The 16th workshop on Shielding aspects of
Accelerators, Targets and Irradiation Facilities

Measurement of nuclide production cross sections via the $^{208}Pb(p,X)$ reactions at GeV-energy proton incidence

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Structure of presentation

1. Introduction
2. Experiment
3. Data analysis
4. Obtained nuclides
5. Excitation functions
6. Conclusion and future work

Introduction

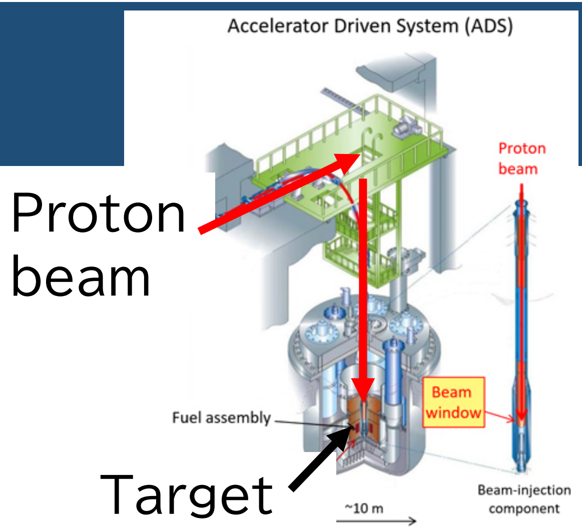
Accelerator-Driven System (ADS)
Transmutation of nuclear waste

Radiation safety at ADS facility by JAEA
Estimation of residual γ-ray dose rate
-> Nuclide production cross section
Systematic measurements at J-PARC[1-8]
GeV-energy proton + targets

Examples of targets (candidate materials) and their usage

Pb, Bi	LBE
Ti, Nb	Accelerator Cavity
Cr, Fe, Zn, Mo	Proton beam window
Al, Si, Cu, Zn	Beam duct

Target in this study: ^{208}Pb instead of ^{nat}Pb
1. Contained in LBE
2. Simplify the nuclear reaction
   and deepen the understanding of it



Concept of ADS

Conditions of ADS by JAEA

E_p [GeV]	1.5
Power [MW]	30
Neutron-production target/Coolant	LBE*

* Lead-Bismuth Eutectic

Blue filled: already published
Green filled: Exp. currently
Red filled: Analysis completed

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rh	Cn	Nh	Fl	Mc	Lv	Ts	Og

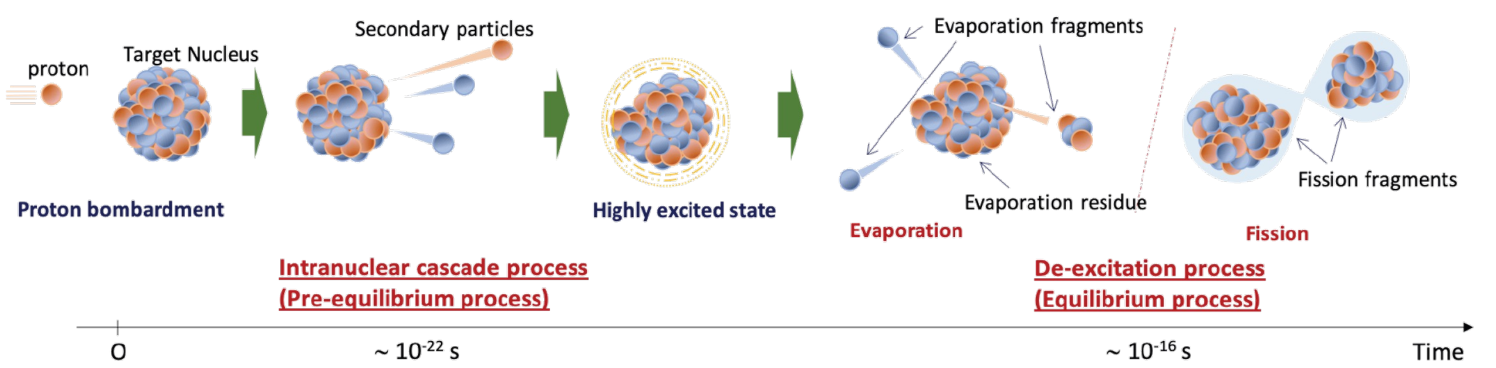
Measured data list

1) H. Matsuda *et al.*, JNST 55(8), (2018), pp. 955-961.
2) H. Takeshita *et al.*, NIM B 511, (2022), pp. 30-41.
3) H. Takeshita *et al.*, NIM B 527, (2022), pp. 17-27.
4) H. Matsuda *et al.*, JPS Conf. Proc. 33, (2021), 011047.
5) H. Iwamoto *et al.*, EPJ Web of Conf. 284, (2023), 01033.
6) K. Sugihara *et al.*, NIM B 545, (2023), 165153.
7) K. Sugihara *et al.*, NIM B (in press).
8) K. Nakano *et al.*, JAEA-Research, 2021-014.

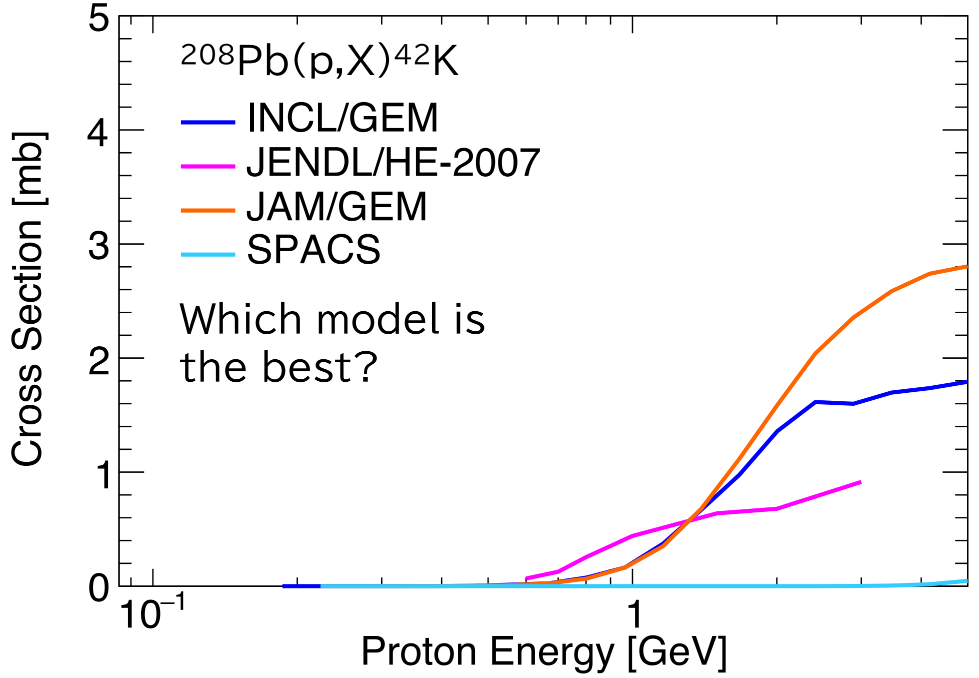
Introduction

Predictions based on theories
PHITS[9]: INCL[10], JAM[11], GEM[12]
Library: JENDL/HE-2007[13]
Empirical formula: SPACS[14]
Without Exp. data, reliability is unclear.
-> Benchmark study is still necessary.

