Science Facilities with Inverse Compton Photon Beam in Japan and Their New Developments
Soft Photons and Light Nuclei
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Contents:

1) SPring-8 with HD target facility
2) Low Energy facilities at SPring-8, New SUBARU, ERL
3) New Challenge at KPSI and ATF in relation with non-linear Compton scattering
   Start of new era for non-perturbative QED
4) Present status of PNC measurements
5) Summary
Laser photons are energy boosted up by a factor of about $\gamma^2$

$$\gamma = \frac{Ee}{mc^2}$$

For 8 GeV electron beam
LEPS facility

a) SPring-8 SR ring

Collision

8 GeV electron

Recoil electron

Electron tagging

Laser light

Inverse Compton $\gamma$-ray

c) experimental hutch

RCNP, JAERI, JASRI collaboration
Missing mass spectrum

- $p(\gamma, K^+) \Lambda (1116)$
- 72,500 events
- $p(\gamma, K^+) \Sigma^0 (1193)$
- 48,900 events
- $1.5 \sim 2.4 \text{ GeV}$
- $0.6 < \cos \theta_{cm} < 1$

Photon beam asymmetry
Photon beam asymmetry for $K^+\Sigma^0$ in LH2 data

\[
\frac{(nN^\gamma_N - N_H)}{(nN^\gamma_N + N_H)} \quad E_\gamma = 1.9-2.0 \text{ GeV}
\]

$\Lambda$, $\Sigma^0$, $\Sigma^0$ 2$\sigma$ cut

$\Lambda^*(1405)$, $\Sigma^*(1385)$, $\Lambda(1520)$

Missing mass (GeV)

Azimuthal angle (deg.)

Missing mass $N(\gamma, K^+)X$

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

Note: Present situation is in controversy.
Beam-target asymmetry and exotic processes with unnatural parity exchange \((ss\text{-}k\text{nockout})\)

\[
C_{BT}^{p} \approx 2|\alpha^{pU}| \cos \delta_{N-U}^{p},
\]

\[
\alpha^{pU} \approx \frac{\sigma^{pU}}{\sigma_{\text{int}}}.
\]

LEPS, Spring-8
(calculated by Titov)
with 1% ss-bar content
Error estimation for $C_{BT}$ measurement

$$C_{BT} = \frac{(\sigma_p - \sigma_{BG}) - (\sigma_A - \sigma_{BG})}{(\sigma_p - \sigma_{BG}) + (\sigma_A - \sigma_{BG})} = \frac{\sigma_p - \sigma_A}{\sigma_p + \sigma_A - 2\sigma_{BG}}$$

$$R = \frac{\sigma_{BG}}{(\sigma_p + \sigma_A)/2}$$

$$\left(\frac{\Delta C_{BT}}{C_{BT}}\right)^2 = \frac{\{1-C_{BT}^2(1-R)\}^2 + C_{BT}^2 R^2}{2C_{BT}^2(1-R)^2} \left(\frac{\Delta \sigma_p}{\sigma_p}\right)^2 + \frac{R^2}{(1-R)^2} \left(\frac{\Delta \sigma_{BG}}{\sigma_{BG}}\right)^2$$

![Graph showing precision of $C_{BT}$ measurement over experimental period (days)]
Dilution Refrigerator

Leiden Cryogenics
DRS-3000 (He3-He4)

Cooling power
3000 $\mu$ W at 120 mK

Lowest temperature
6 mK

Magnetic Field
17 T

Homogeneity of Magnetic Field
$5 \times 10^{-4}$ for 15 cm
The polarization glow up slowly upper \( T = 100 \text{mK} \)

But the it glow up fast under \( T = 100 \text{mK} \)

\( \rightarrow \) So it’s important to what degree of cooling because the present “Super Conductive Magnetic” technology have one’s limits on 10-20T.
Dig a hall

Dower

Distiller

DRS

SC

TC

17T Magnet

IBC

Recondenser He^4

He4 recovery line

Connection test of TC with DR

Road map
IBC (In Beam Cryostat)

This instruments will be inserted on Leaps beam line

Inside IBC

5 cm
2.5 cm
Al wire
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.

