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

Narrow-band $\gamma$-ray is obtained by collimating the scattering angle $\theta$.
However, inhomogeneous broadening exists – emittance, energy spread.
LCS $\gamma$-ray Sources in the world

**HI$\gamma$S @ Duke Univ.**
1.2 GeV Storage Ring FEL  
$E_\gamma = 1\text{--}158$ MeV  
User Facility for Nuclear Physics and Applications

**The National Institute of Advanced Industrial Science and Technology (AIST) in Japan**
300-700 MeV Storage Ring  
$E_\gamma = 4\text{--}40$ MeV  
User Facility

**NewSUBARU in SPring-8**
1-1.5 GeV Storage Ring  
$E_\gamma = 1.7\text{--}40$ MeV  
User Facility
Next generation of LCS $\gamma$-ray Sources

- **T-REX @ Lawrence Livermore Natl. Lab.**
  - 250 MeV Linac
  - $E_\gamma = 1$-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 Safeguards Applications
Energy-Recovery Linac as a $\gamma$-ray Source

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

$\gamma$-ray beam with high-flux and narrow bandwidth

Small emittance for narrow-band $\gamma$-ray

emittance smears “angle-energy correlation” of $\gamma$-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 $\varepsilon_n = 1\text{mm-mrad}$, collision spot $\sigma_x = 10\mu\text{m} \rightarrow \Delta E_\gamma/E_\gamma = 2\%$

normalized emittance $\varepsilon_n = 0.1\text{mm-mrad}$, collision spot $\sigma_x = 10\mu\text{m} \rightarrow \Delta E_\gamma/E_\gamma = 0.02\%$

normalized emittance of 0.1mm-mrad is the key parameter.
On-axis Spectral Brightness (analytical estimation)

\[ \varepsilon_n = 1.0 \text{mm-mrad} \]

\[ \varepsilon_n = 0.1 \text{mm-mrad} \]

\[ \varepsilon_n \approx \frac{\lambda}{4\pi} \]

Calculation by using a formula in [1].

Nuclear Engineering
Measurement of Nuclear Material by $\gamma$-rays

Laser Compton Scattering

Mono-energetic & tunable $\gamma$-ray beam (not like bremsstrahlung)

Nuclear Resonance Fluorescence

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.

Experimental Demonstration at AIST (Tsukuba)

Pb block shielded by 15mm-thick iron box

5512 keV Pb-208

Position and shape of the Pb block were clearly identified.

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.

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

<table>
<thead>
<tr>
<th>Composition</th>
<th>Density</th>
<th>11.0g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO₂</td>
<td>90 %</td>
<td>(U-238 100 %)</td>
</tr>
<tr>
<td>PuO₂</td>
<td>10 %</td>
<td>(Pu-239 52%) (Pu-240 48%)</td>
</tr>
</tbody>
</table>

We make a model based on our Ge detector.
Our designed system can observe $^{239}\text{Pu}$ in all rods.

We can measure with statistical error of 2%.

LCS-$\gamma$ experiment at the Compact ERL

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

- Installation of a LCS chamber
- Generation of LCS $\gamma$-rays
- Demo-Experiment of NRF measurement

Mockup of spent nuclear fuel assembly

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

T. Yoshida, PRL (2005)
Synthesis of Light elements $^7\text{Li}$ and $^{11}\text{Be}$ constrains the energy spectrum of the neutrino.

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

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

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

+1 for M1 transition

−1 for E1 transition
Experimental Results

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

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

Nuclear Reactions in neutrino-process


\[ ^{138}\text{Ce} \quad ^{140}\text{Ce} \]
\[ (\gamma, n) \text{ reactions} \]

\[ ^{138}\text{La} \quad ^{139}\text{La} \]
Neutral current reaction

\[ ^{136}\text{Ba} \quad ^{137}\text{Ba} \quad ^{138}\text{Ba} \]
Charged current reaction

Charged Current Reaction (CC) is most important.

Neutrino-process production for \(^{7}\text{Li}, ^{11}\text{Be}, ^{138}\text{La}, \text{and} ^{180}\text{Ta}\) were calculated. Former three isotopes are reproduced (normalized \(^{16}\text{O}\)) BUT \(^{180}\text{Ta}\) is overproduced.
Improvement of Charged Current Reaction Rate for $^{138}\text{La}$ and $^{180}\text{Ta}$

A. Byelikov, Phys. Rev. Lett. 2007

They measured the Gamow-Teller Strength at RCNP

The abundance of $^{138}\text{La}$ can be reproduced by + CC at 4MeV but that of $^{180}\text{Ta}$ is overproduced.

This magnitude depends on unknown branching ratio of the isomer.
New Result

Normalized to $^{16}\text{O}$

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.

Nucleosynthesis in supernovae

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

The mass is 8 times heavier than our Sun.


Evidence for this process has been found in the solar abundances.


Two neutrons are picked off.
Measurement of (gamma, n) reaction cross-sections at AIST

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

Fundamental Physics
Parity Mixing in Nuclei

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

Standard Nucleon-Nucleon Interaction

\[ Z^0 : \text{Neutral Current Boson} \]

Interaction between \( Z^0 \) and Mesons.

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

\[
\begin{align*}
\frac{1}{2}^+ & \rightarrow 109.9\text{keV} \\
\frac{1}{2}^+ & \rightarrow 19\text{F}
\end{align*}
\]

Target and detector

K. Kawase, submitted.
Other candidates and final goal

\[ 17/2^+ \quad 15/2^+ \quad 11/2^+ \quad 9/2^+ \]
\[ 800.1 \quad 595.4 \quad 251.5 \quad 113.8 \]
\[ 13/2^+ \quad 11/2^+ \quad 7/2^+ \]

\[ 5/2^+ \quad 353.3 \]
\[ 343.4 \]
\[ T_{1/2} = 281 \text{ ps} \]
\[ T_{1/2} = 1.49 \text{ us} \]
\[ dE = 9.9 \text{ keV} \]

Deutron Neutron

Proton

Gamma-rays

E > 2 MeV

Measurement of Neutrons

M. Fujiwara, Private comm.
10^7 \text{ photons/s} \quad \rightarrow \quad 10^{13} \text{ photons/s}

New Frontier!

Thank you very much