^{208}Pb(p,X) reaction
Number of preceding study: unsatisfactory
-> Accumulating the measured data
of the ^{208}Pb(p,X) reactions
Confirming the prediction accuracy of models



Nuclear reaction process



Excitation function

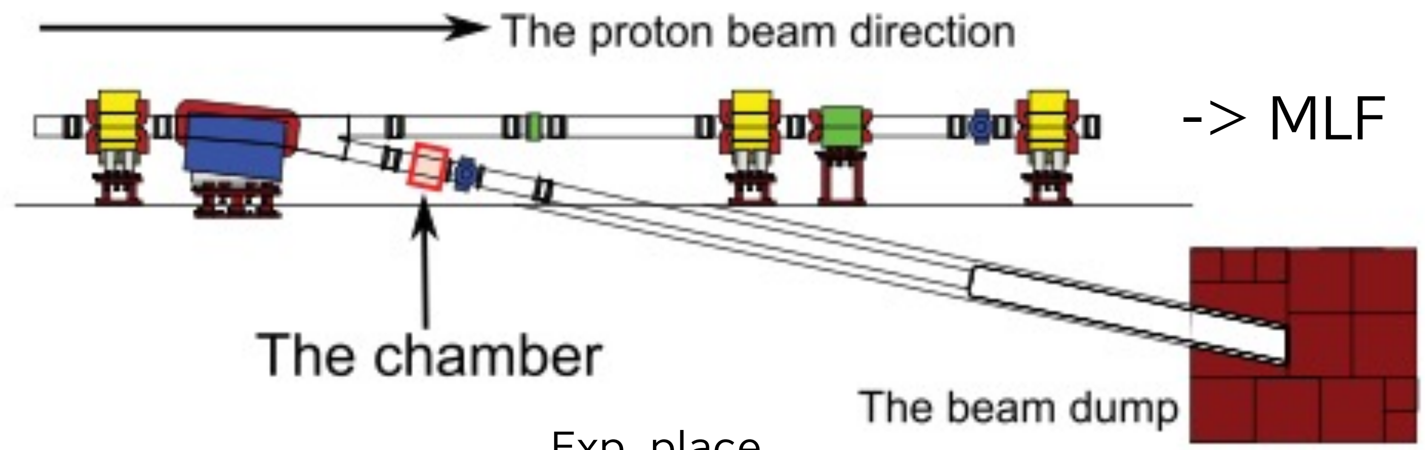
Purpose of this study

1. Measurement of the ^{208}Pb(p,X) reactions
2. Comparison among our present data, previous studies, and aforementioned models

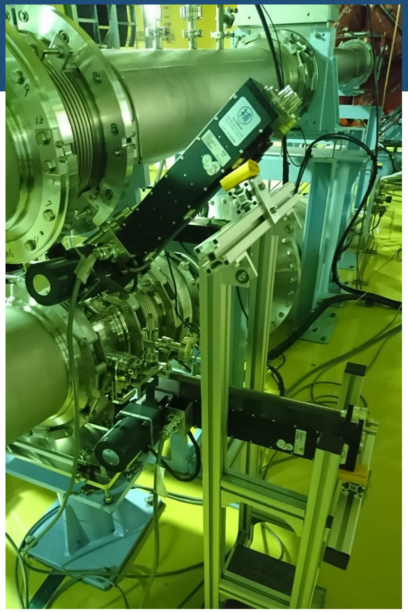
9) T. Sato *et al.*, JNST 61(1), (2024), pp. 127-135.
10) A. Boudard *et al.*, PRC 87, (2013), 014606.
11) Y. Nara *et al.*, PRC 61, (1999), 024901.
12) S. Furihata, NIM B 171, (2000), pp. 251-258.
13) Y. Watanabe *et al.*, JKPS 59, (2011), pp. 1040-1045.
14) C. Schmitt *et al.*, PRC 90, (2014), 064605.