Supernova Explosion

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

Goko et al., (Konan group) PRL 96, 192501 (2006)
High intensity laser beam $\rightarrow$ Back Compton scattering
1. Collision of Laser light with electron beam at SR facility
2. Wiggler lights
3. Alcohol laser (about 100 mm wave length)
   Energy Recovery Free Electron laser (ERFEL)
4. Laser itself

$119 \, \mu m \, FIR + 8 \, GeV \, electron \, beam$

K. Kawase et al., in print NIM A (2008)
NewSUBARU in SPring-8

University of Hyogo

NewSUBARU: Synchrotron Radiation Facility, $E=1$ or 1.5 GeV

SPring-8
Large Synchrotron Radiation Facility, $E=8$ GeV

Facility for Inverse Compton γ-ray beam at New-Subaru at SPring-8

1W YVO 1064 nm Laser, 200mA e-beam

$E_\gamma = 16.7$ MeV
 Photon intensity: $2 \times 10^6$ photons/sec without collimator ($\rightarrow 10^7$ /sec.)

Half-life of 184Re via 185Re($\gamma$,n): Hayakawa et al., PRC 74, 065802 (2006)
Spectra of Compton Scattering Gamma-rays

Spectra by a GSO detector (Dr. Shima)

Measured and Calculated spectrum

Ge detector

6-16.7 MeV calculated

$\lambda=1064\text{nm}$ measured

13-33.4 MeV calculated

$\lambda=532\text{nm}$ measured

By Prof. S. Miyamoto

Flux

Total: $(1-2) \times 10^6$ photons/s

$(1-2) \times 10^5$ photons/s/MeV

Measured spectrum

1064nm No additional Collimator

Single gamma-ray peak

Two fold gamma-ray peak

Backgrounds

Laser On

Laser Off

Energy [MeV]
Plan: Introduce of CO$_2$ Laser

17 MeV is too high to carry out Nuclear Resonance Fluorescence Experiments.

CO$_2$ Laser

1 GeV (Top Up) 1.7 MeV
1.5 GeV 4 MeV

Suitable Energy to NRF

Diameter 1mm -> 2.5 mm
Wavelength 1 um -> 10 um

1.7 MeV:
(1.3-2.6) x 10$^6$ photons/s/MeV

Also CO Laser with 5.2-6 $\mu$m
$\Rightarrow$ 3 MeV – 8 MeV
Energy-Recovery Linac = ERL

Energy-Recovery = large beam power, high repetition rate
single turn = no emittance degradation, high quality beam
superconducting linac = precise phase control, ~10 fs accuracy
excellent matching to lasers
Coherent radiation is obtained, if …

\[ \varepsilon < \frac{\lambda}{4\pi} \]

- intrinsic diffraction of photons
- emittance
  - = divergence of e-beam
  - = size of radiation source

for 1 Å X-ray

\[ \varepsilon < 8 \text{ pm-rad} \]

Radiation from a small aperture shows coherence.

### emittance of ERL

- 8 pm-rad
- 8 pm-rad

Small emittance from the gun is preserved

### emittance of SPring-8

- 3 pm-rad
- 3 nm-rad

Emittance growth after many turns

Small coherence
High-Flux gamma-ray Source

10^7 higher flux than existing facilities

crossing of laser and accelerator

laser compton gamma-ray

high average power laser

radioactive waste

shallow 0.3M JPY ea.

intermediate 3M JPY ea.


flux = 10^{13}/MeV/sec
17MeV ERL at JAERI

Principle of energy-recovery:
- Accelerate
- Decelerate

Energy-recovery by SC cavity:
- High current beam
- Small RF sources

Design, Construction and Operation of ERL (1999-)

\[ \sigma_T = \frac{8\pi}{3} \left( \frac{e \times e}{4\pi\varepsilon_0 mc^2} \right)^2 = 6.7 \times 10^{-25} \text{ cm}^2 \]

\[ \sigma_T \]

\[ Z^2\sigma_T \]

\[ N^2\sigma_T \]
F.V. Hartemann, T. Tajima et al., Lawrence Livermore Lab. reprint

