Production of the Gamma-ray via narrow resonance reaction and its applications

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Outline

Background

Development of nuclear power is the strategic choice for solve the energy supply and ensuring the sustainable development of economy and society.

thermal power plant

nuclear power plant (Daya Bay)

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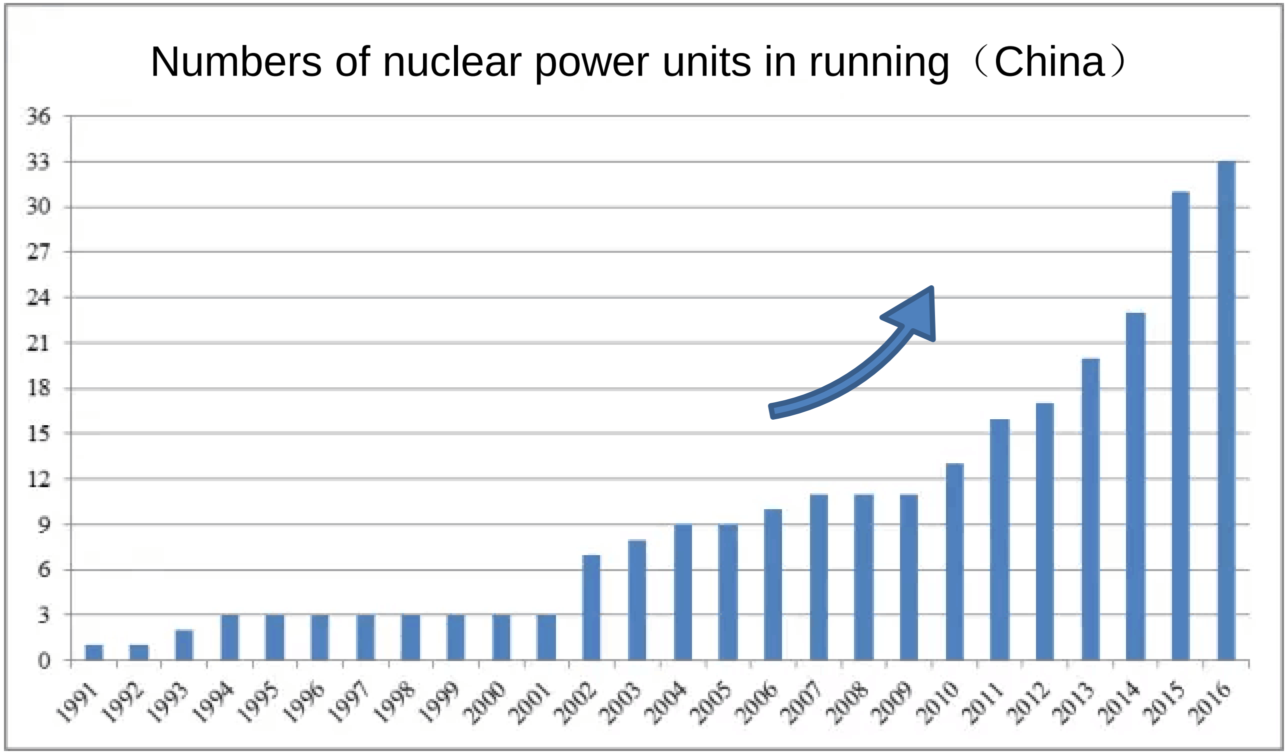

Background

- Nuclear reactor(1Gwe) can product about 30-50 tons nuclear waste one year, including long-lived radioactive waste about 150 kg.

- Disposal of long-lived radioactive wastes:
  - Deeply bury→hundreds meters underground or deeper strata (Yucca mountain project in US, $30 billion)
  - Transport to the space→outside of solar system (launcher & space capsule filled with nuclear waste)
  - Ice cover
  - …

Unable to ensure absolute safety which is the fundamental requirement of long-lived radioactive wastes disposal !

- Neutron Transmutation→ with the bombardment of neutron，long-lived radioactivity become short-lived or stable.

Neutron transmutation

Typical nuclear waste from the nuclear reactor (1 Gwe)

Nuclei	Half Decay (year)	Neutron Cross Section (b)	Production (Ci/year)	Amount (kg/year)
FP				
85Kr	11	1.7	3.0×10^5	0.79
90Sr	29	0.014	25×10^6	17.8
93Zr	1.5×10^6	2.6	61	24.0
99Tc	2.1×10^5	20	433	25.5
107Pd	6.5×10^6	1.8	3.6	7.0
129I	1.6×10^7	27	1.0	5.8
135Cs	2.3×10^6	8.7	13.5	11.7
137Cs	30	0.25	3.5×10^6	39.5
151Sm	90	15,000	1.1×10^4	0.4
TRU				
237Np	2.1×10^6	181	11	14.4
241Am	432	603	5.0×10^3	1.46
243Am	7380	79	601	3.03
243Cm	28,5	720	55	0.01
244Cm	18	15	5.8×10^4	0.72
245Cm	8500	2,347	4.1×10^3	0.03

Imasaki K, Li D, Miyamoto S, et al. Lasers and Nuclei. Springer Berlin Heidelberg, 2006.

