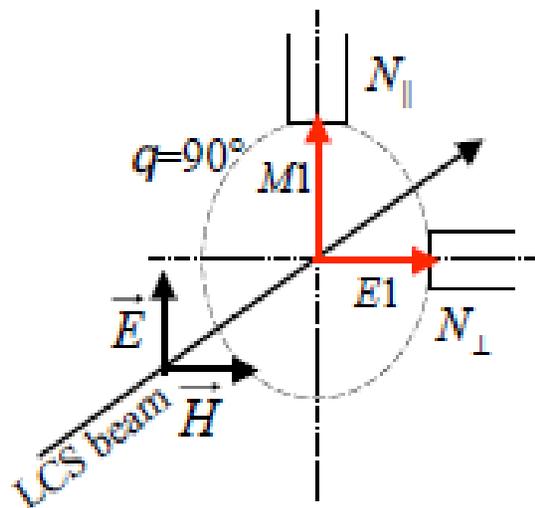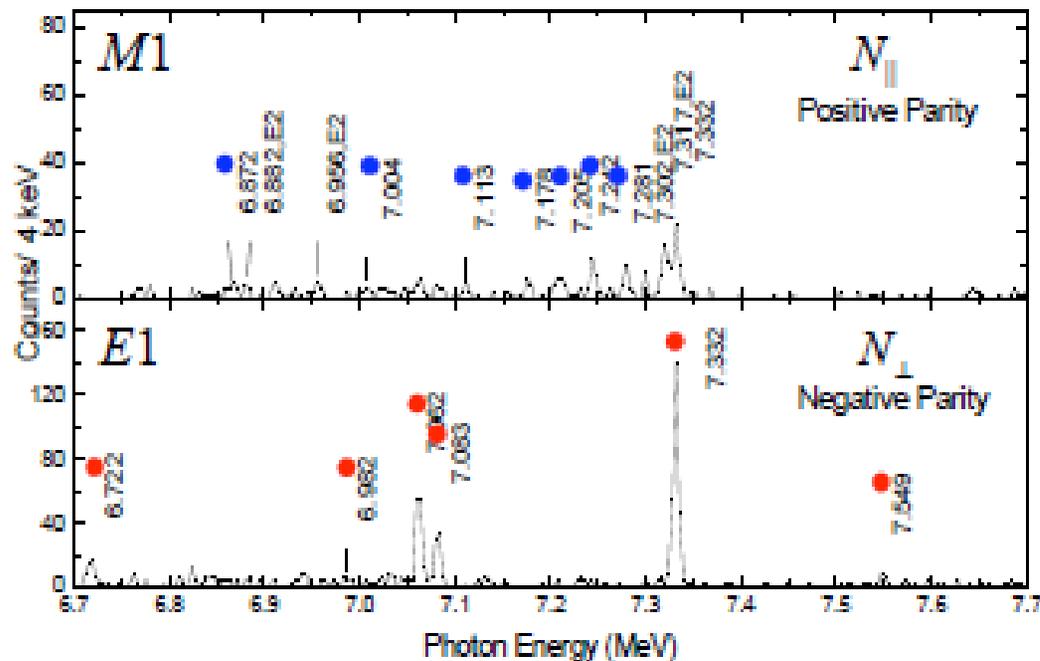
(M. Fujiwara)

Nuclear Astrophysics

High energy photons with 8-10 MeV create new isotopes

Supernova Explosion

Massive Star

H
He
C
Mg/Si
Fe
O/Ne

Nucleosynthesis

Seed Nucleus
New nucleus
Photon
Neutron
Photon
Neutron
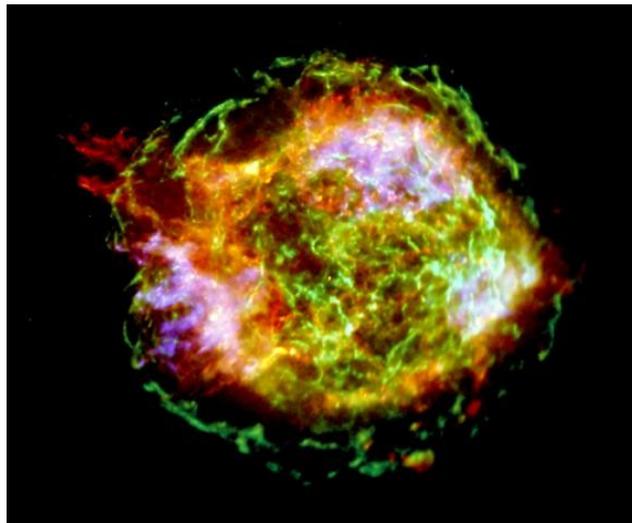
Supernova Residual: Cassiopeia A
There are many new isotopes.
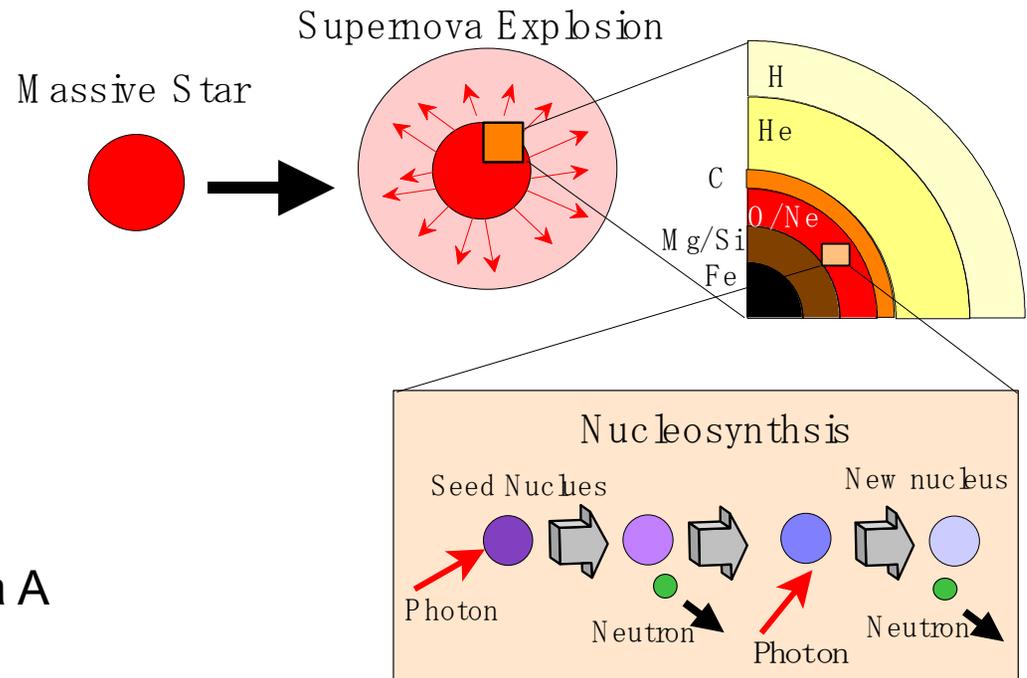
JAEA-NAO team found a piece of evidence for such the nucleosynthesis.
Hayakawa, Phys. Rev. Lett. (2004)

Photonuclear reaction rates are important for theoretical verification. 36
T.Hayakawa

Nucleosynthesis of the ^{180}Ta Isomer

^{180m}Ta --- $T_{1/2} > 1.2 \times 10^{15}$ y, $E_x = 75$ keV

Only the naturally occurring isomer
Nature's rarest isotope
One of the p nuclei

9^- _____ 75 $>1.2 \times 10^{15}$ y

1^+ _____ 0 8.1h

^{180}Ta b^- decay
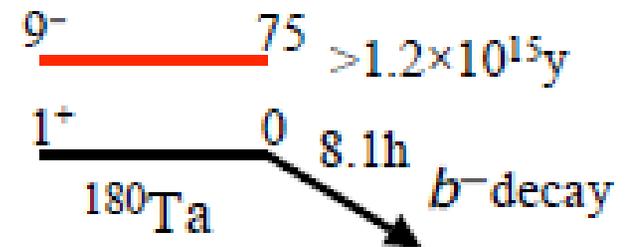
Production process?