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

Microtron (Electric Gun)

Laser

Beam Transport Line

Sub-MeV tunably polarized X-ray production with laser Thomson backscattering

Laser Acceleration

Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.
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)

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

By laser-electron collision point, evidence has been indicated at SLAC in 1997, Burke et al., PRL 79, 1626 (1997).
Non Linear Compton Scattering

\[ e + n\hbar\omega \rightarrow e' + \hbar\omega' \]
$P = 2.8(0.45) \times 10^{-3}$


**181Ta:** N. Tanner, Phys. Rev. 107 (1957) 1203.
V.M. Lobashov et al., PL 25B (1967) 105,

$P = -6(1) \times 10^{-6}$

\[
\frac{1}{2}^+ \rightarrow \frac{1}{2}^- \rightarrow \frac{1}{2}^+ \quad \text{Fr}^{19}
\]

\[
A_{RL} = \frac{2}{\Delta E} \left\langle \frac{1}{2}^+ \right| H_{PNC} ^{1/2} \left| \frac{1}{2}^- \right\rangle \left( \frac{\langle \frac{1}{2}^+ | \mu | \frac{1}{2}^+ \rangle - \langle \frac{1}{2}^- | \mu | \frac{1}{2}^- \rangle}{\langle \frac{1}{2}^+ | O(E1) | \frac{1}{2}^- \rangle} \right) \left( 1 + \cos \theta \right)
\]

\[
1^+ \rightarrow 0^- \rightarrow 1^+ \quad \text{F}^{18}
\]

\[
A_{RL} = \frac{2}{\Delta E} \left\langle 0^- \right| H_{PNC} ^{0^-} \left| 0^+ \right\rangle \left( \frac{\langle 0^+ | O(M1) | 1^+ \rangle}{\langle 0^- | O(E1) | 1^+ \rangle} \right)
\]

\[
\frac{3}{2}^+ \rightarrow \frac{1}{2}^- \rightarrow \frac{3}{2}^+ \quad \text{Ne}^{21}
\]

\[
A_{RL} = \frac{-2}{\Delta E} \left\langle \frac{1}{2}^+ \right| H_{PNC} ^{1/2} \left| \frac{1}{2}^- \right\rangle \left( \frac{\langle \frac{1}{2}^+ | O(M1) | \frac{3}{2}^+ \rangle \langle \frac{1}{2}^- | O(E1) | \frac{3}{2}^- \rangle}{\langle \frac{1}{2}^- | O(E1) | \frac{3}{2}^- \rangle} \right) \left( 1 + \frac{1}{4} \cos \theta \right)
\]
### Angle dependence of asymmetry measurements

<table>
<thead>
<tr>
<th>Energy transition</th>
<th>Asymmetry formula</th>
<th>Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1/2^+ \rightarrow ^1/2^- \rightarrow ^1/2^+$</td>
<td>$A_{RL}(\theta) = (1 + \cos \theta) \langle A_{RL} \rangle = (1 + \cos \theta) \frac{2\langle 1/2^+</td>
<td>V_{PNC}</td>
</tr>
<tr>
<td>$^1^+ \rightarrow ^0^- \rightarrow ^1^+$</td>
<td>$A_{RL}(\theta) = \langle A_{RL} \rangle = \frac{2\langle 0^-</td>
<td>V_{PNC}</td>
</tr>
<tr>
<td>$^3^+ \rightarrow ^1^- \rightarrow ^3^+$</td>
<td>$A_{RL}(\theta) = -2(1 + \frac{1}{4}\cos \theta) \frac{\langle 1/2^+</td>
<td>V_{PNC}</td>
</tr>
<tr>
<td>$^0^+ \rightarrow ^1^- \rightarrow ^0^+$</td>
<td>$A_{RL}(\theta) = \left(1 + \frac{\cos \theta}{1 + \cos^2 \theta}\right) \langle A_{RL} \rangle$</td>
<td>$^{20}\text{Ne}$</td>
</tr>
<tr>
<td>$^0^+ \rightarrow ^2^- \rightarrow ^0^+$</td>
<td>$A_{RL}(\theta) = \left(1 + \frac{2\cos \theta(2\cos^2 \theta - 1)}{1 - 3\cos^2 \theta + 4\cos^4 \theta}\right) \langle A_{RL} \rangle$</td>
<td>$^{16}\text{O}$</td>
</tr>
<tr>
<td>$^1^+ \rightarrow ^1^- \rightarrow ^1^+$</td>
<td>$A_{RL}(\theta) = \left(1 + \frac{2\cos \theta}{5 + \cos^2 \theta}\right) \langle A_{RL} \rangle$</td>
<td>$^{18}\text{F}$</td>
</tr>
<tr>
<td>$^1^+ \rightarrow ^2^- \rightarrow ^1^+$</td>
<td>$A_{RL}(\theta) = \left(1 + \frac{90\cos \theta}{73 + 21\cos^2 \theta}\right) \langle A_{RL} \rangle$</td>
<td>$^{14}\text{N}$</td>
</tr>
</tbody>
</table>