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- Several nucleus have small neutron capture cross section
- Stable nucleus may transmute to long-lived radioactive nucleus

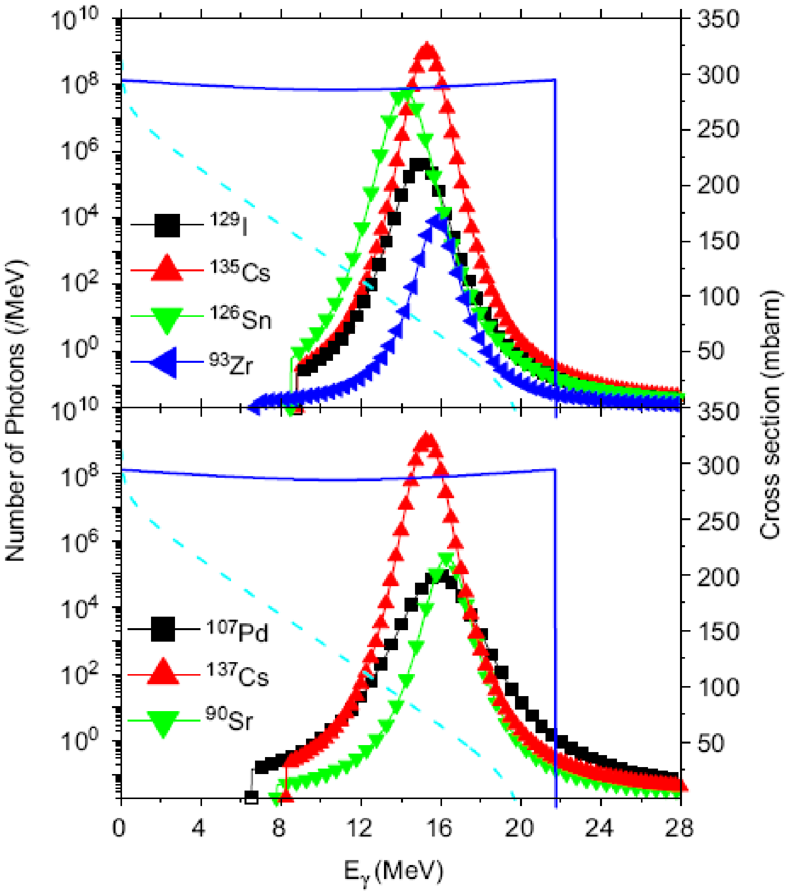
$$^{133}Cs \longrightarrow {}^{134}Cs \longrightarrow {}^{135}Cs \longrightarrow {}^{136}Cs$$

stable 2.06 y 2.3 My 13.16 d

Imasaki K, Li D, Miyamoto S, et al. Lasers and Nuclei. Springer Berlin Heidelberg, 2006.

Photonuclear transmutation

Giant dipole resonances may result in a number of de-excitation events, such as nuclear fission, emission of neutrons or gamma rays, or combinations of these. Classical causes of the giant dipole resonances are irradiation with gamma rays at energies from 7 to 40 MeV.



$^{129}I+\gamma \rightarrow {}^{128}I(25m)+n$

$^{128}I \rightarrow {}^{128}Xe+\beta^{-}+\nu^{-}$ (93.1%)

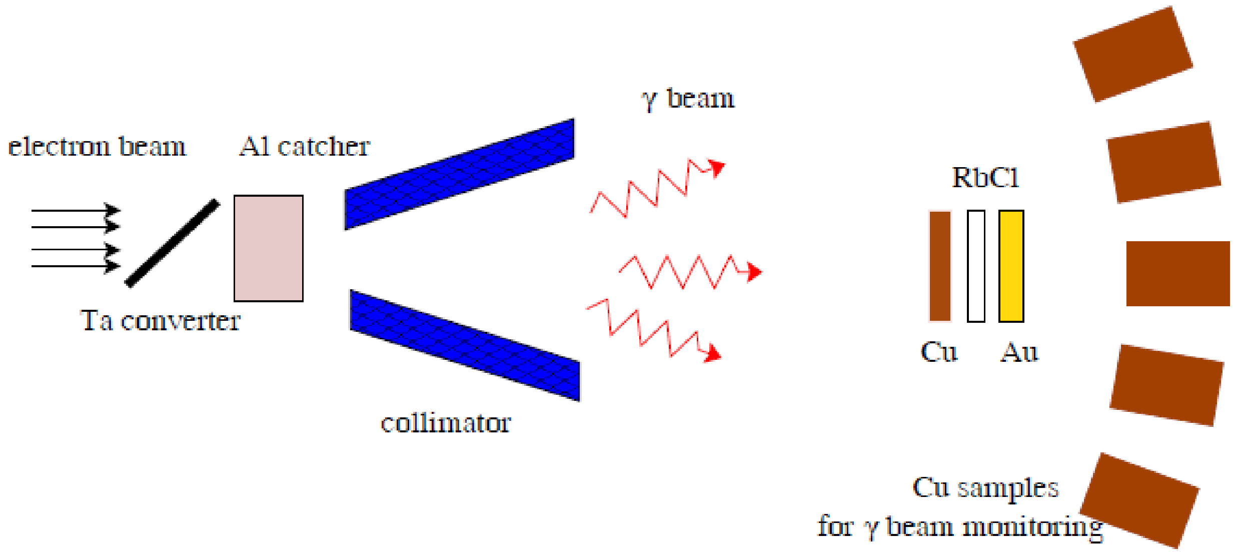
$^{128}I \rightarrow {}^{128}Te+\beta^{+}+\nu \rightarrow {}^{128}Xe+2\beta^{-}+2\nu^{-}$

