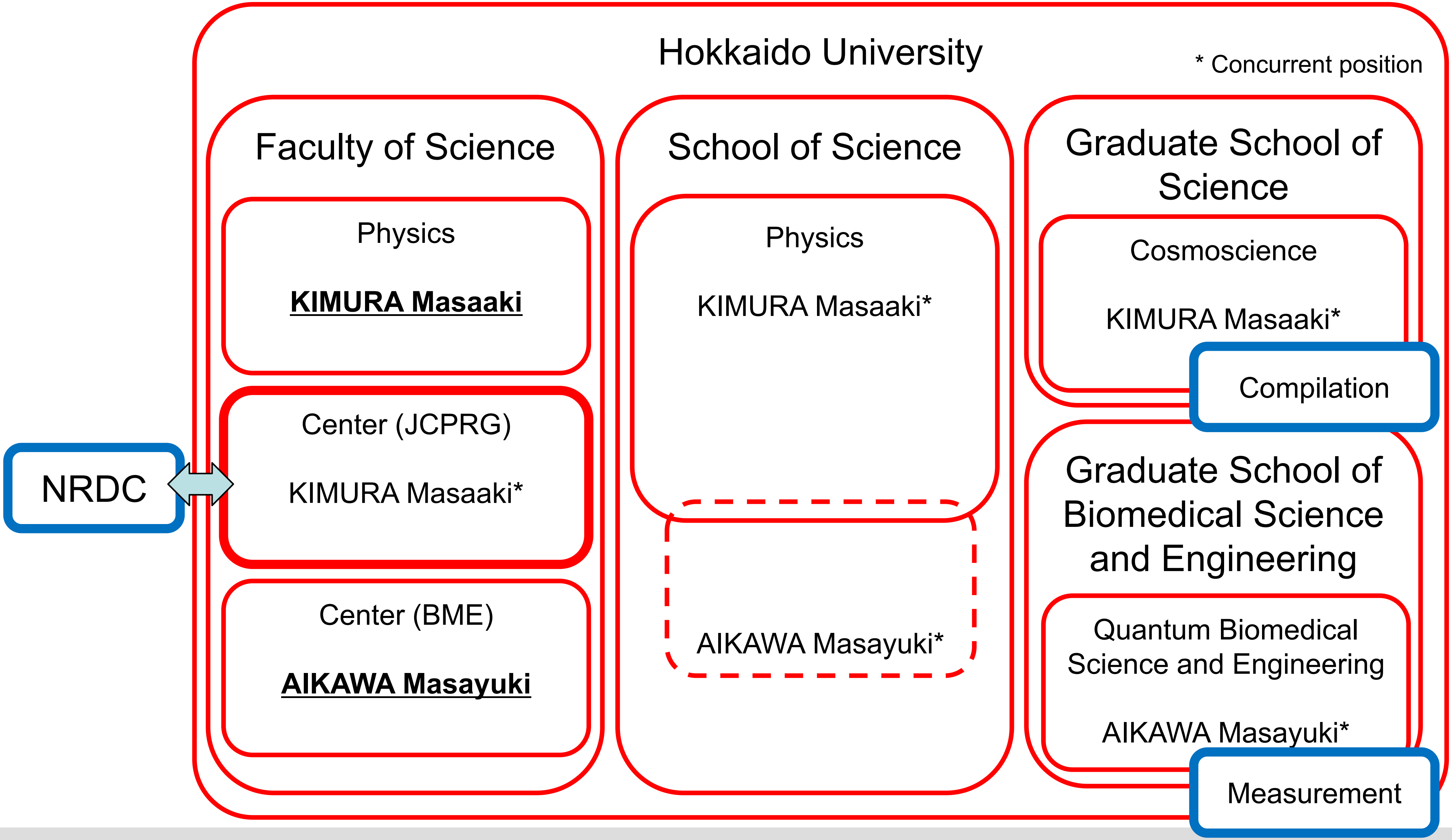
Activation cross sections of charged-particle-induced reactions for medical radionuclide generator