Experiment

Beam dump line near the extraction port of 3 GeV RCS



Exp. place



Target chamber

Incident proton condition

E_p: 0.4, 1.3, 2.2, 3.0 GeV

t_{irrad}: 100 sec

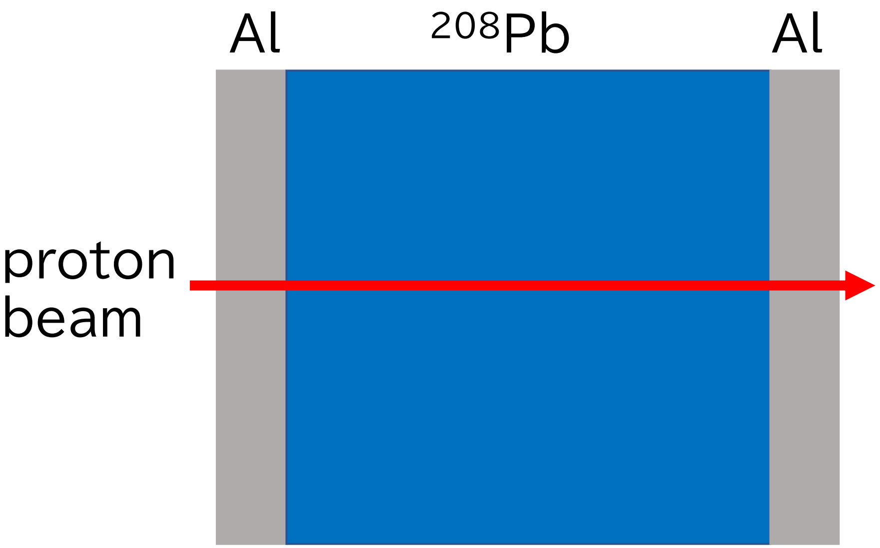
N_p: 1.1 x 10^{14} protons

^{208}Pb target conditions

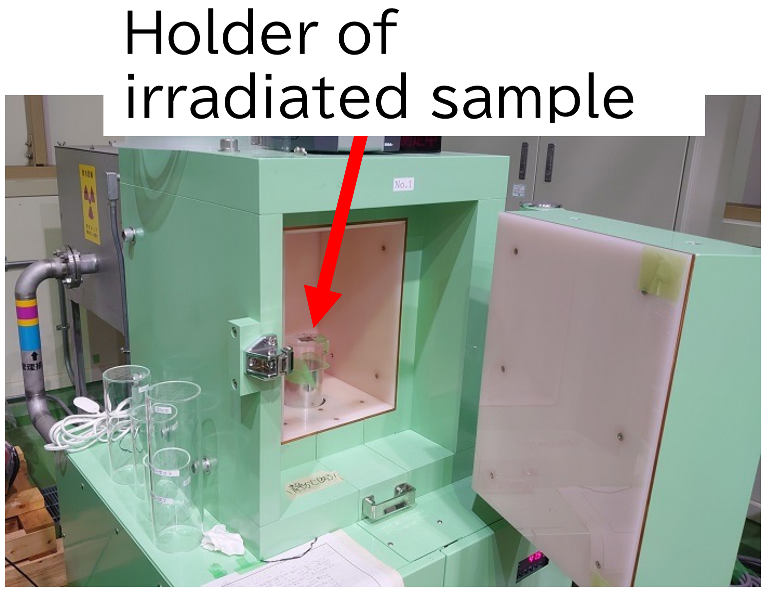
Size: 25 x 25 x 0.38 mm^3

Weight: 2.5 g

Cover: 0.1-mm-thick Al



Target foil structure

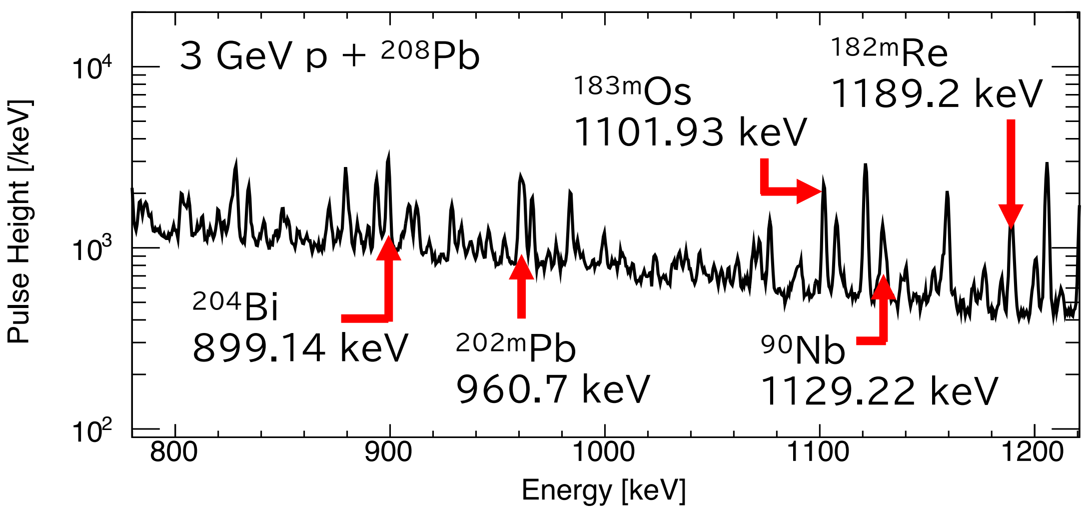


HPGe detector

Data analysis

1. Obtain the net area of objective nuclides
2. Determine N_0 of attenuation curve ($N_0 e^{-\lambda t}$)
   (N_0: the number of nuclides at t=0,
   λ: decay constant)
3. Derive the cross sections

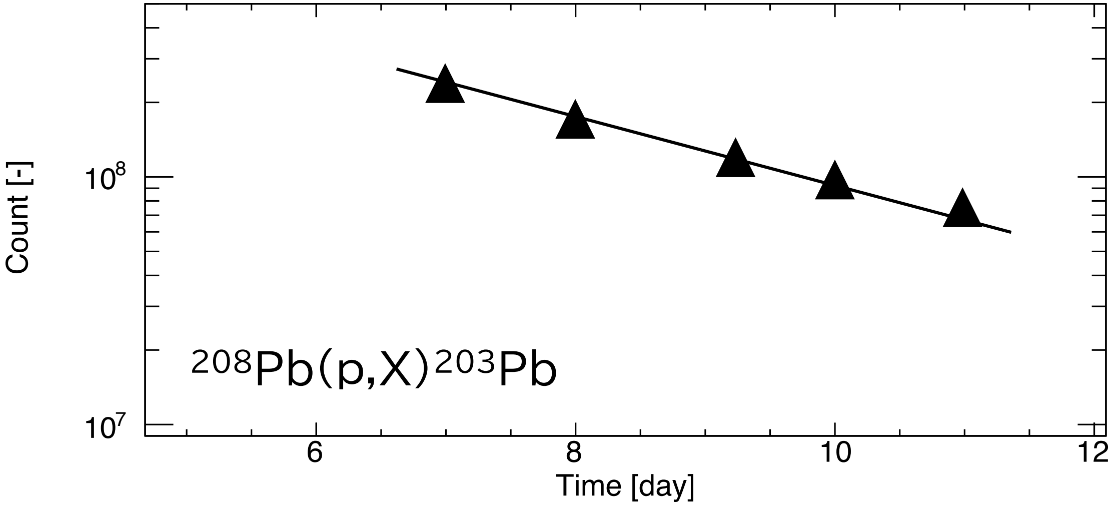
$$\sigma = \frac{f_{abs} f_{sec} f_{esc} N_0}{n f_{beam} N_p}$$



γ-ray spectrum

σ: cross section [mb], n: areal density of ^{208}Pb [/cm^2]
N_p: proton beam intensity, f_{abs}: factor of self-absorption
f_{beam}: factor of proton beam intensity (imaging plate)
f_{esc}: factor of incoming and outgoing nuclei (PHITS)
f_{sec}: factor of secondary particles (PHITS)

Uncertainty of Exp. data
1. Fitting parameter
2. Proton beam intensity* (2%)
3. Branching ratio
4. Standard γ-ray source intensity (2.5%)



Attenuation curve

* Monitor reactions, uncertainties of which are about 10%, were used to get the proton intensity in references. Thus, J-PARC has the advantage to measure the Exp. data with smaller uncertainties.