$^{135}Cs \rightarrow {}^{134}Cs/{}^{133}Cs$

$^{133}Cs \rightarrow {}^{132}Cs(6.5\ d)/{}^{131}Cs(9.7\ d)$

Ledingham K, Magill J, Mckenna P, et al.Journal of Physics D Applied Physics, 2003, 36(18):L79-L82.

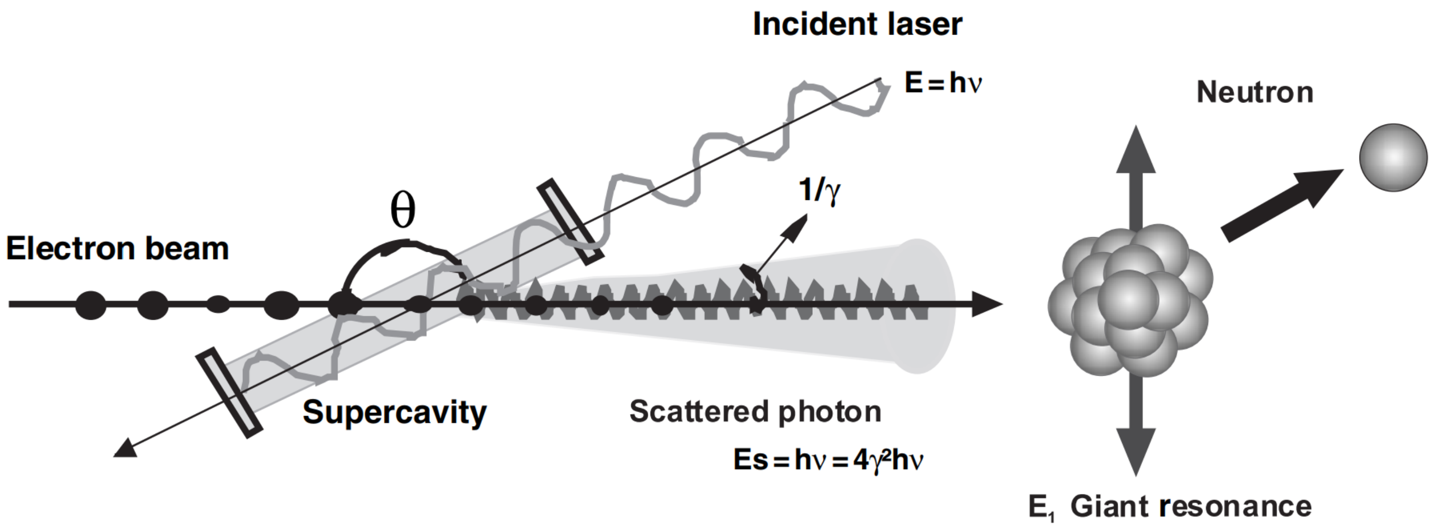
Bremsstrahlung-γ



- Electron accelerator, ELBE & S-DALINAC
- Continuous gamma-ray spectrum

G. Rusev, R. Schwengner, F. Donau *et al.*, Phys. Rev. C **73**,044308(2006).

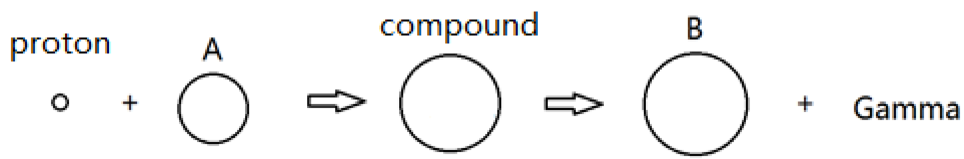
LCS-γ (Laser Compton Scattering γ-ray)



- New SUBARU
- Electron beam: 1 GeV
- Laser light: 1064nm, 0.67 W
- Photon energy: max around 17 MeV
- γ-ray photon yield: 2×10^5 photons/MeV/s

Imasaki K, Li D, Miyamoto S, et al. Lasers and Nuclei. Springer Berlin Heidelberg, 2006.

resonance reaction γ-ray



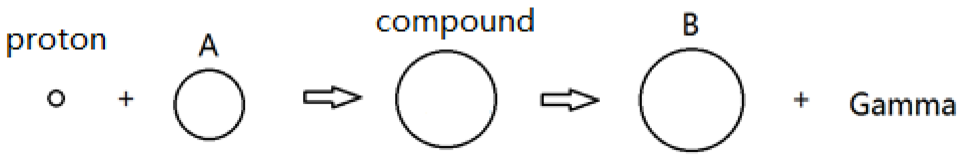
Energy of the emission γ-ray：

Energy of proton＋S_p of the B nuclei

Reaction	$E_\gamma(MeV)$	$E_R(MeV)$
^{19}F(p,$\alpha\gamma$)	6.1	≤ 0.96
^{19}F(p,$\alpha\gamma$)	7.0	≤ 0.96
^{13}C(p,γ)	9.17	1.747
^{7}Li(p,γ)	14.8	0.44
^{7}Li(p,γ)	17.6	0.44
^{3}H(p,γ)	19.8-30	---