December 15, 2022

Masayuki AIKAWA
Faculty of Science/
Graduate School of Biomedical Science and Engineering,
Hokkaido University

Affiliation: Hokkaido University, Japan



Introduction

- Many radionuclides are used for diagnosis and therapy.
  - Diagnosis
    - positron emitters for PET
    - gamma emitters for SPECT
  - Therapy
    - beta, alpha, and Auger electron emitters

Chemical Reviews — Review

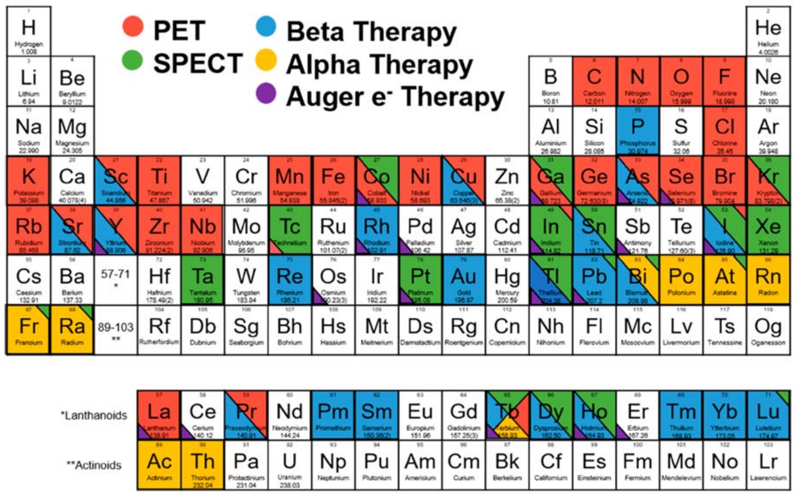


Figure 1. Color-coded periodic table with current or potential applications of each element in diagnostic and/or therapeutic radiopharmaceuticals.[2−14] Periodic table reproduced by permission of International Union of Pure and Applied Chemistry. Copyright © 2018 International Union of Pure and Applied Chemistry.

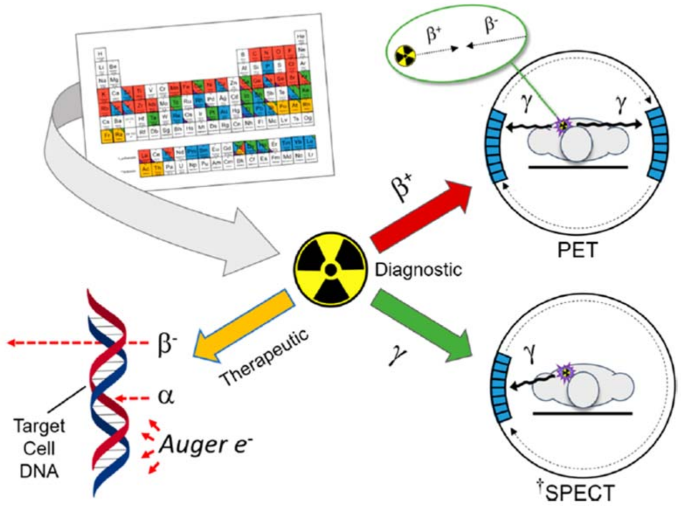


Figure 3. Radiometal decay types and their corresponding applications in nuclear medicine. †Indicates that degree of rotation, number of detectors, and orbital path may vary depending on instrument.