Obtained nuclides

H																	He
Li	Be 1											B	C	N	O	F	Ne
Na 2	Mg 1											Al	Si	P	S	Cl	Ar
K 2	Ca 1	Sc 2	Ti	V 1	Cr 1	Mn 1,1	Fe 1,1	Co 1,1,1	Ni 1	Cu	Zn 2,1	Ga 1	Ge 1	As 2,1	Se 2	Br 1	Kr
Rb 2,1	Sr 3	Y 1,3	Zr 3,1	Nb 3,1	Mo 1	Tc 1,1	Ru 2	Rh 2,2	Pd	Ag 1,1	Cd	In 1,1	Sn 1,2	Sb 1,1,1	Te 2,3	I 2	Xe 2
Cs 2	Ba 1,1		Hf 3	Ta 4	W	Re 3	Os 1,3	Ir 1,4	Pt 3,1	Au 1,2,3	Hg 3,3	Tl 6,2	Pb 4,1	Bi 4	Po	At	Rn
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rh	Cn	Nh	Fl	Mc	Lv	Ts	Og
			La 1	Ce 2,1	Pr 1	Nd	Pm 1	Sm	Eu 2,4	Gd 5	Tb 1,7	Dy 4	Ho	Er 1	Tm 4	Yb 1	Lu 3

red: first data
green: above 1 GeV first
black: already measured in previous studies

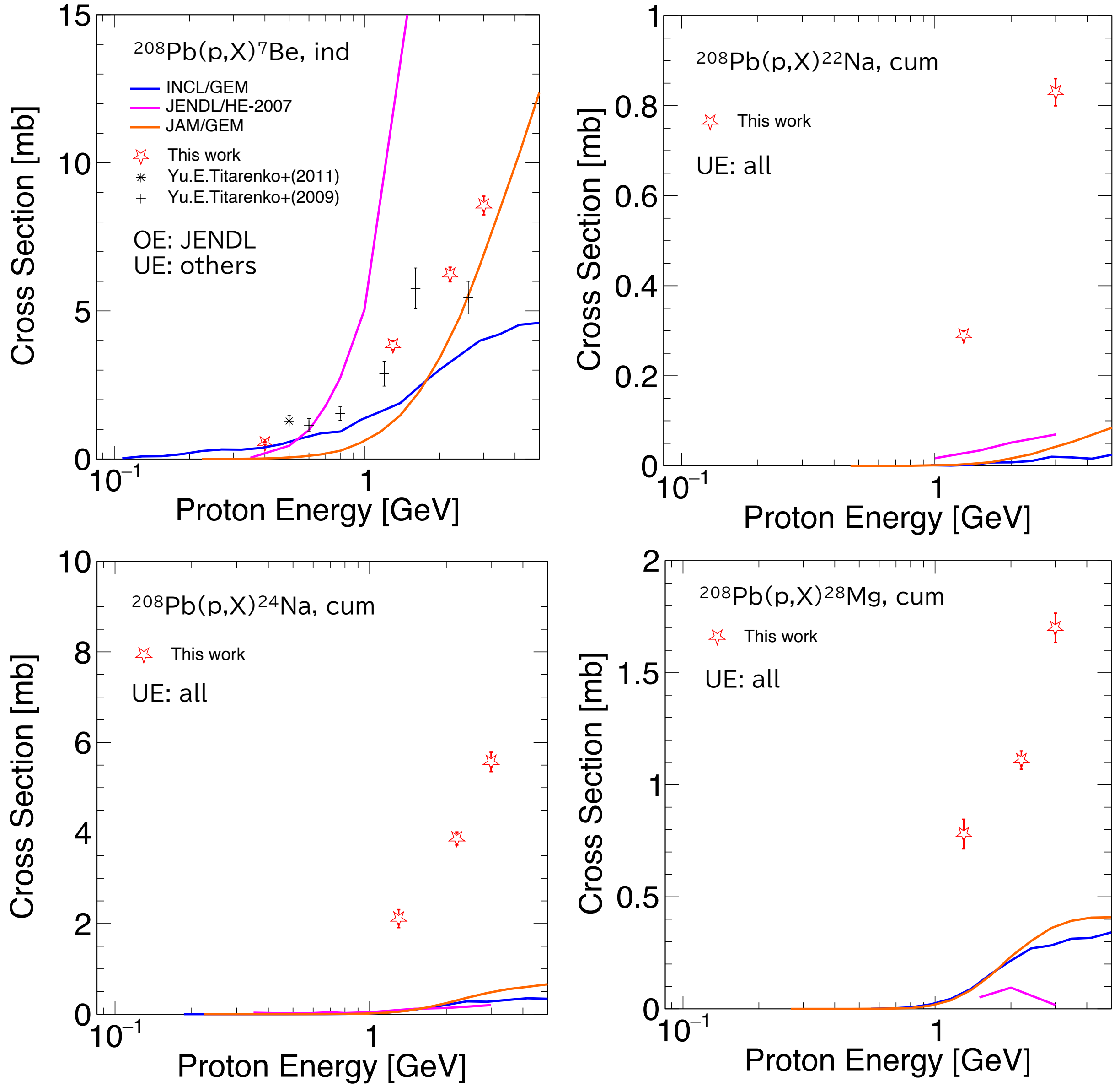
e.g., Au nuclides
Total: 6 nuclides
first: 1 of 6
first > 1 GeV: 2 of 6
already: 3 of 6

As a result of our measurement,
a total of 506 data (170 nuclides) were acquired.