Fowler W A, Lauritsen C C, Lauritsen T. Reviews of Modern Physics, 1948, 20(1):236-277.

resonance reaction γ-ray



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resonance reaction γ-ray

$^{13}\boldsymbol{C}$(p, $\boldsymbol{\gamma}$) $@E_p = 1.747\ MeV$

$$\Gamma_T = 122eV$$

$$^{13}C + p \rightarrow {}^{14}N^* \begin{cases} {}^{13}C + p & \Gamma_p = 115.7eV \\ {}^{14}N + \gamma & \Gamma_\gamma = 6.3eV \end{cases}$$

Breit-Wigner formula

$$\sigma(E_p) = \frac{\pi \lambda_p^2 g \Gamma_p \Gamma_\gamma}{(E_{pc.m.} - E_{Rc.m.})^2 + (\frac{\Gamma_T}{2})^2}$$

$$\sigma_{max} = \sigma(E_p = 1.747MeV) = \frac{4\pi \lambda_p^2 g \Gamma_p \Gamma_\gamma}{(\Gamma_T)^2} \approx \boldsymbol{106\ mb}$$

Vartsky D, Goldberg M B, Engler G, et al. Nuclear Physics A, 1989, 505(2): 328-336

resonance reaction γ-ray

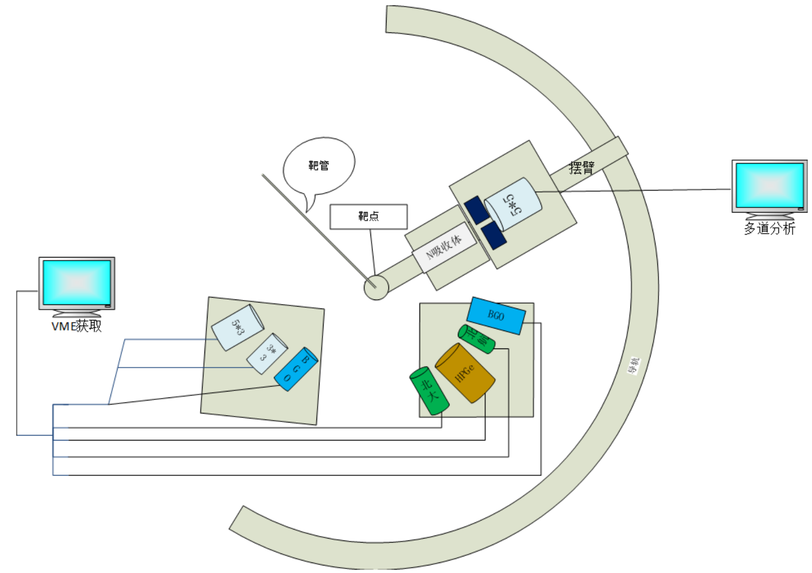
Experimental setup:

- Proton beam： E=1.75 MeV， I=8 μA， 1‰
- Isotopically pure target: ^{13}C， 100 μg/cm^2
- Detector： HPGe: φ55.5 mm × 78.1 mm, 35%