T.I. Kostelnik et al., Chem. Rev. 119 (2019) 902

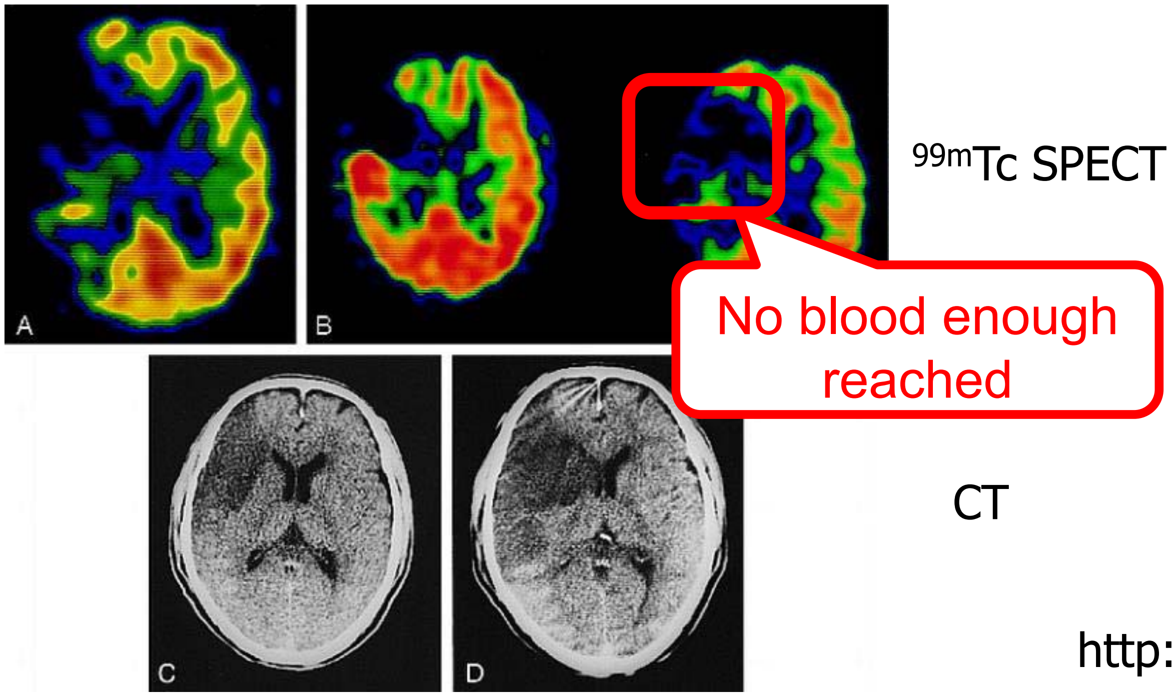
^{99m}Tc Single photon emission computed tomography (SPECT)

- Radiopharmaceuticals with ^{99m}Tc are injected to patients.
- The radiopharmaeuticals concentrate on specific parts, e.g., tumores.
- 140-keV γ rays emitted from the decay of ^{99m}Tc can be detected.
- The location of the concentration can be recognized from outside of the patient body.

SPECT, Wikipedia

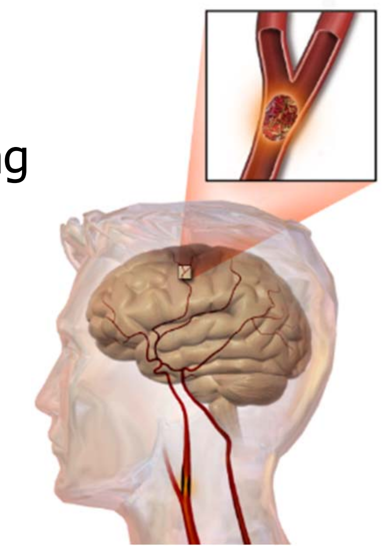
SPECT imaging

- 140-keV γ rays emitted from the radiopharmaeuticals with ^{99m}Tc were detected for imaging.



^{99m}Tc SPECT Imaging

CT



Stroke, Wikiwand, http://www.wikiwand.com/en/Stroke

Kuniaki Ogasawara et al., "^{99m}Tc-Bicisate and ^{99m}Tc-HMPAO SPECT Imaging in Early Spontaneous Reperfusion of Cerebral Embolism", Am. J. Neuroradiol. 20 (1999) 626.

$^{99m}Tc/^{99}Mo$ supply

- The half-life of ^{99m}Tc is 6 hours.
- Its parent ^{99}Mo ($T_{1/2}$ = 66 h) is more appropriate to deliver.
- In Japan, all amounts required for ~900,000 scans/year are imported.