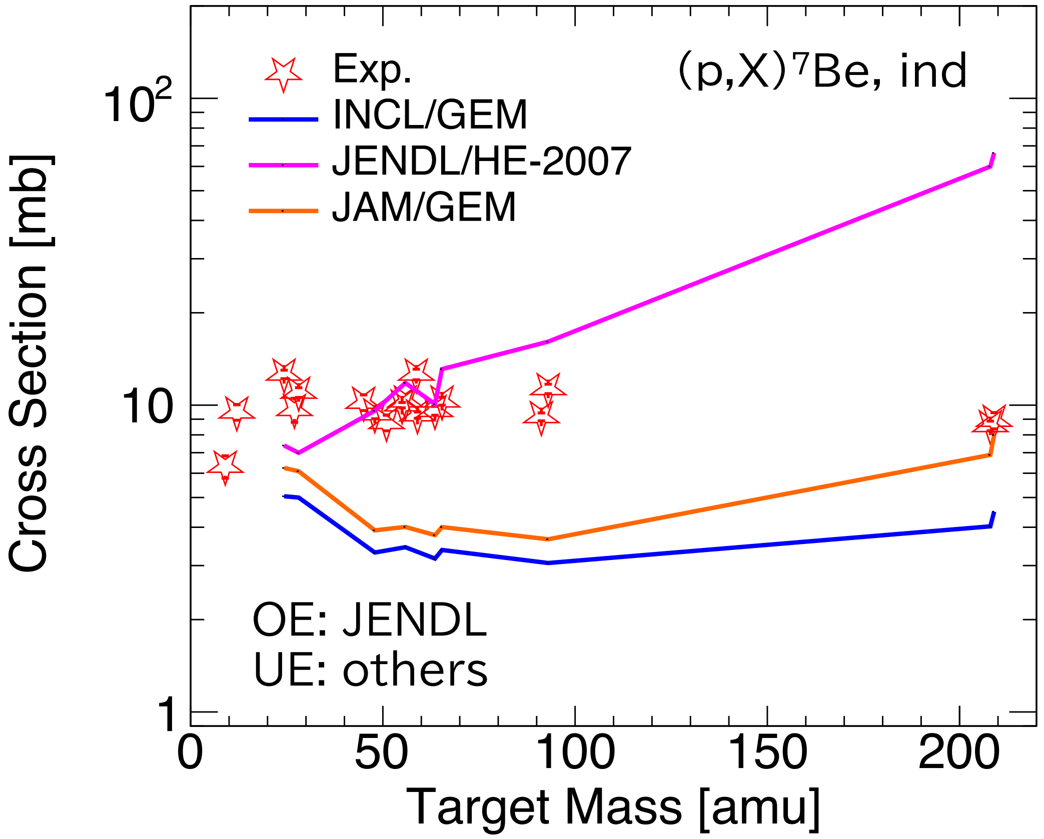
28 nuclides were obtained for the first time.
109 nuclides above 1 GeV were measured firstever.

Light nuclides

OE: overestimate
UE: underestimate



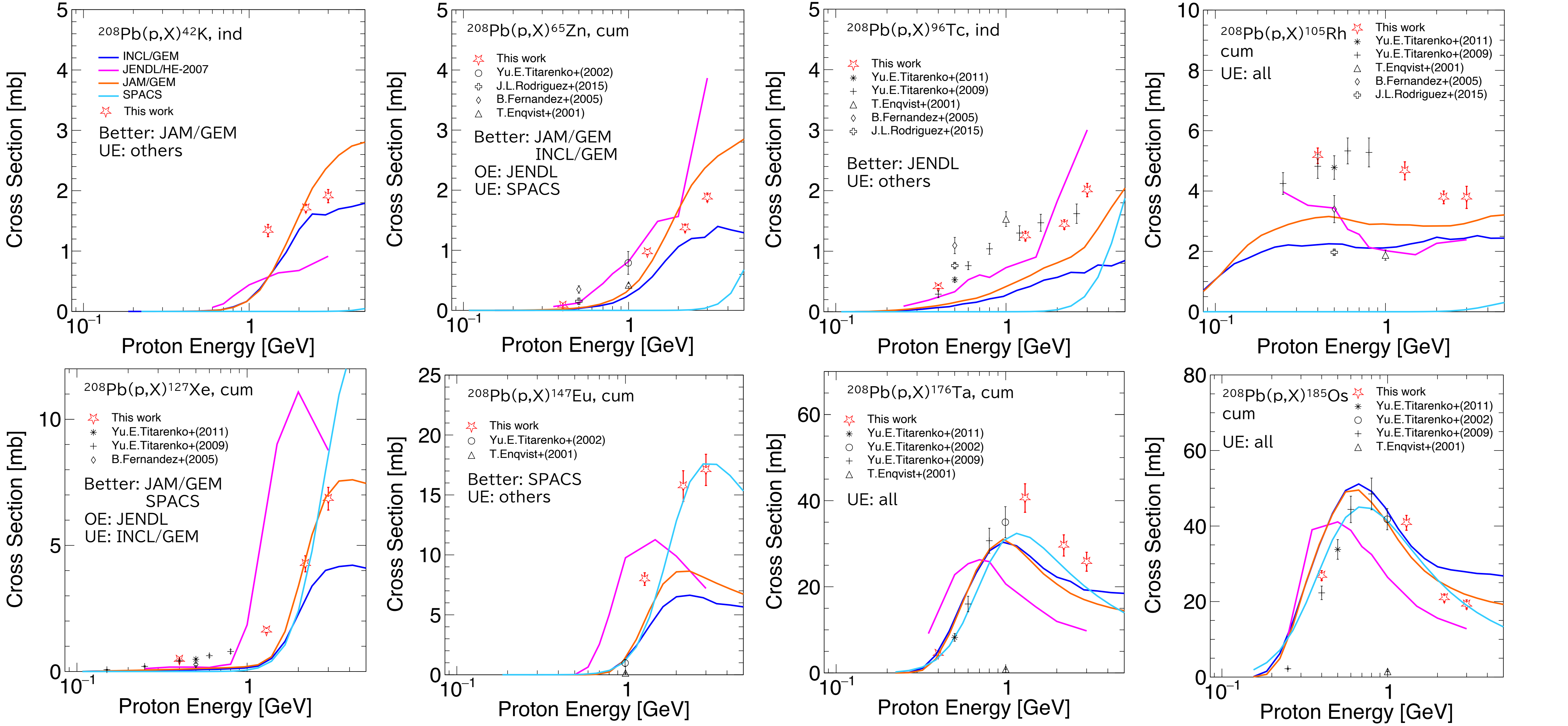
Excitation functions



Cross sections of the (p,X)^{7}Be reaction at 3-GeV proton incidence

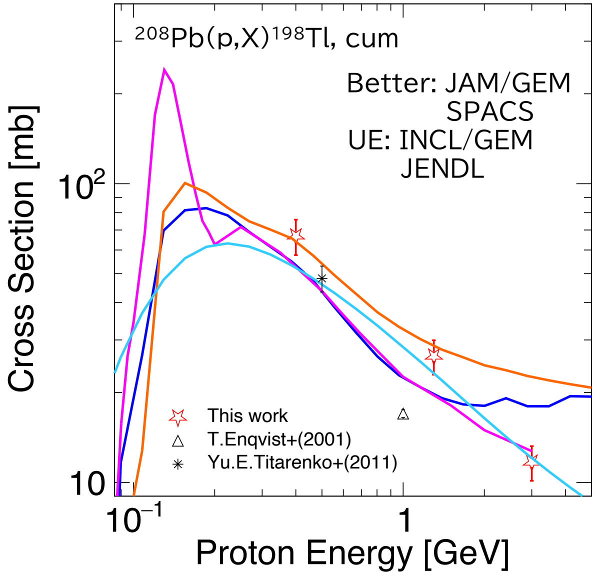
(p,X)^{7}Be: Underestimation of Exp. data
This suggests that the formation of the light nuclides in the calculations has room for improvement.