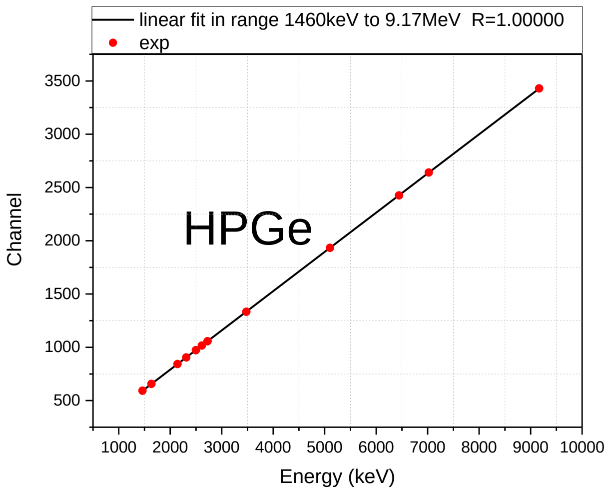
  $LaBr_3$: 3″ × 3″

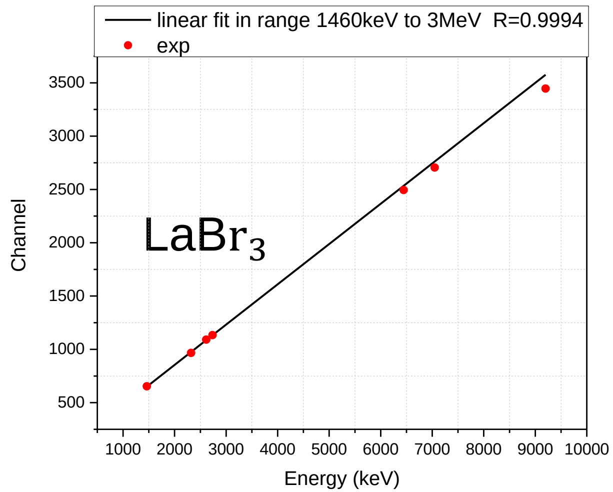
  NaI: 5″ × 5″

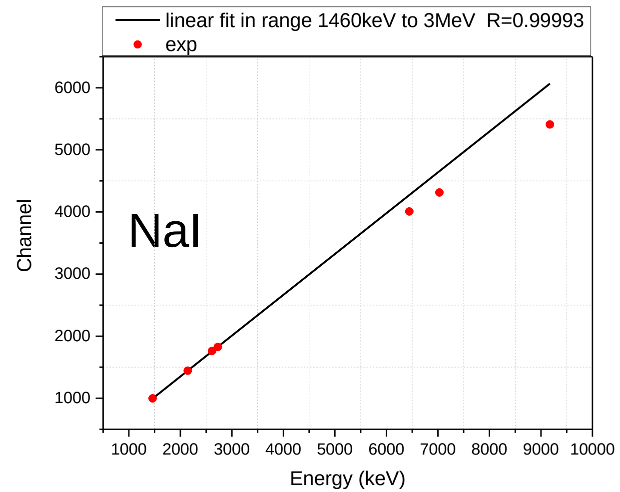
Detector	Distance/cm	θ/°
HPGe	69	28
$LaBr_3$	81	38
NaI	43.5	81



Energy response



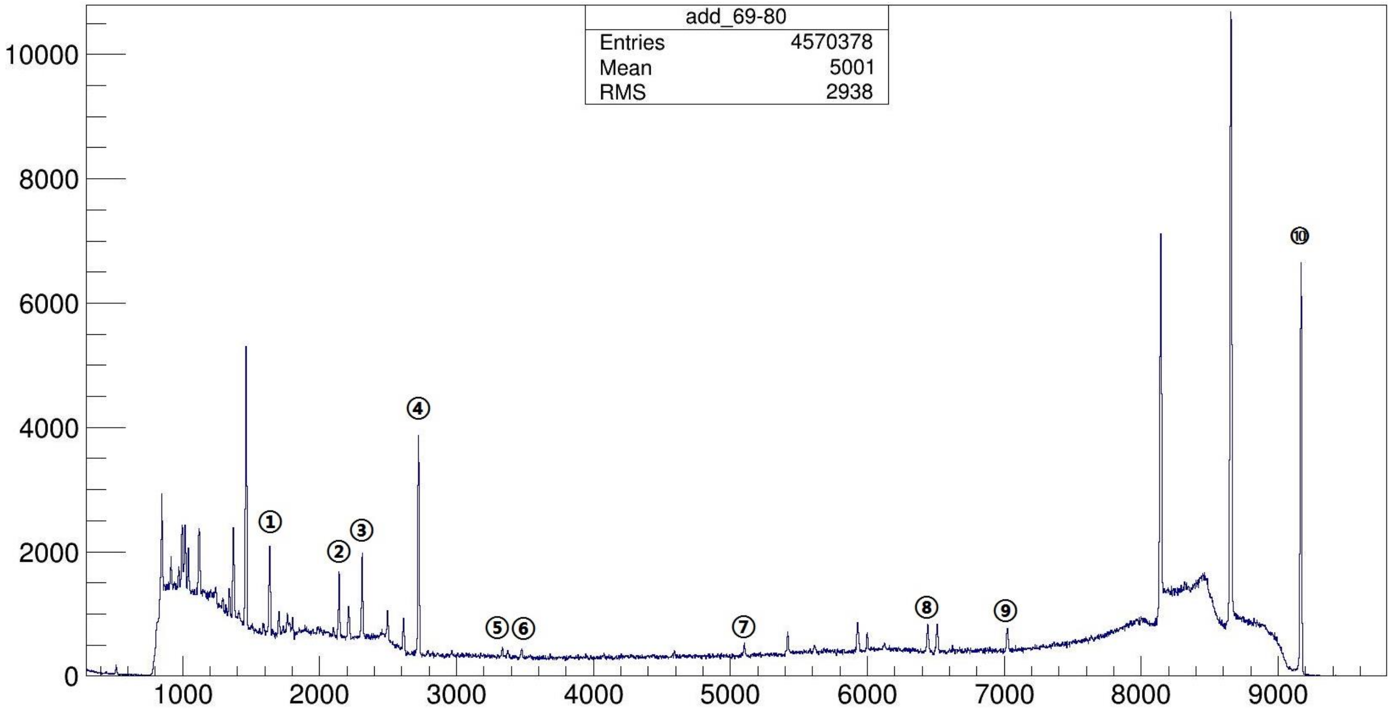




- The energy response of HPGe is linear in the energy range 1.5-9 MeV ;
- The energy responses of $LaBr_3$ and NaI are linear in the energy range 1.5-3 MeV, but the nonlinearity of $LaBr_3$ comes up to 3.5% and NaI comes up to 11% at 9 MeV.