Photo-disintegration ^{181}Ta(g,n)^{180m}Ta

^{180}W	^{181}W	^{182}W
^{179}Ta	^{180m}Ta	^{181}Ta
^{178}Hf	^{179}Hf	^{180}Hf

s process

r process
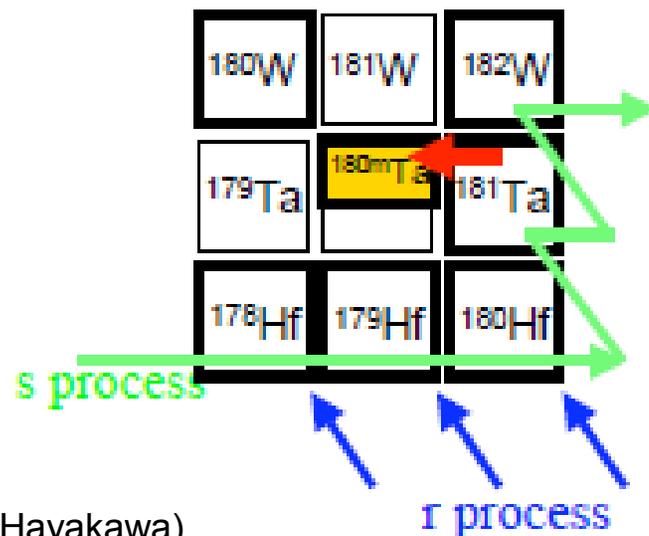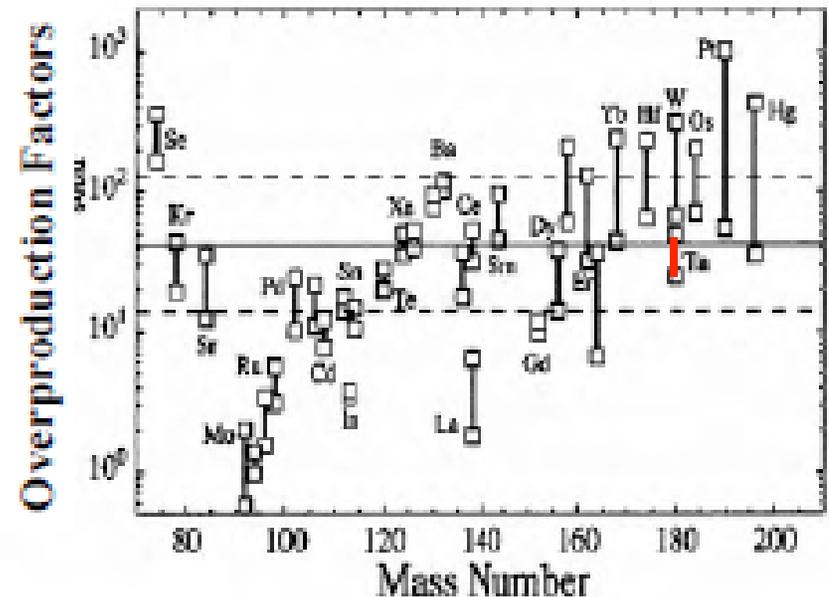
(T. Hayakawa)

H. Utsunomiya et al.,
Phys. Rev. C67, 015807 (2003)

Nuclear Cosmochronometer

^{187}Re

β - decay
$T_{1/2}$=44Gy

^{187}Os

Method using long-lived
radioactivity to measure time from
material production to the present
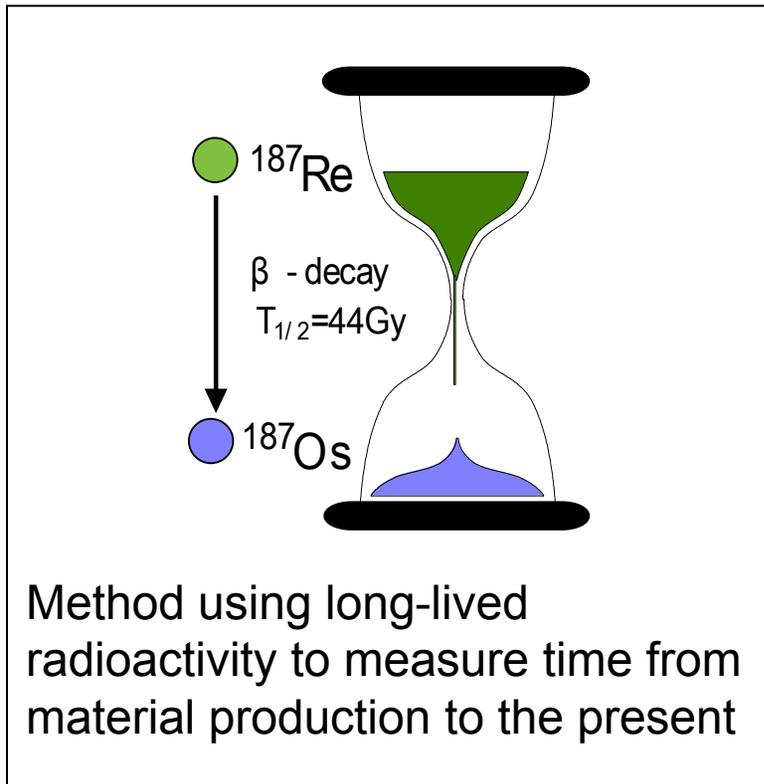
Neutron capture reaction rate
using nuclear reactor
Hayakawa, Astrophys. J (2005).

Reaction rates are important for evaluation of
the initial abundance.

p- process

Os	185	186	187	188	189
		s	s+decay	s+r	s+r

4.4 x 10^{10}y

Re	184	185	186 / 186m	187
		s+r		s+r

W	183	184	185	186
	s+r	s+r		r

s- process

post r- process
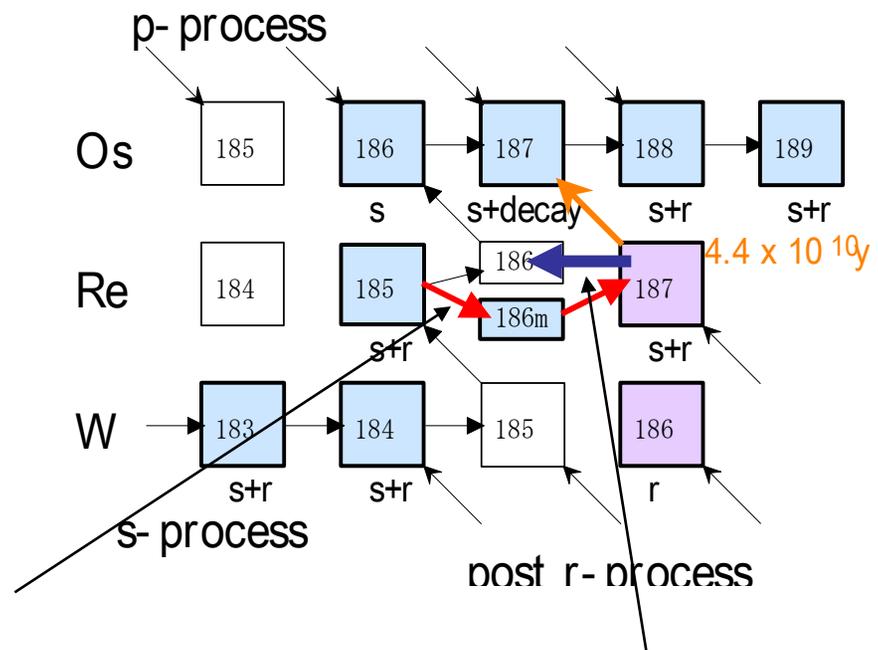
Photonuclear reaction rate
using LCS gamma-rays at AIST
Shizuma, Phys. Rev. C (2005). 38