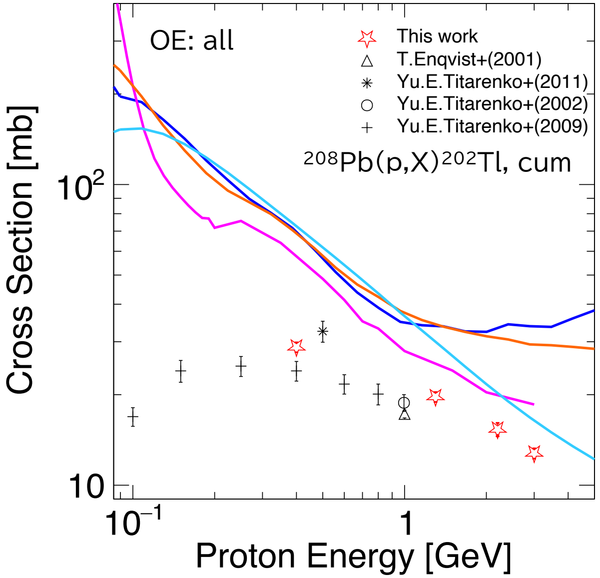
Medium-heavy to heavy nuclides

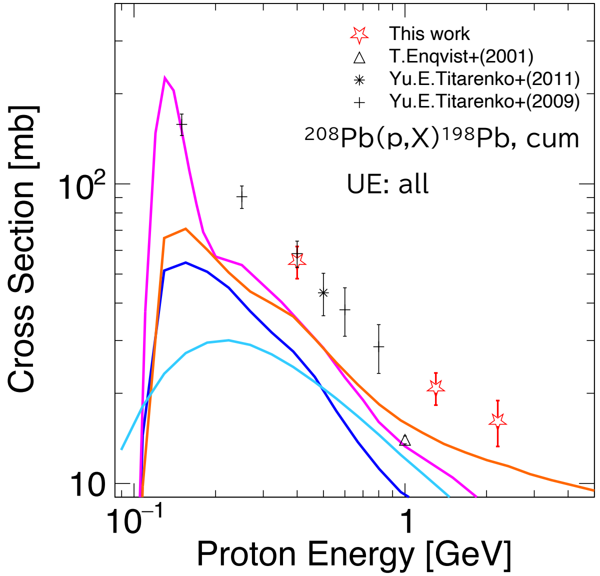


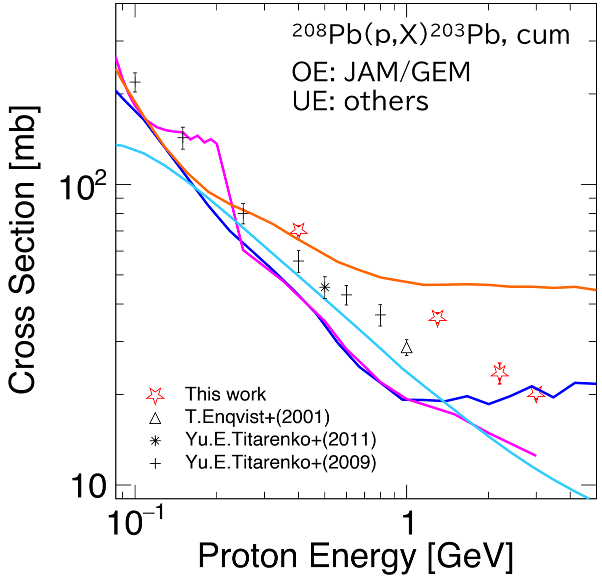
Excitation functions

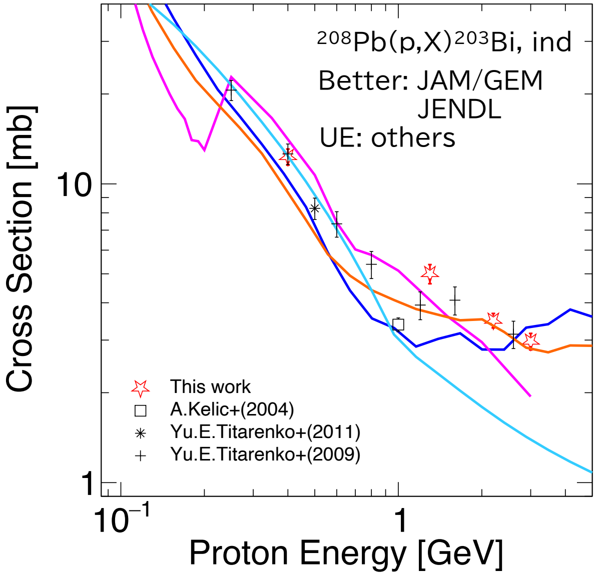
Adjacent nuclides of ^{208}Pb

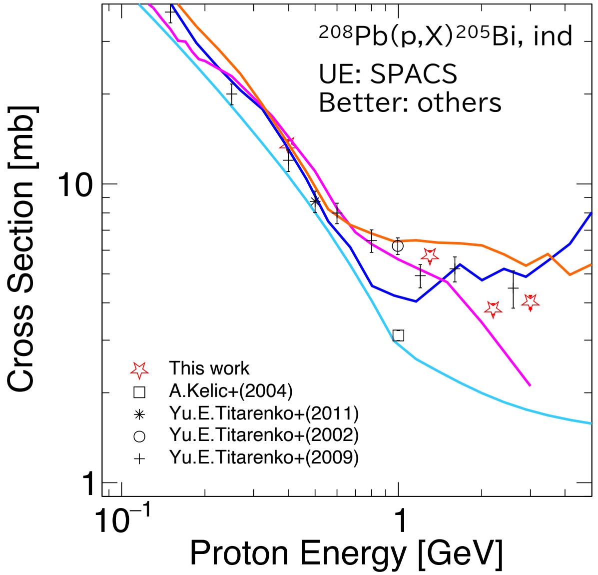












Reduced χ-square values for all obtained nuclides

INCL/GEM	4.5
JENDL/HE-2007	6.2
JAM/GEM	3.9
SPACS	5.2

Excitation functions

Conclusion and future work

Conclusions

・Nuclide production cross sections

^{208}Pb(p,X) reaction at 0.4, 1.3, 2.2, and 3.0 GeV proton incidence

A total of 506 cross sections (170 nuclides) were acquired.

・Comparison with models

Calculations cannot reproduce the measured data.

-> There still remains the room for improvement for calculations.

Future work

・Revision of nuclear reaction models

A lot of data with various targets are already taken.