resonance reaction γ-ray

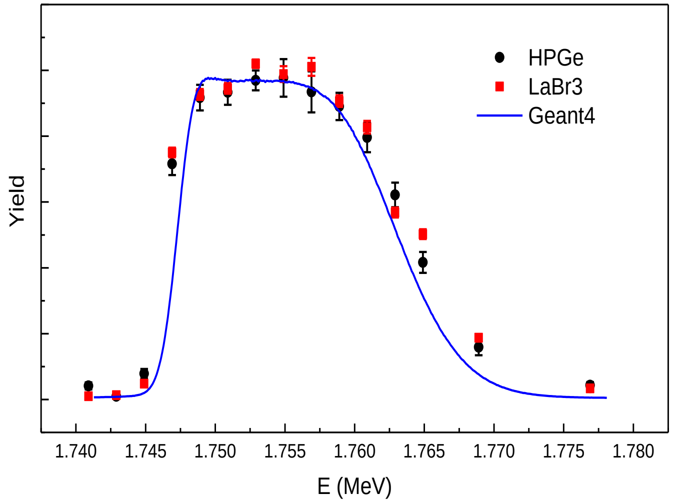
Spectrum of HPGe



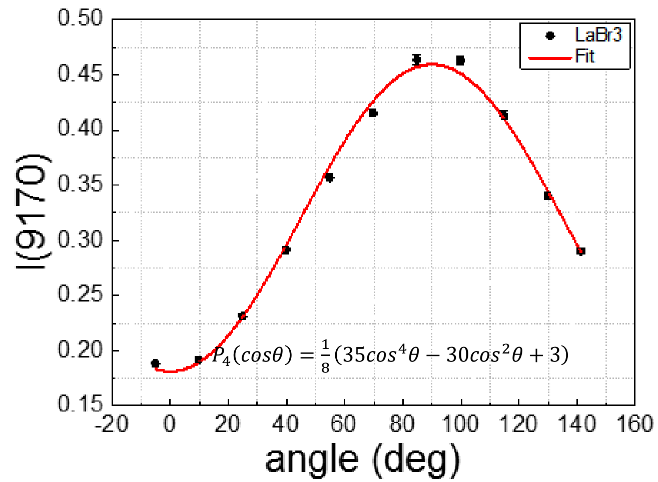
E_γ/keV

Num	Energy/keV
①	1635
②	2143
③	2313
④	2726
⑤	3338
⑥	3480
⑦	5105
⑧	6445
⑨	7027
⑩	9169

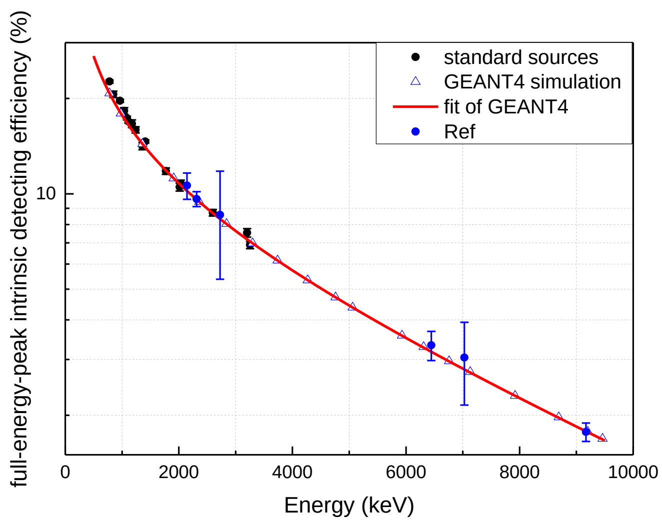
resonance reaction γ-ray



thick target yield curve of 9.17MeV γ-ray



angular distribution of 9.17MeV γ-ray



efficiency calibration of HPGe

Thick target yield of 9.17MeV γ-ray

$$Y_{max} = 4.7 \pm 0.4 * 10^{-9} \gamma/proton$$

Flux of 9.17MeV γ-ray at proton current 8μA

$$I_\gamma = 2.3 \pm 0.2 * 10^5 s^{-1}$$

$^{197}Au(\gamma, n)$

- The $^{197}Au(\gamma, n)$ reaction produces the unstable nucleus ^{196}Au that decays either to ^{196}Pt by electron capture or positron emission (EC+β^+)($T_{1/2} = 6.18\ d$) or to ^{196}Hg by β decay (β^-).