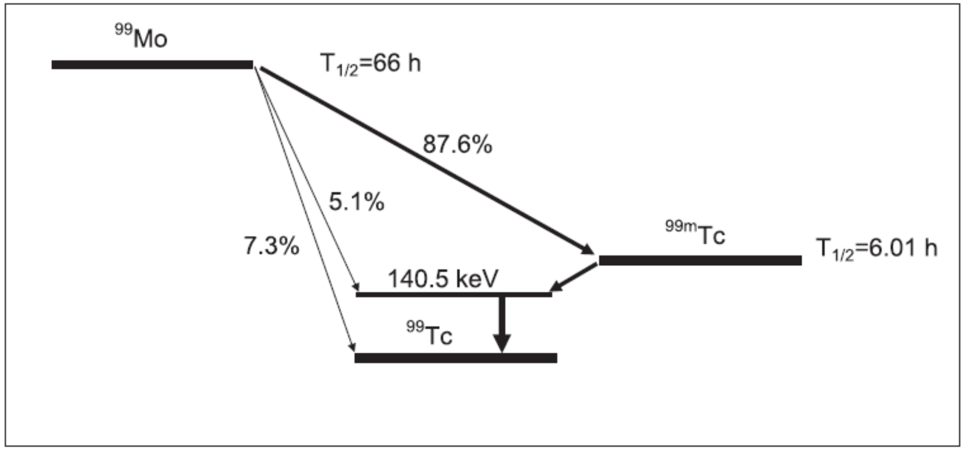
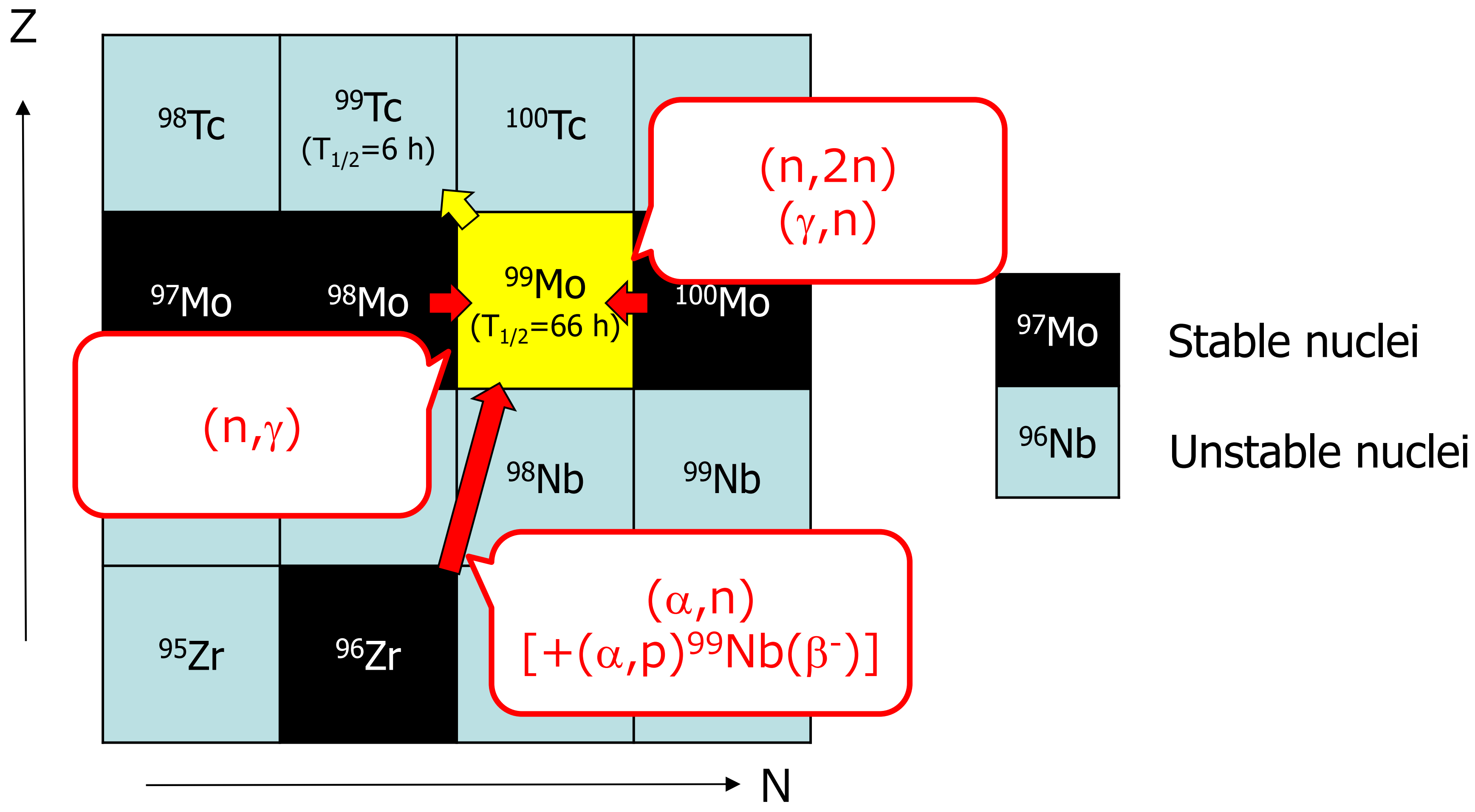