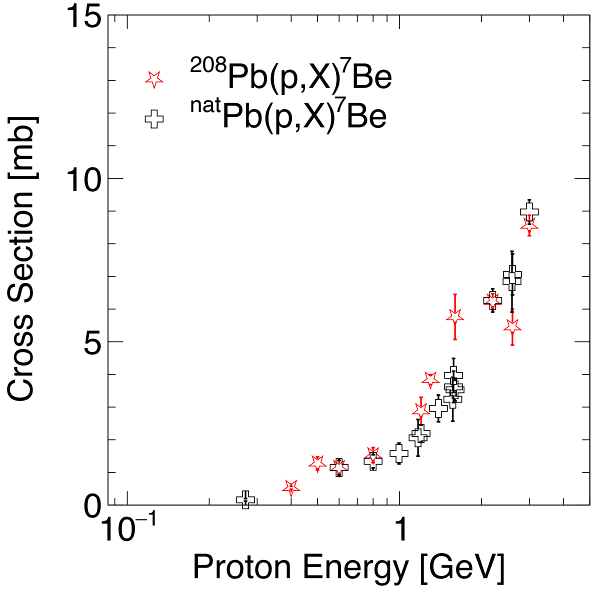
These data are useful to improve nuclear reaction models.

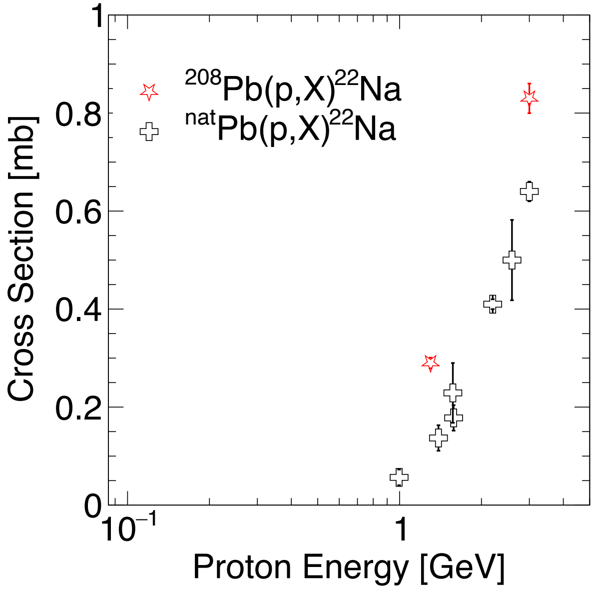
・Comparison with ^{209}Bi data

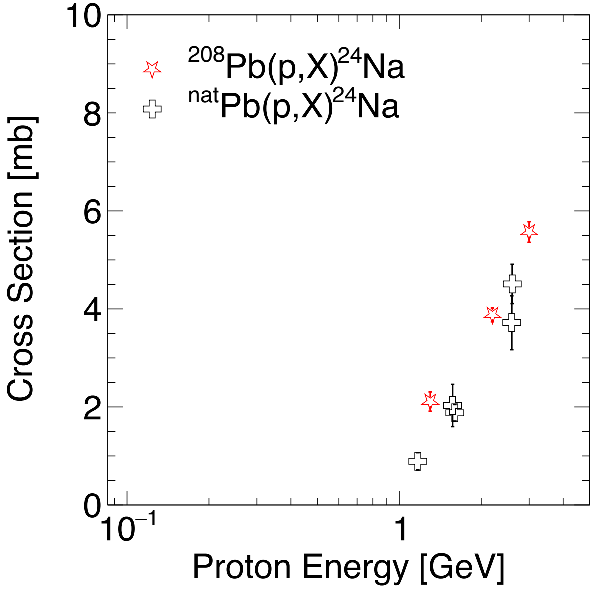
We will compare between the ^{208}Pb(p,X) and ^{209}Bi(p,X) reactions.

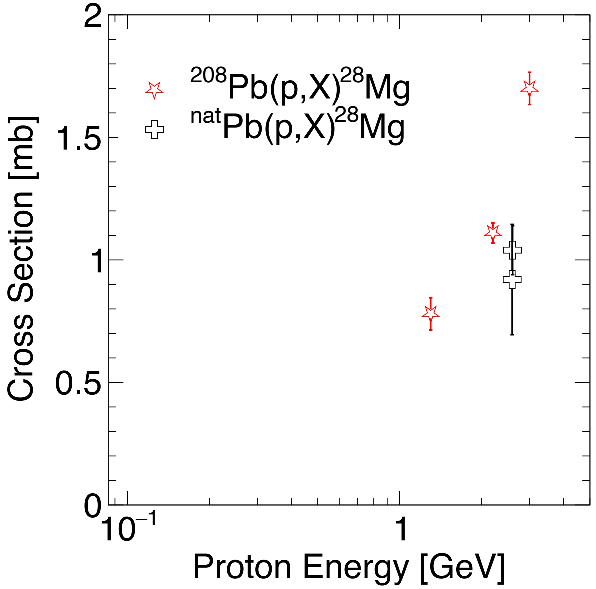
Q&A slides

Comparison with $^{nat}Pb(p,X)$









Correction of the proton intensity

Measurement of γ-rays' distribution from irradiated samples
γ-rays' distribution = incident proton spatial distribution
Fitting by Gauss function of the distribution

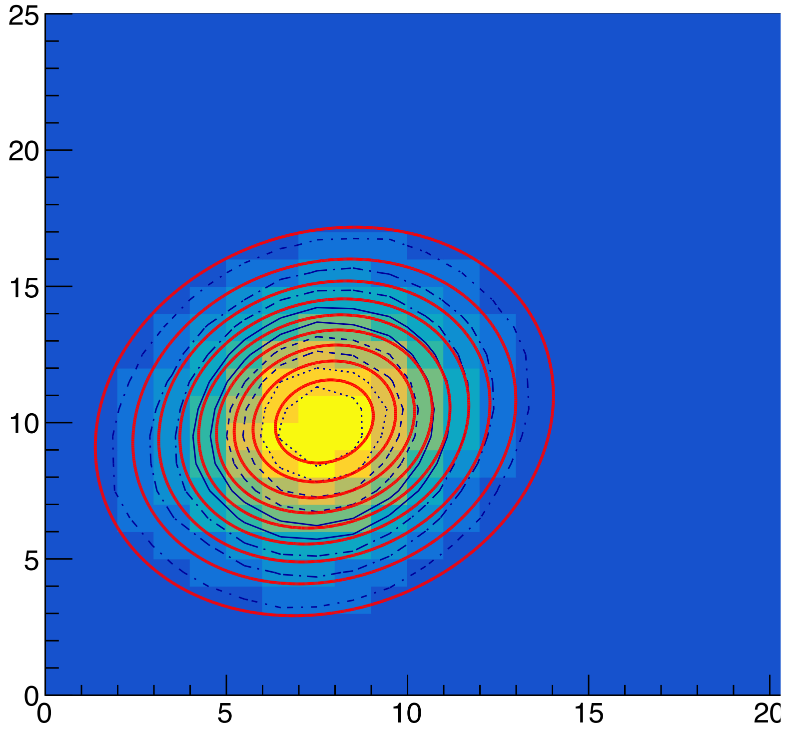
$$f(x,y) = \frac{N}{2\pi\sigma_x\sigma_y\sqrt{1-r^2}} exp\left[-\frac{1}{2(1-r^2)}\left\{\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2r(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right\}\right]$$