Decay properties of the ^{196}Au nucleus

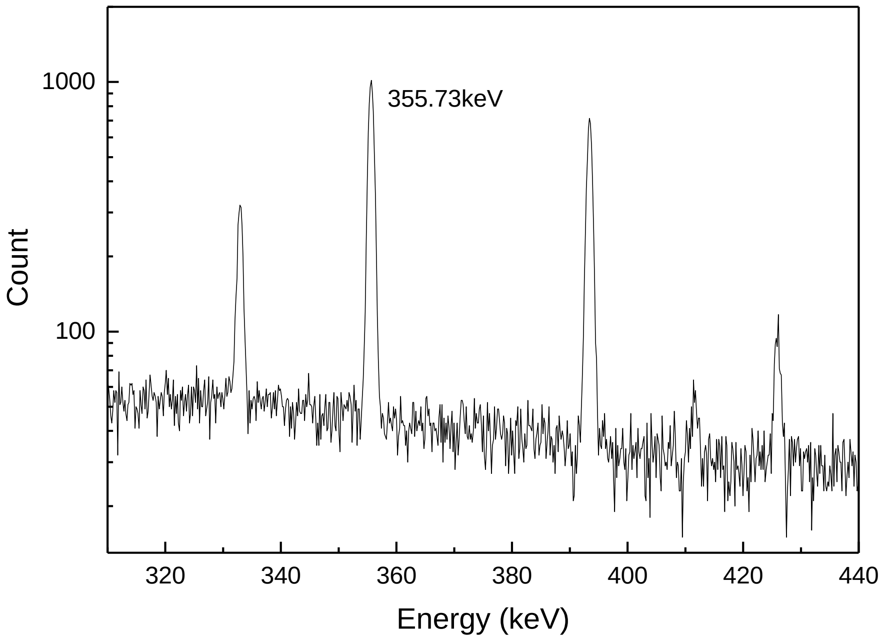
Nuclide	$E_\gamma(keV)$	p
^{196}Pt	333.03(5)	0.229(10)
^{196}Pt	355.73(5)	0.87(3)
^{196}Hg	426.10(8)	0.066(3)

- Experimental setup：

Proton beams of 6-8 μA intensity were directed onto an isotopically pure ^{13}C target of 100 μg/cm^2, evaporated on a gold disk which thick is 2 mm. The targets were irradiated for 6 hours.

$^{197}Au(\gamma, n)$

Low-background and anti-Compton HPGe detector



355.73keV γ-ray in the decay of ^{196}Au

The calibration of the detector’s efficiency :
356.01keV γ-ray from ^{133}Ba decay which branching ratio is 62.05%

$^{197}Au(\gamma, n)$

For the response rate of photo neutron P，

$$\Delta P = I(\theta)\left(1 - e^{-N_s(\theta)*\sigma_T}\right)s\Delta\Omega$$

$I(\theta)$ is the flux of 9.17 MeV γ-ray of unit solid angle at θ.

$$I(\theta) = I(0)\frac{W(\theta)}{W(0)},\ \ \Delta\Omega = 2\pi sin\theta\Delta\theta$$

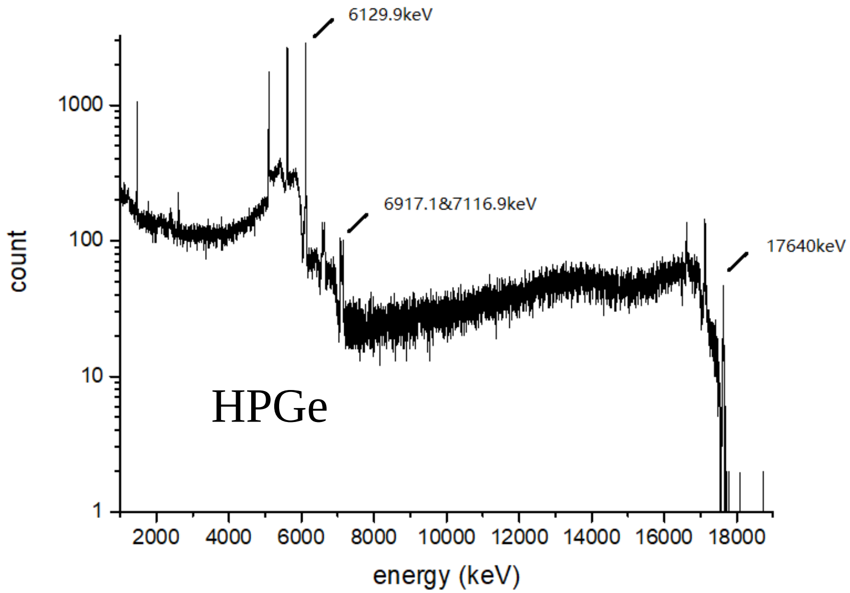
$$N_\gamma = P(1 - e^{-\lambda t}\frac{e^{-\lambda t_1}}{\lambda}\ (1 - e^{-\lambda t_2})\ * \varepsilon I_\gamma$$

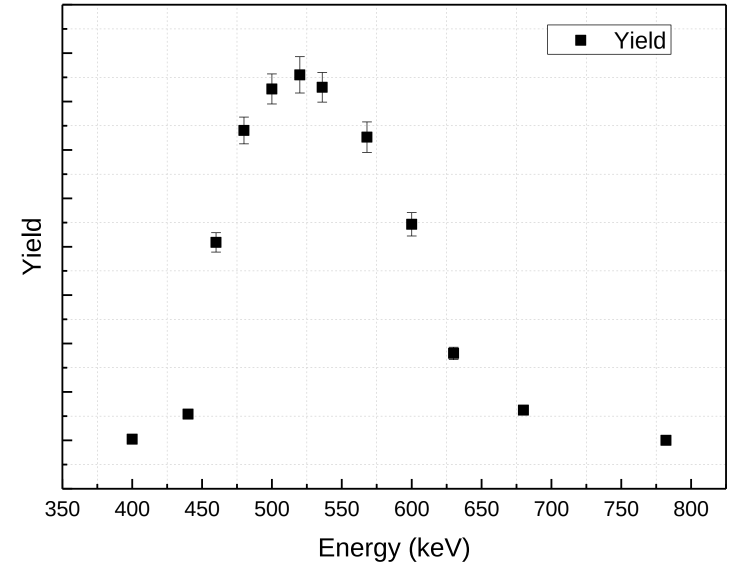
$$\sigma' = \frac{N_\gamma * \sigma_T}{(\frac{P}{s})(1 - e^{-\lambda t})\frac{e^{-\lambda t_1}}{\lambda}\ (1 - e^{-\lambda t_2})\ * \varepsilon I_\gamma}$$