Transmutation of actinide by photo-fission
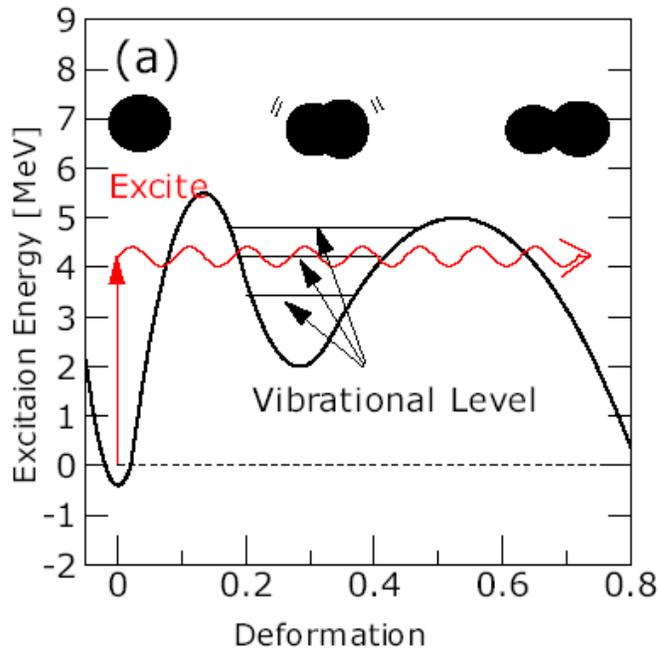
Potential barrier and photo-fission

Horizontal axis: nuclear deformation,
Vertical axis: depth of potential.
We irradiate 4 MeV photons to a stable
nucleus with a deformation 0. Then, the
levels in the first potential with 0
deformation are excited. The excited
levels couple to the vibration level in the
second potential, inducing an abnormal
photo-fission mode.

For example, the transmutation of Np by neutron induced nuclear
fission, fission fragments with wide masses near A=120 remain. One
serious RI is ^{129}I with a long half-life. Can we control the fission mode
by selecting a special mode of fission ?

One possible route is to use Nuclear Resonance
Fluorescence (NFR)

It is well known that there are the second-, and third-potential
in addition to the first potential in actinide nuclei, when we consider
the fission processes. One can use the coupling mechanism between
the levels in the first- and second potentials. Theoretically, it is
predicted that the mass distribution of the fission fragment is different
from those of the usual neutron induced fission fragments.

Feasibility test by photon-beams from FEL Back-Compton photons
are an interesting research subject.

Parity mixing may also play a role !

Idea comes from by Dr. Nishio of JAERI.

Shizuma

Possible layout in a nuclear fuel reprocessing plant

✓Fuel assemblies are transported
  from the storage to the measurement cell.
✓All the process is done in the water pool.

upper level

lower level

water pool

spent fuel

γ-ray

Ge detector

rack

transport

γ-ray source

measurement cell

spent fuel storage
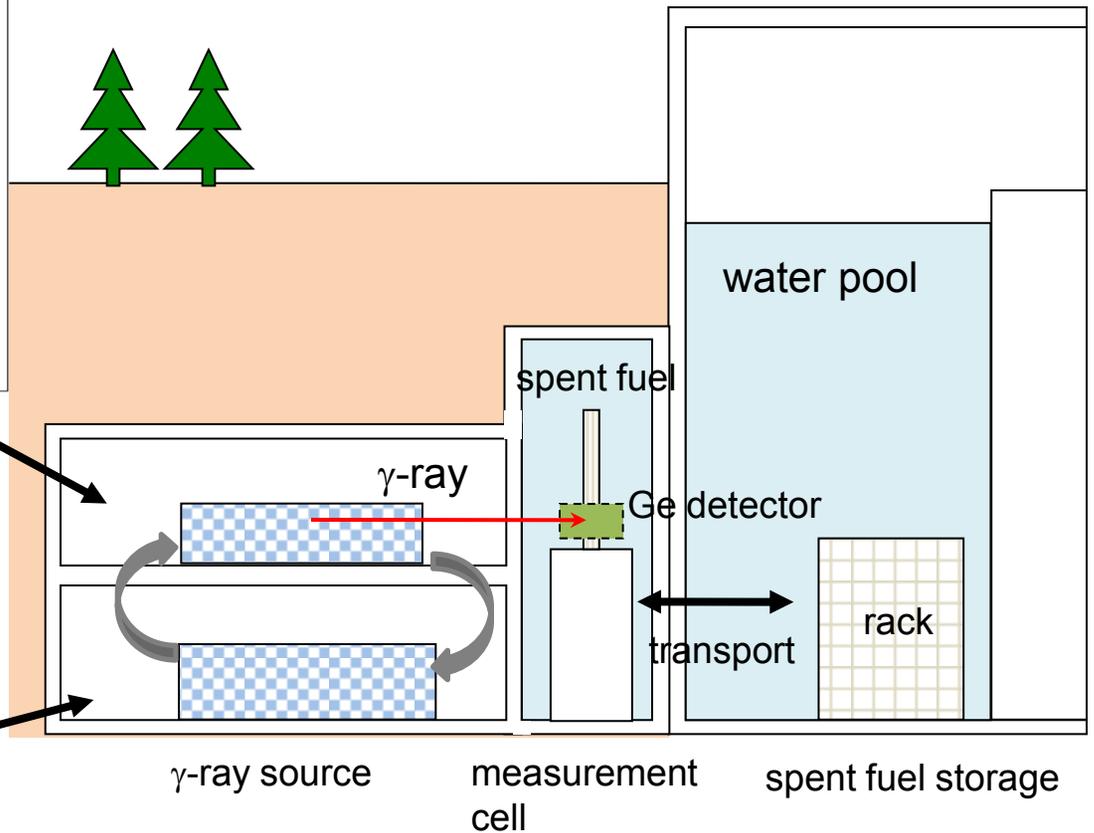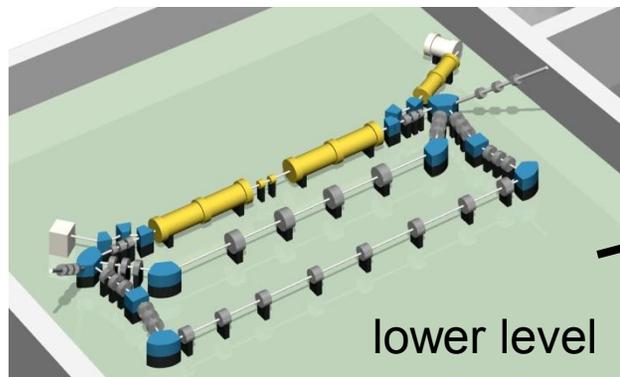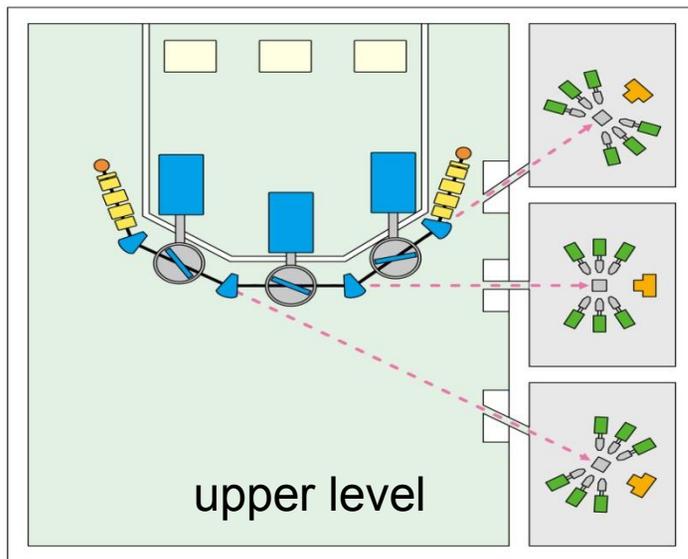
(Hajima et al)