Fig. 3. Simplified decay scheme of ^{99}Mo and ^{99m}Tc.

S. Takacs et al., "Reexamination of cross sections of the $^{100}Mo(p,2n)^{99m}Tc$ reaction", Nucl. Instrum. Methods B 347 (2015) 26.

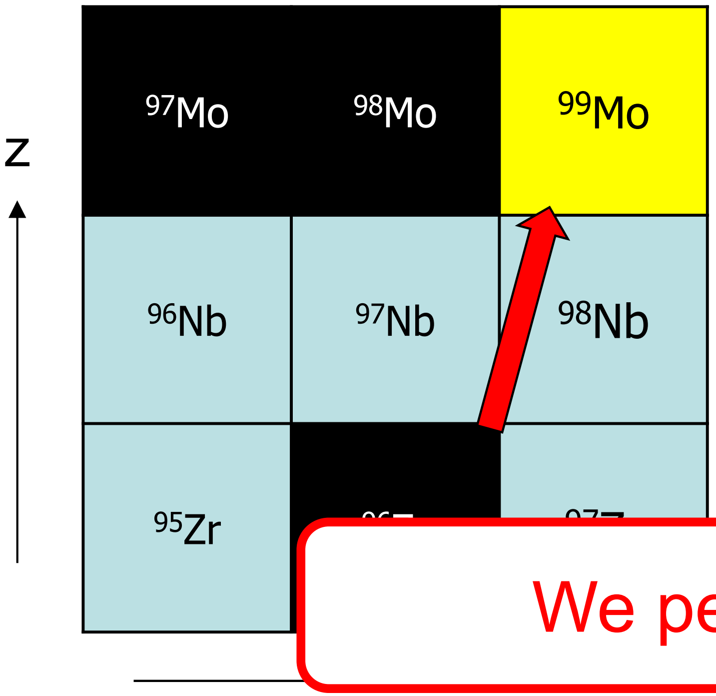
^{99}Mo production route other than U fission