\[|A_{RL}| = 2 \frac{\langle \varphi^+ | V_{PNC} | \varphi^- \rangle}{E_{\varphi^+} - E_{\varphi^-}} \Re\left(\frac{M1}{E1}\right)\]
Nuclear Resonance Fluorescence

Energy spectrum of synchrotron radiation from Elliptical Multipole Wiggler

ΔE=0.1 keV!

SPring-8 SR
Wiggler
Si crystal monochrometer
Ge detector
Multi-segmented Ge detectors

\[ \frac{1}{2}^+ \quad 109.9\text{keV} \]

\[ \frac{1}{2}^+ \]

\[ {_{19}}\text{F} \]

DAQ system

Counts

\[ \begin{array}{c}
\text{Counts} \\
\text{109.9 keV } \gamma\text{-ray} \\
\text{Compton} \\
\text{Compton scattering} \\
\end{array} \]

Energy (keV)

Photon Energy (keV)
Previous Seattle best result on $^{19}$F

\[ A_\gamma = -(8.5 \pm 2.6) \times 10^{-5} \]

30% error

Improvement is needed

\[ \frac{\Delta A_\gamma}{A_\gamma} = \frac{1}{1.4 A_\gamma} \sqrt{\frac{1}{N}} \]

10% error measurement by new independent method

Yield rate $\rightarrow 10^8$/seconds
Polarization measurements of wiggler radiation

Measure the angular distribution of Compton scattering by using rotation table

Klein-Nishina formula

\[ Y_{\text{Compton}} = a \times [B - 2\rho \sin^2 \theta \cos^2 (\phi + \delta) - (1 - \rho) \sin^2 \theta] \]

\( \rho \) : linear polarization
\( \eta = 1 - \rho \) : circular polarization
\( \delta \) : angle between the polarization plane and horizontal plane

Degrees of circular polarization

\[ |\eta_+| = 0.338 \pm 0.005 \]
\[ |\eta_-| = 0.324 \pm 0.003 \]
Comparison with other results

Seattle (PRC 27, 2833 (1983))

\[ A_\gamma = (-8.5 \pm 2.6) \times 10^{-5} \]

Zürich (PRL 52, 1476 (1984))

\[ A_\gamma = (-6.8 \pm 1.8) \times 10^{-5} \]

Present result (preliminary)

\[ A_\gamma = (-9.6 \pm 4.3(stat) \pm 7.0(instr)) \times 10^{-4} \]

We have to improve instruments to reduce systematic errors.

Origins of the large systematic errors

Instability of mono-chromator and detector signals.
Finally ……..

1. There are many scientific challenges in developing inverse Compton photon beams with intense lasers.

2. Strong photon intensity is still required.  
   Key word: Intensity and Resolution!  
   More light please!

3. Cooperation of laser and nuclear scientists is strongly encouraged.  
   → Non Perturbative QED