MeV photons from inverse Compton scattering and applications for science

M. Fujiwara @ Saskatoon workshop 22-23, April 2010

1. Coherent Compton Scattering
   New aspect for inverse Compton Scattering
   (BCS $\gamma$-ray generation)

2. Nondestructive Radionuclide Assay
Collaborators:

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T. Shizuma, N. Nishimori, M. Seya, K. Kawase,
and others (JAEA)

Special Thanks to

D. Habs, T. Tajima, J. Schreiber, C.P.J. Barty,
P.G. Thirolf
\[
\sigma_T = \frac{8\pi}{3} \left( \frac{e \times e}{4\pi\varepsilon_0 mc^2} \right)^2 = 6.7 \times 10^{-25} \text{cm}^2
\]
F.V. Hartemann, T. Tajima et al., Lawrence Livermore Lab. reprint

$$\frac{d^2 N}{d\omega d\Omega} \propto \sum_{n=1}^{N} \int_{-\infty}^{+\infty} n \times (n \times u_n(\phi)) \exp(i\omega(\phi + z_n(\phi) - n \cdot x_n(\phi))) d\phi$$

Electrons are trapped by laser force

Inverse Compton scattering

Very short electron packet

Very short laser
Mono energetic electron beams from Laser Wakefield Accelerator

Mono energetic high quality electron beams first produced by AIST (JAPAN), IC/RAL (UK), LOA (FRANCE), LBNL (US), and JAERI-CRIEPI (JAPAN)

\[ F = ev \times B \]

C. Murphy et al., IC/RAL, UK

Laser → Short pulse laser → electron beam → gas jet target

accelerated electron spectrum

(N)^2

inverse Compton scattering
\[ \omega = \frac{4 \omega_0 E^2}{(m_c c^2)^2 + 4 \omega_0 E_c} \left( 1 + \frac{1}{E^2} \right) \theta^2 \]

LCS γ-ray Energy (MeV)

Laser Energy (eV)

Transmutation of actinide nuclei by photo-fission

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.
Nucleosynthesis by high energy photons

Heavy elements have been produced by stars in the Galaxy.

Massive stars have contaminations of heavy elements synthesized at early generation stars.

New isotopes are produced by photons in supernova explosions.

Temperature: $3 \times 10^9$ K!

Goko et al., (Konan group) PRL 96, 192501 (2006)
Hajiam et al. has proposed a novel method that measure any radionuclide inside a heavy shield as a few cm thickness steel.

- Energy tunable mono-chromatic gamma-ray beam
- Identification with Nuclear Resonance Fluorescence

Management of nuclear waste

Dramas of nuclear wastes

Depending on radioactivities

Nondestructive radionuclide assay is crucial for the classification.

Correct classification is important for the safety and cost

Clearance

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Cycle of used nuclear fuel

A new generation of nuclear fuel cycle

Project for Nuclear Separation and Transmutation technology (under discussion at government level)

In this method, standard assay system Can not be used.
Development of Detection methods

- A proof-of-principle experiment
- Selection of detector (Ge semi-conductor, NaI, LaBr$_3$)
- Design of geometry of detectors
- High background from RI

We have developed a simulation code based on a library GEANT 4 for design of the detection system.

An example of simulation

Drams of nuclear waste including U-238

Expected energy spectrum

Peak of U-238
A proof-of-principle Experiment at AIST TERAS

Electron Storage Ring

Electrons

Laser

Collision

LCS $\gamma$ rays

Flux Monitor

Target

$\gamma$ Ray Detector

LCS gamma-ray source at TERAS in AIST

Electron storage ring TERAS

- Nd:YVO4 Q-switched laser 1064 nm
- 570 MeV electrons
Detection of Pb hidden by 15-mm thickness iron plates

Experimental Setup

- Two High Pure Ge semi-conductor detectors
- NaI(Tl) Flux Monitor

There occurs Nuclear Resonance Fluorescence, if Pb-208 exists.
Result

We used Pb-208 instead of U-238, since we cannot use it at AIST.

We detected Pb-208 hidden by 15mm iron

Counter Terrorism

Monitor system in a gate in nuclear plant, military base, and airport

- Passport System Inc. (http://www.passportsystems.com/)

Detection of Uranium bomb in a cargo.

Pruet, Apply. Phys. Lett. 2005
Proposal of nondestructive assay of chemical compound

We extend the nondestructive assay method to chemical compound.

In this method, several key elements are measured at the same time with energy tuned LCS gamma-ray.

We carry out a proof-of-principle experiment.

A chemical compound, melamine ($C_3H_6N_6$), is used as a test material.
A proof-of-principle experiment

Melamine target is shielded by 15-mm iron and 5-mm lead.

We carried out a proof-of-principle experiment

Development of a new generation of ERL systems in JAPAN

Compact LCS Gamma-ray source based on ERL with energy of a few 10 keV for material science (2008-2012)

Prototype of high-power ERL is under Construction by KEK-JAEA-ISSP (complete in 2012)

Laser Super Cavity for generation of Gamma-rays
We have designed extremely high-flux gamma-ray source based on ERL. This system is constructed by new generation of accelerator and laser technology.

\[ 10^{10} \text{ photons/(kev s)} \]

Flux is 6-8 order magnitudes higher than available sources.

Applications for Nuclear Engineering
Proposal for detection system for nuclear material safeguards

Terrorist and spy cannot access spent nuclear fuel to steal fissional materials.

Hayakawa, et al. submitted to NIMA.
Simulation for proposed system

We have extended GEANT4 to calculate NRF

Our designed system can observe Pu-239 in all rods.

Hayakawa, et al. submitted to NIMA.
Development for industrial application with Microtron

In general industrial applications, although extremely high flux is not required, the size should be small.
Generation of LCS gamma-rays with Microtron in JAEA

We have generated LCS gamma-rays using 150 MeV microtron in JAEA.

Nd:YAG laser
- (Continuum Powerlite 9010)
- Pulse duration: 23 ns (FWHM)
- Output: 1 J (1064 nm)
- Repetition: 10 Hz

Microtron
- Energy: 150 MeV
- Pulse duration: 10 ps (rms)
- Charge: 60 pC/pulse
- Repetition: 10 Hz

Electron beam dump

Detector

LCS gamma-rays

Incident angle: 16°

Bending magnet

4 m

Nd:YAG laser

Synchronized operation

Photocathode RF-gun

Microtron
Result

Total energy of LCS gamma-rays in an electron pulse by LYSO

(Mean energy $\times$ number of photons)

Number of gamma-rays is about 200 photons/pulse

K. Kawase et al., NIMA, in press (2010).
UK’s ALICE facility collides beams to make X-rays

Physicists working on an R&D prototype for the next generation of accelerator-based light sources – Accelerators and Lasers in Combined Experiments (ALICE) at the Daresbury Laboratory in the UK – are celebrating after successfully colliding electrons and a powerful laser beam to produce short-pulsed X-rays. This is the first time this has been done in the UK and the first time that the concept of using an accelerator and laser source together has been demonstrated on ALICE.

The Compton Back Scattering project saw a team of scientists from the Cockcroft Institute, the University of Manchester, the Max Born Institute and the Science and Technology Facilities Council (STFC) accelerate bunches of electrons and then collide them head-on with a high-energy, short-pulse multi-terawatt laser photon beam. The technique converts the optical laser light to X-rays, as the electrons transfer energy to the photons.

X-ray generation from inverse Compton scattering between laser and ERL electrons
Summary

1. Possibility of Coherent LCS

2. New projects with ERL