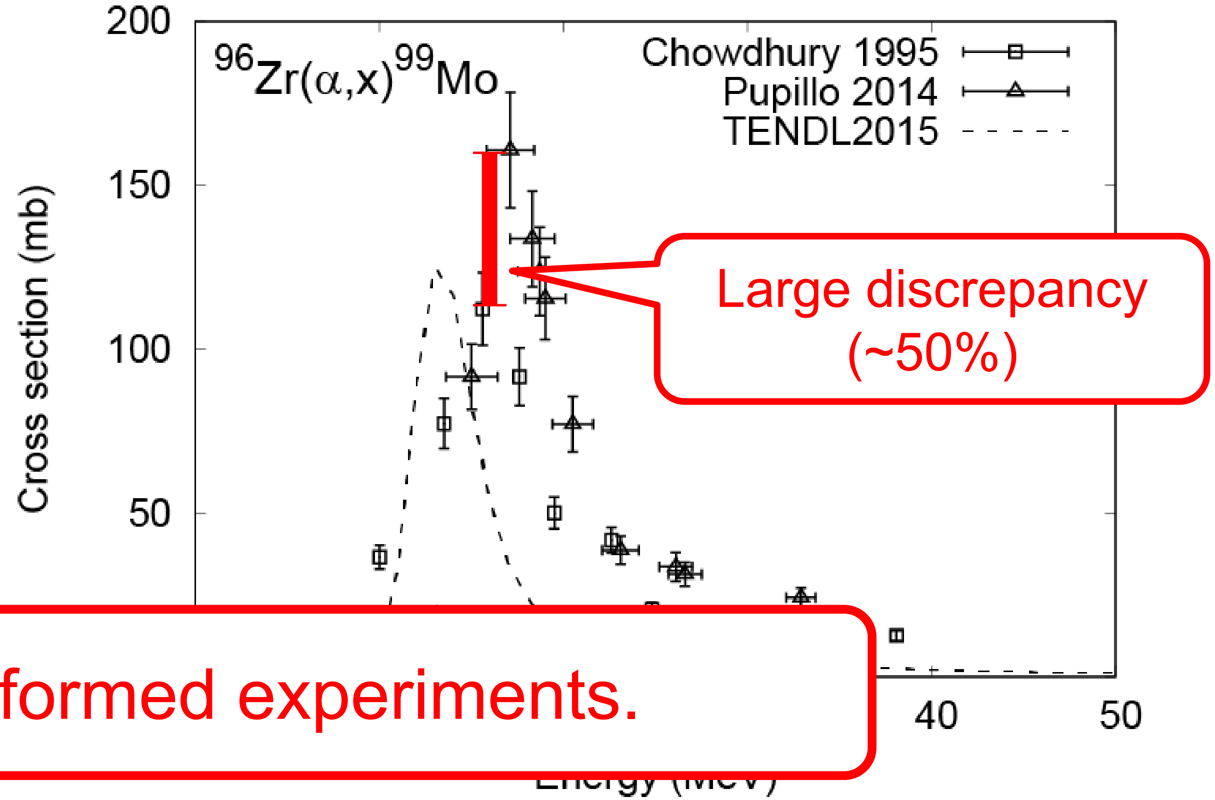
- Production reactions of ^{99}Mo from stable nuclei.



$^{96}Zr(\alpha,n)^{99}Mo$ reaction

- One of the reactions to produce ^{99}Mo is the $^{96}Zr(\alpha,n)^{99}Mo$ reaction.
- Cross sections had been studied in two earlier experiments.

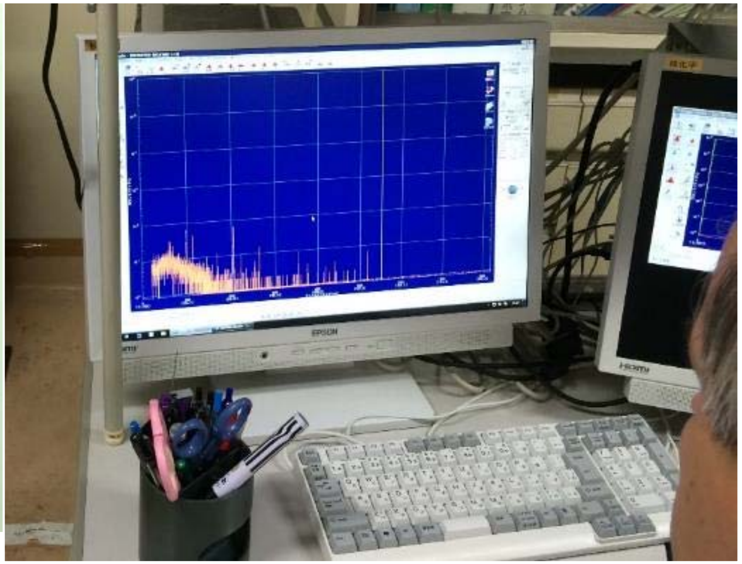




We performed experiments.