Possible layout in a nuclear fuel reprocessing plant

Detectors are located outside the pool in measurement rooms where people can go inside when SF is not in the measurement point.

SF pool water

concrete wall

dump

water

concrete wall   concrete wall

water

Measurement Room   Measurement Room

(Hajima et al)

concrete wall   concrete wall

Linac / Laser Area   Spent Fuel Assembly

LCSγrays
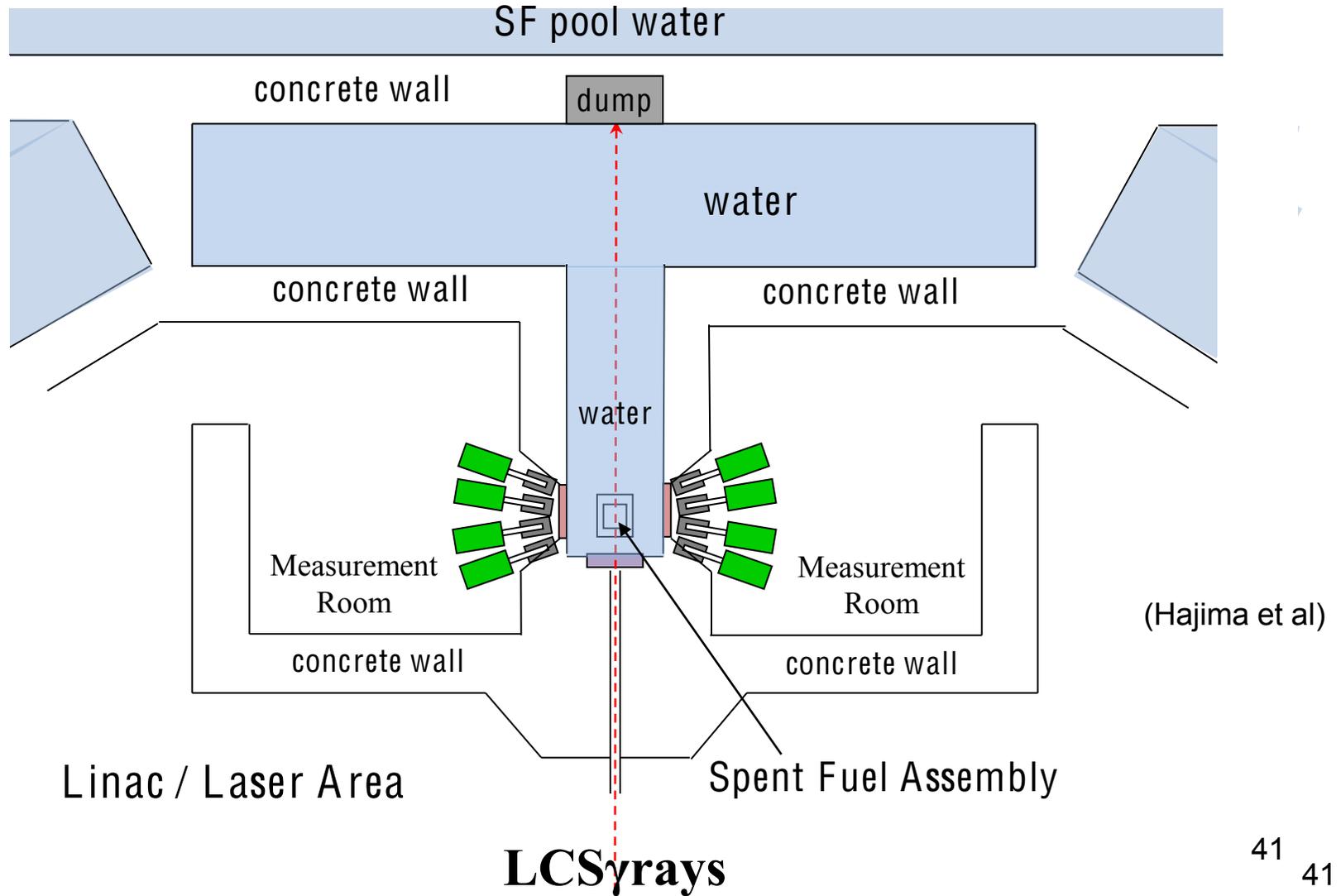
Gamma-driven Neutron beams
Photonuclear Reactions : Neutron yield

$(\gamma,n) \leftrightarrow (n,\gamma)$

(γ,n)

(n,γ)