We determined the value of the cross section of ^{197}Au(γ，n) reaction at 9.17 MeV to 43.79±1.1 mb，which correspond with the result of bremsstrahlung-γ and LCS-γ.

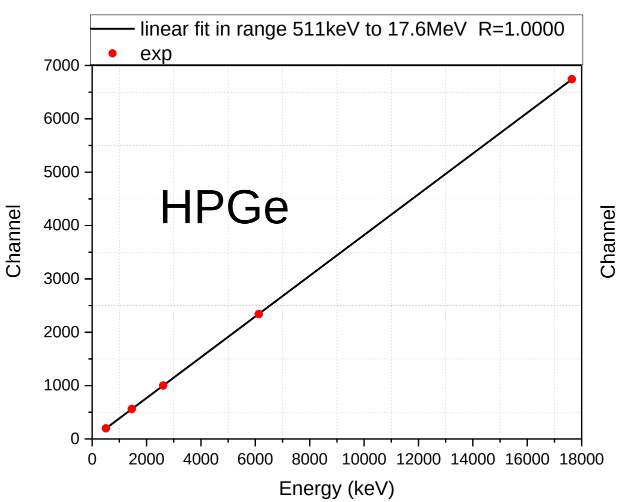
Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 48, No. 5, p. 834–840 (2011)
Journal of NUCLEAR SCIENCE and TECHNOLOGY, Vol. 48, No. 7, p. 1017–1024 (2011)
Physical Review C, 2008, 78(5):186-200

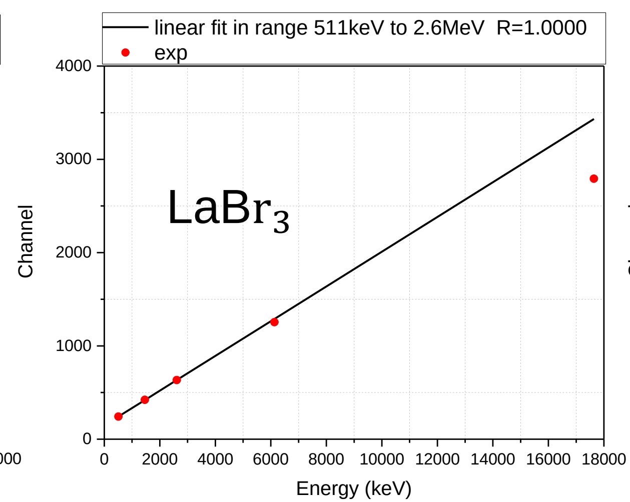
$^7Li(p, \gamma)$

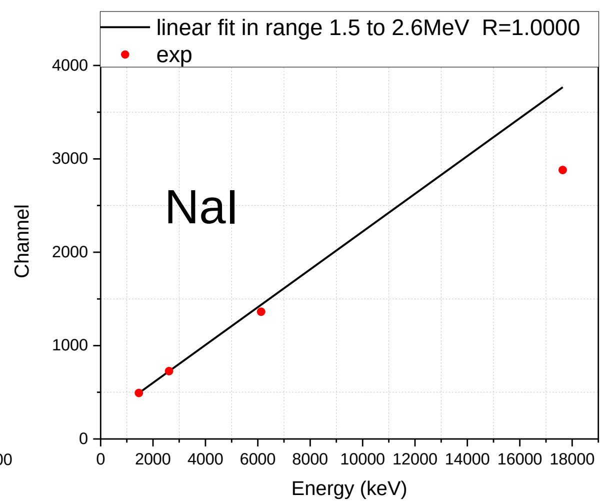




17.6MeV γ-ray yield curve







Conclusion

- High and single energy γ-ray not only have important potential in the nuclear wastes disposal, but also is of great significant in nuclear structure, flash photography and nuclear astrophysics.
- We determined the thick-target yield of the 9.17MeV γ-ray in $^{13}C(p, \gamma)$ to $4.7 \pm 0.4 * 10^{-9} \gamma/proton$. For the proton with 10mA flux, the γ-ray brightness will be 3×10^8/s which is considerable with LCS-γ equipment.
- The energy response of HPGe detector is linear for γ-ray under 18 MeV.
- The measurement of the cross section in $^{197}Au(\gamma, n)$ verified the feasibility of photonuclear transmutation.

THANK YOU!

Inadequacies, please criticize!