Integration of f(x,y) in the sample area

$$f_{beam} = \frac{1}{N}\int_{foil} f(x,y)dxdy$$

Values of f_{beam}

E_p [GeV]	f_{beam}
0.4	0.9990
1.3	0.9689
2.2	0.9943
3.0	0.9717



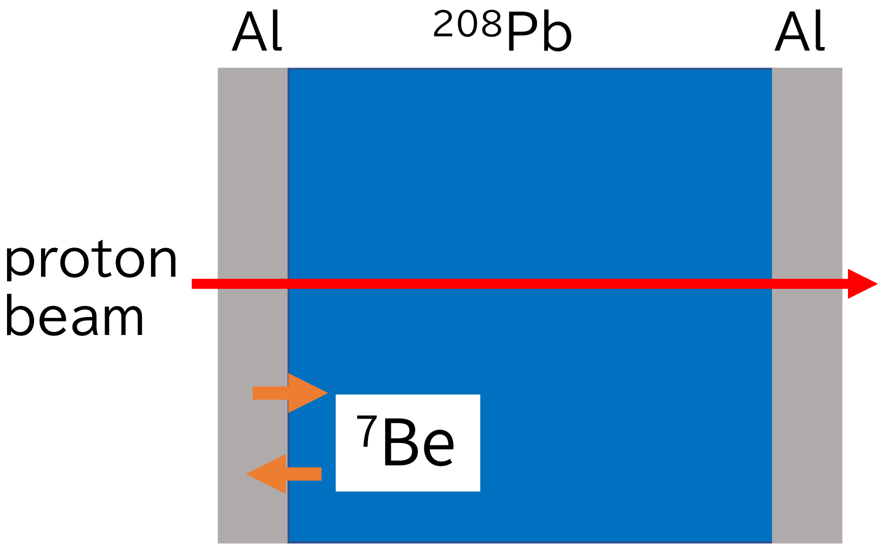
Activation distribution of irradiated sample

Correction of the in/out nuclei

Nuclides generated in ^{208}Pb layer:
Moving to Al layer-> decreasing the cross section

Nuclides generated in Al layer:
Moving to ^{208}Pb layer-> increasing the cross sections

Correction factor: PHITS (T-Yield)



Target foil structure

Values of f_{esc} for ^{7}Be

	0.4 GeV	1.3 GeV	2.2 GeV	3.0 GeV
f_{esc}	0.9692	1.087	1.116	1.108

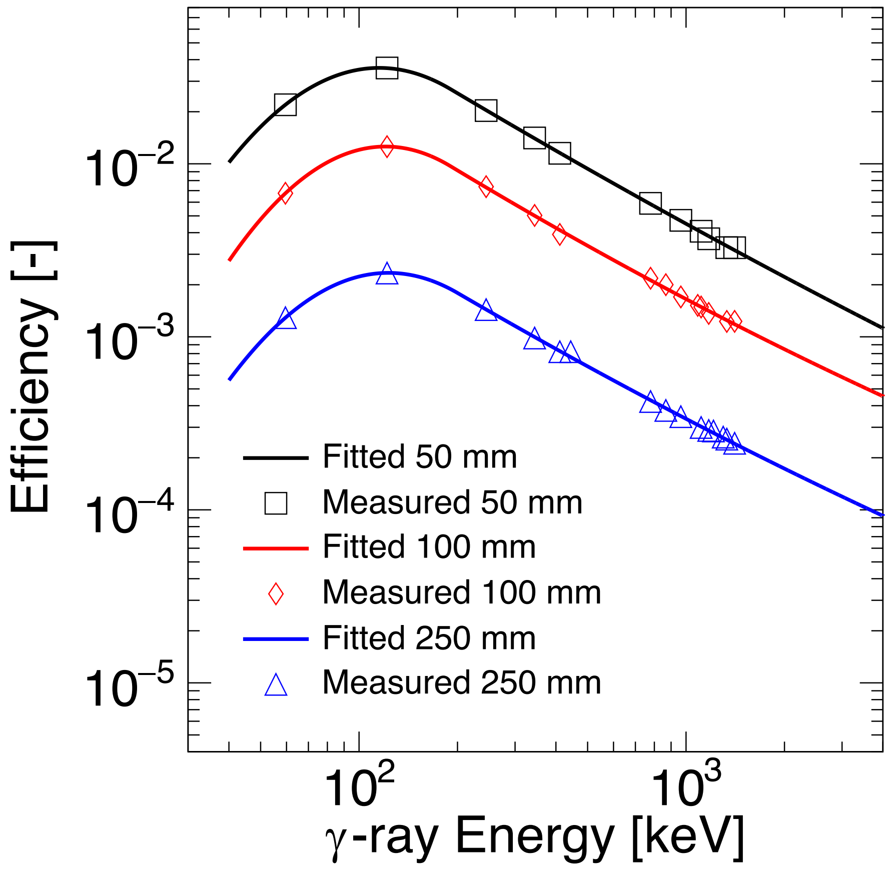
γ-ray detection efficiency

$$ln\{\varepsilon(E_\gamma)\} = \begin{cases} a_0 + a_1 \times \ln E_\gamma + a_2 \times (\ln E_\gamma)^2 & (E_\gamma < E_{knee}) \\ b_0 + b_1 \times \ln E_\gamma + b_2 \times (\ln E_\gamma)^2 & (E_\gamma \geq E_{knee}) \end{cases}$$

$\varepsilon(E_\gamma)$: γ-ray detection efficiency
E_γ: γ-ray's energy [keV]
E_{knee}: separation energy [keV]
a_i, b_i (i=0,1,2): fitting parameters

Fitting parameters at 50-mm distance

a_0	-28.6452
a_1	10.6654
a_2	-1.12329
b_0	2.97939
b_1	-1.38888
b_2	0.0253932
E_{knee} [keV]	190



γ-ray detection efficiency