B_n

n

A-1

$E_\gamma = B_n + \Delta$

E

A

E_n

A

B_n

many cascades

A+1
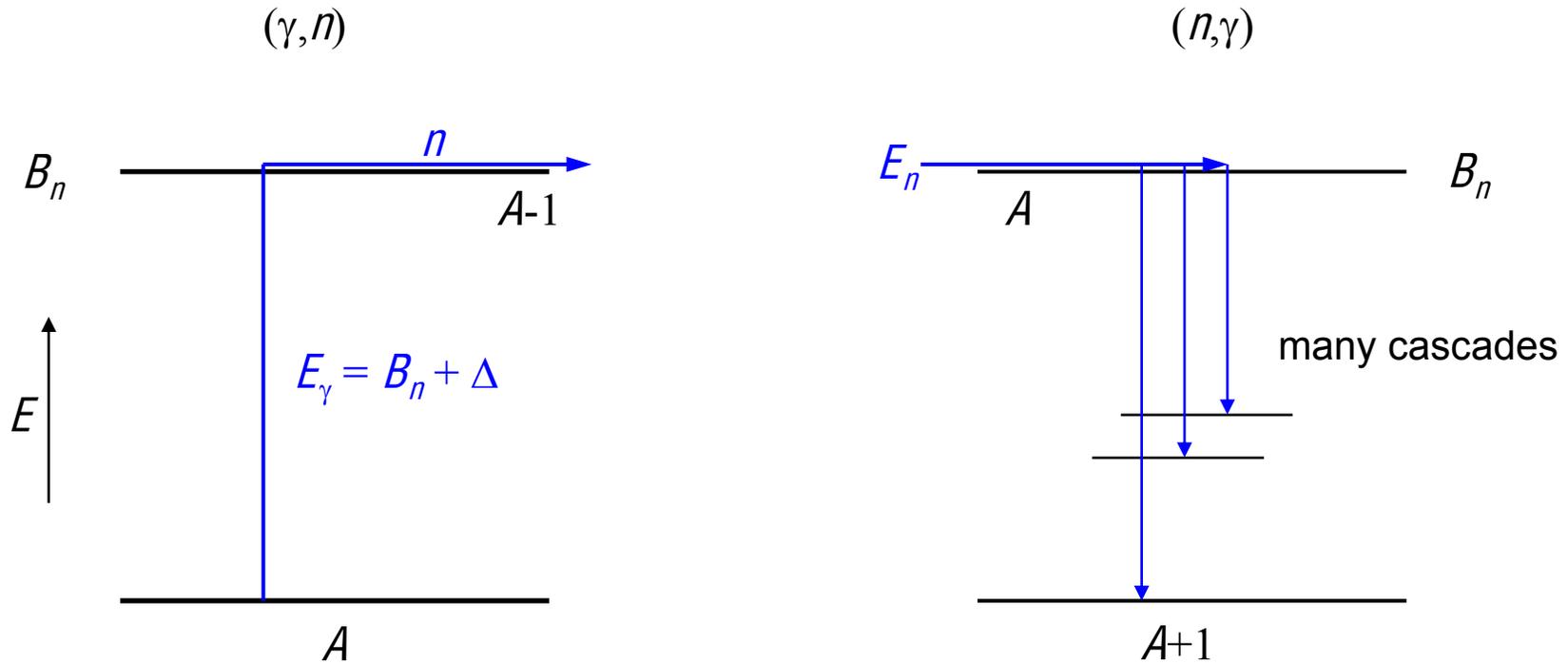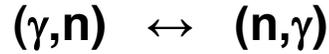
Cross sections and resonances unknown
Γ_n, Γ_γ

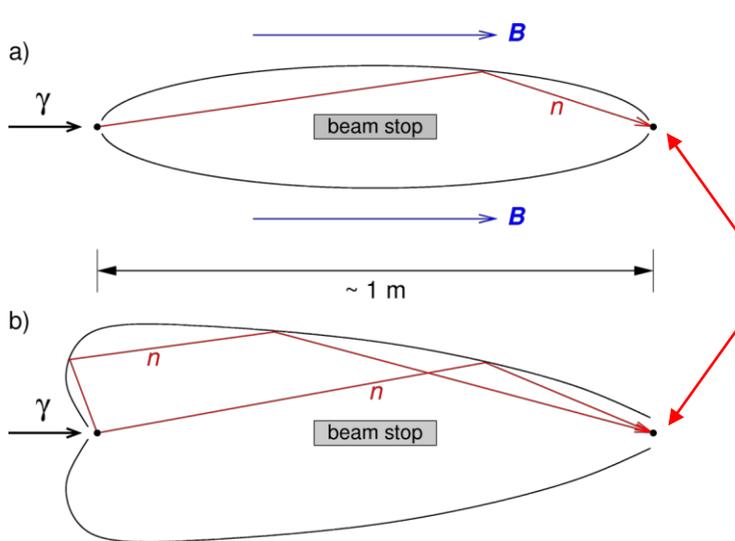Many studies $\rightarrow$ level densities at B_n

42

(Habs)

Gamma-driven micro-neutron beams

$E_\gamma = 6\,\text{MeV}$ $A = 240$ $E_{\text{rec}} = \dfrac{(6\,\text{MeV})^2}{2 \cdot 240 \cdot 10^3\,\text{MeV}} = 75\,\text{eV}$

$$\frac{V}{c} = \frac{1}{4 \cdot 10^4}\,, \qquad V = 7 \cdot 10^3\,\frac{\text{m}}{\text{s}}$$

(compensate by fast centrifuge)

low background focus $E_n = 300\,\text{meV}$

10 m elliptic mirror,
supermirrors: 10^4 Ni layers,
also for hot electrons

Expected optimum flux from reactor: 10^9 cm^{-2} s^{-1},   diameter ~ 1 mm
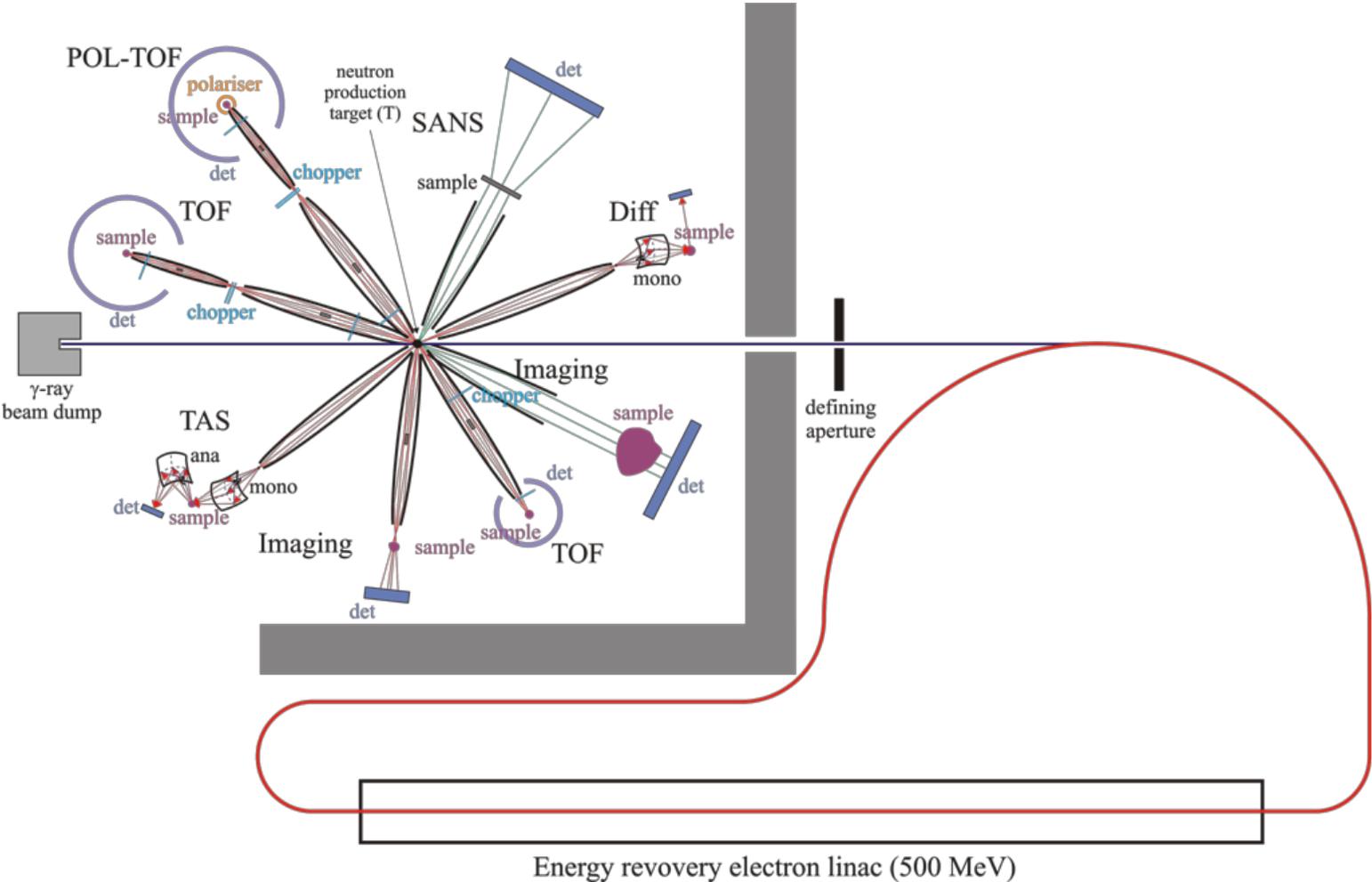photo nuclear: 10^{14} s^{-1}, diameter ~ 10 μm → 10^{18} cm^{-2} s^{-1}, diameter ~ 10 μm

Even 10^2 times higher flux would open up many new applications.

P. Böni, NIM **A 586**, 1 (2008);
R. Valicu, P. Böni, "Focusing neutron beams to sub-mm size", NIM, to be published.
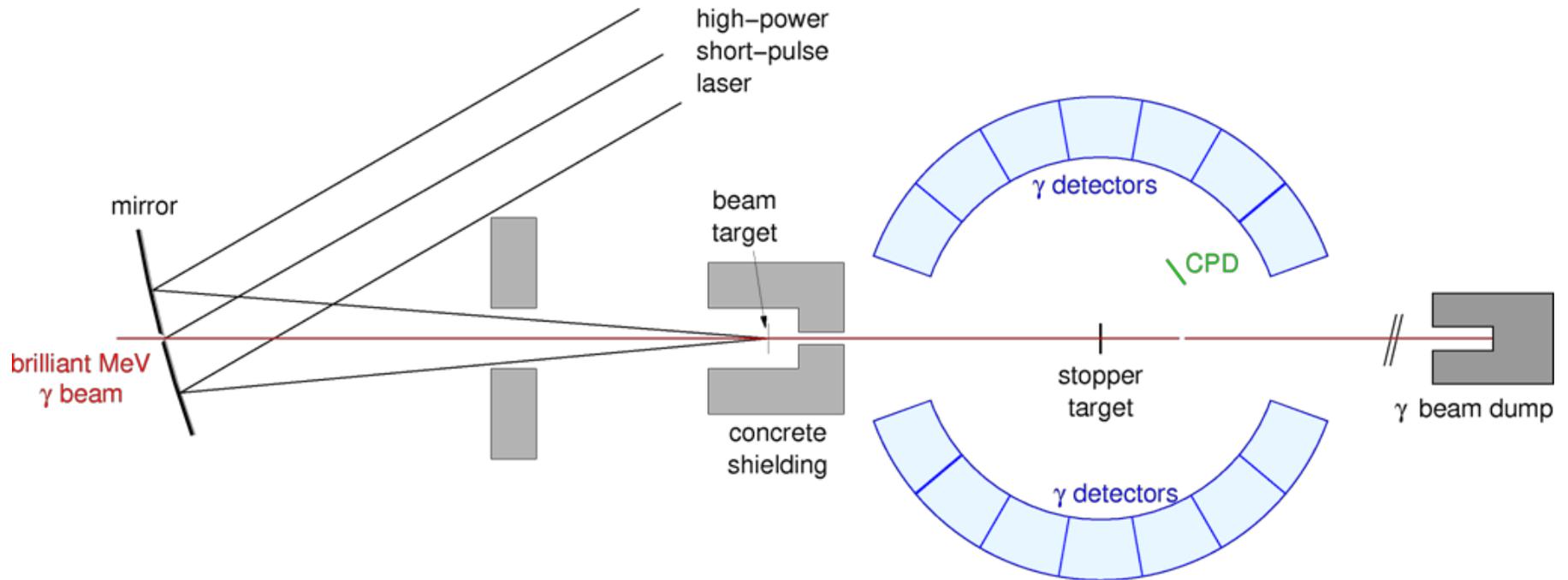
(Habs)

Laser-driven Cold Neutron experiments

(D. Habs)

NRF + radioactive nuclei

ELI (Extreme Light Infrastructure) Nuclear Pillar
APOLLON laser + γ beam

Dense radioactive target of neutron-deficient nuclei
$T_{1/2} \geq 1$ s

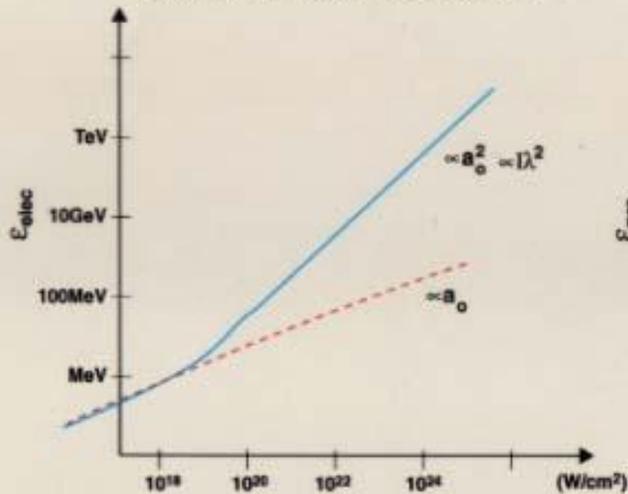(D. Habs)

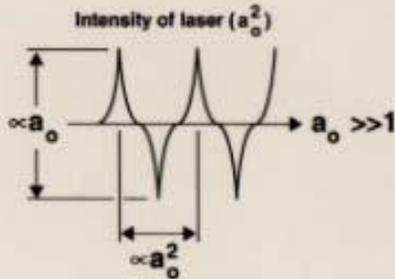# Relativity Helps Acceleration (for Ions, too!)

Extreme Field Science

Ultra-relativistic Regime: charged particles move with photons

Electron Energy in strong field

Proton Energy from Debye sheath in strong field
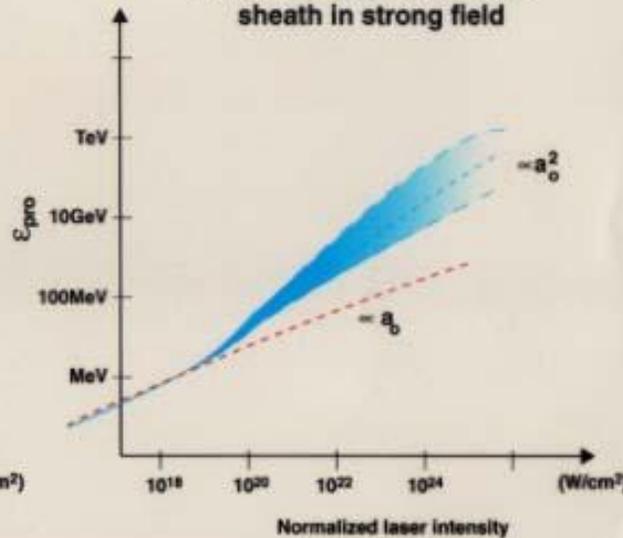
$a_o \sim L.5 \left(\dfrac{\lambda}{1\ \mu m}\right)\left(\dfrac{I}{10^{20}\ W/cm^2}\right)$

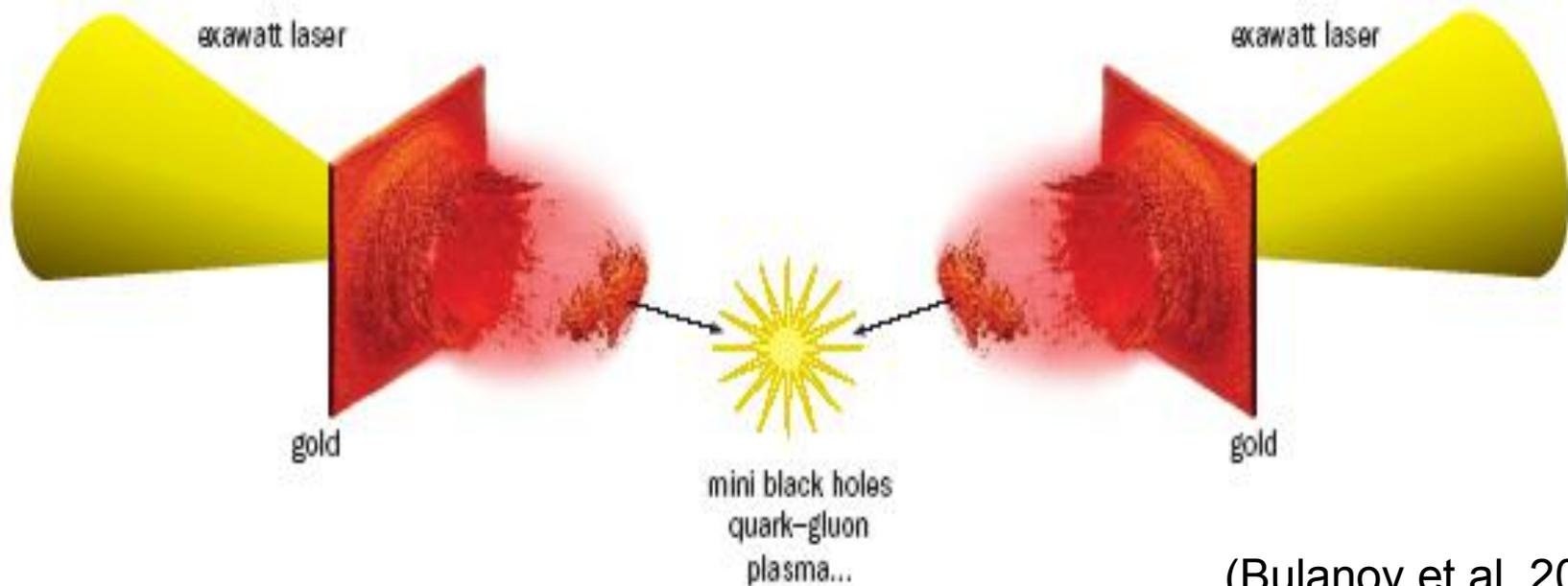Strong fields:
rectifies laser
to longitudinal
fields

In relativistic regime,
photon **x** electrons
and even protons
couple stronger.

(Tajima, 1999
@LLNL;
Esirkepov et al.,
PRL,2004) [46]

Beyond intensity 10^{24}W/cm^2 ions move relativistically like e$^-$

Relativistic and monoenergetic ion beam may constitute compact colliders of ions
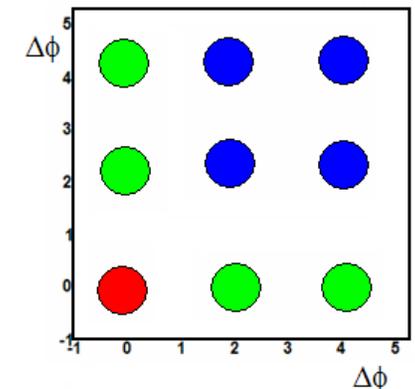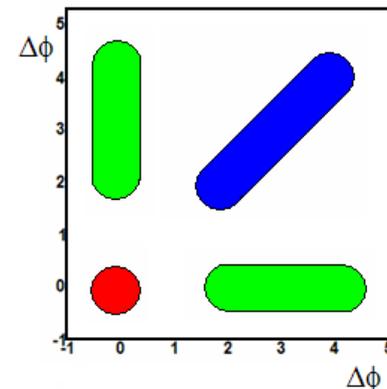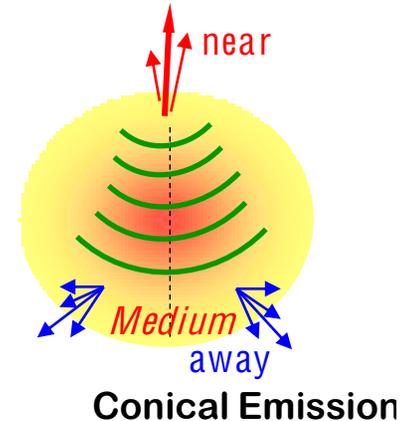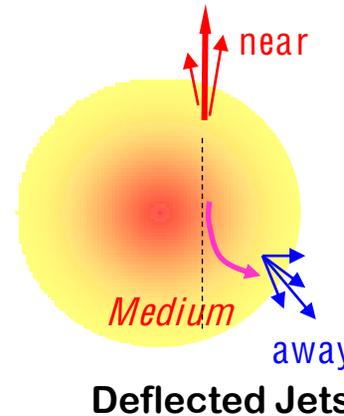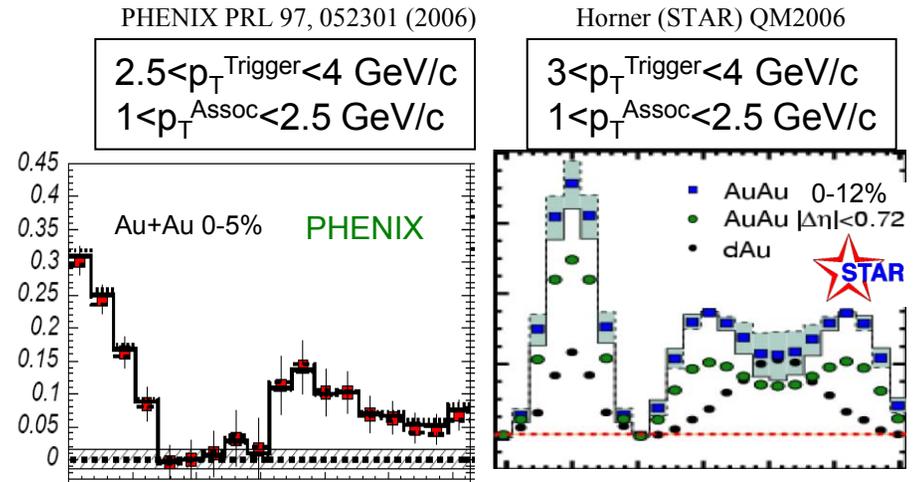→ QCD vacuum exploration

(Bulanov et al, 2004)

Nuclear wakefields

J. Ulery (2007)

- Broadened and maybe double humped structure on the away-side in 2-particle correlations.

- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).

- Three-particle correlations to distinguish them.

PHENIX PRL 97, 052301 (2006)

$2.5 < p_T^{Trigger} < 4$ GeV/c
$1 < p_T^{Assoc} < 2.5$ GeV/c

Au+Au 0-5%   PHENIX

Horner (STAR) QM2006

$3 < p_T^{Trigger} < 4$ GeV/c
$1 < p_T^{Assoc} < 2.5$ GeV/c

AuAu 0-12%
AuAu |Δη|<0.72
dAu
STAR

near

Medium

away

Deflected Jets

near

Medium

away

Conical Emission

PHENIX Results: Nuclear Wake

J. Ulery (2007)

Ajitanand (PHENIX) HP06, IWCF'06

$\sqrt{s_{NN}}=200\,\text{GeV}$

v2 subtracted   Au+Au 10-20%

$2.5 < p_{T,1}^{trig} < 4$ GeV/c

$1 < p_{T,2,3}^{assoc} < 2.5$ GeV/c

$\Delta\phi^*$ $= 0$

2-particle dominated

PH☀ENIX

PHENIX Preliminary

v_2 subtracted

PHENIX PRELIMINARY

2-particle dominated

v_2 and 2-particle subtracted

Deflected

Mach-cone

PHENIX PRELIMINARY

(c) 10-20% PHENIX

PRL 97, 052301 (2006)
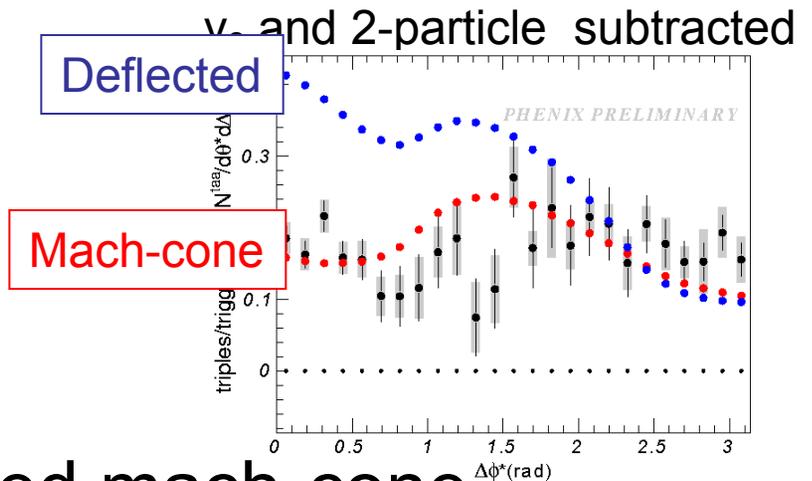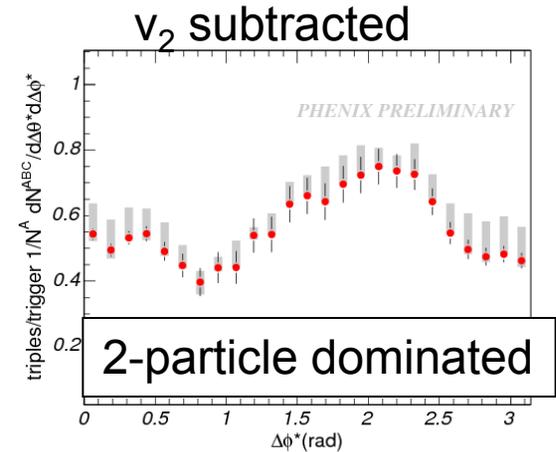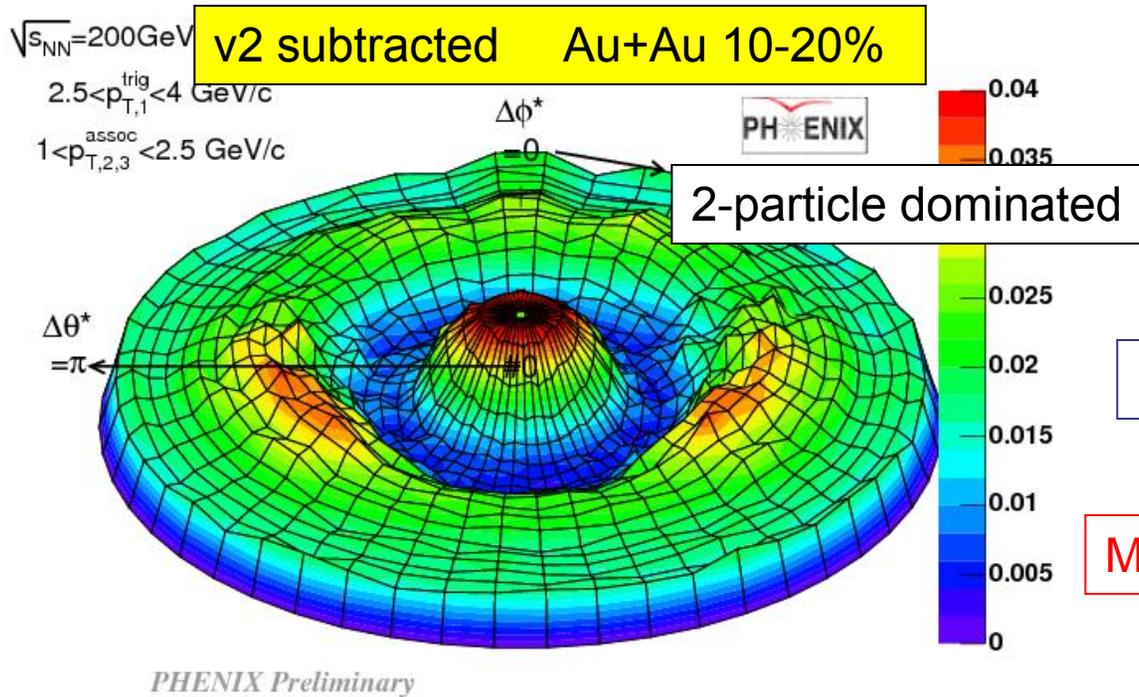
- Shape consistent with simulated mach-cone
- 3-particle/2-particle ~ 1/3, very large
  – Residual background?
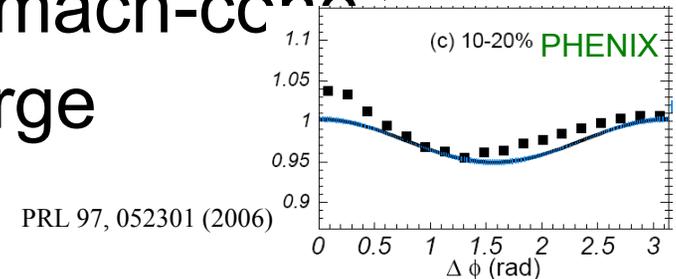
summary

- Contemporary problems to solve in front of us
- Ultrfast intense laser: introduces new ways to <u>revitalize nuclear physics</u>
- Laser Compton γ-rays: first and main access to **<u>photonuclear physics</u>**
- Laser allows: pump and probe in <u>zs regimes</u> of nuclear reactions ('streaking' observation); laser and γbeams collaborate toward marriage of two disciplines of science for new nuclear physics
- Transform nuclear physics with clear specific <u>control</u>: basic science and applications
- γbeam can drive compact cold neutron beams
- New fundamental physics approach by the combination of intense laser + brilliant γbeam: s.a. vacuum physics
- <u>Nuclear fuel</u> monitoring and <u>waste</u> verification

Pascal Lecture Plan

(tentative, need your feedback)

- Oct.22: First Lecture (General) " Laser Acceleration and High Field Science: 1979-2009"
- Nov.18: Second Lecture "Laser Electron Acceleration and its Future"
- Dec.9: Third Lecture "Laser Ion Acceleration"
- January 20,2010: "Relativistic Engineering"
- March 10: "Photonuclear Physics"
- April 14: "High Field Science"
- May: "Medical Applications"
- ……