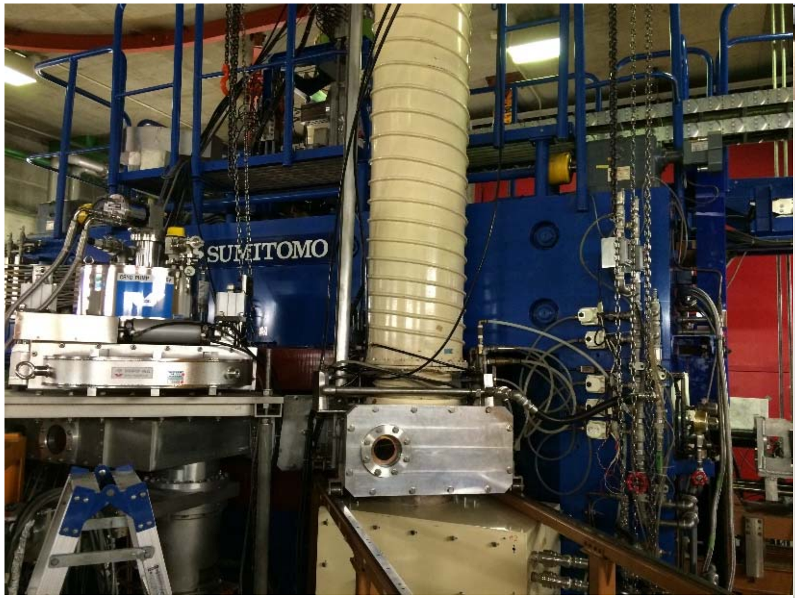
Method

- We used the well-established methods for the cross section measurements.
  - Stacked-foil activation technique
  - γ-ray spectrometry

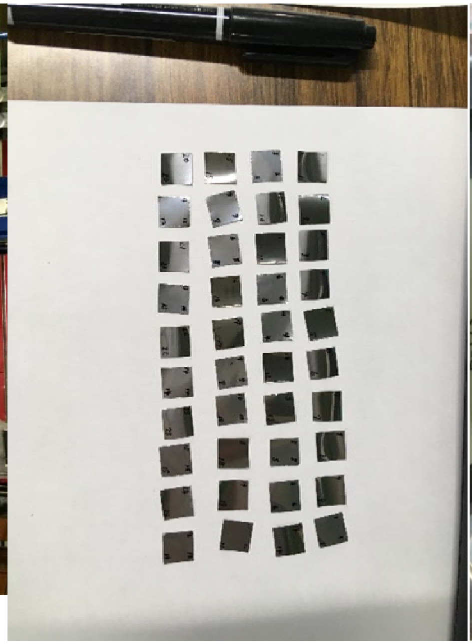


Experimental setup

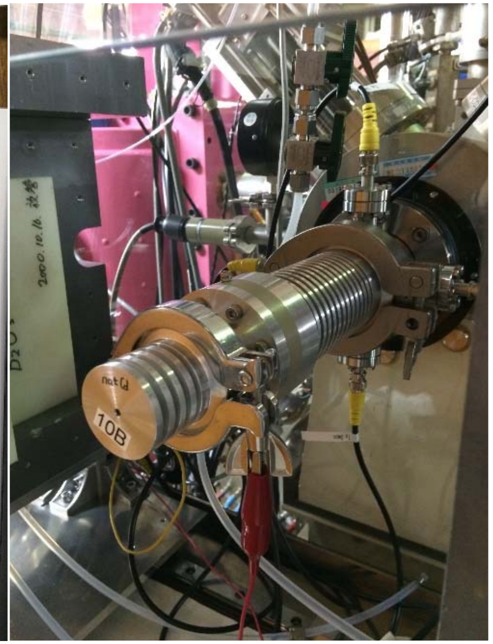
- The two targets consisted of ^{nat}Zr (^{96}Zr: 2.8%) and ^{nat}Ti foils.
- The targets were irradiated by 51 and 29 MeV α-beams with 200 nA for 2 hours at RIKEN AVF cyclotron.



RIKEN AVF cyclotron



Zr/Ti foils



Target holder

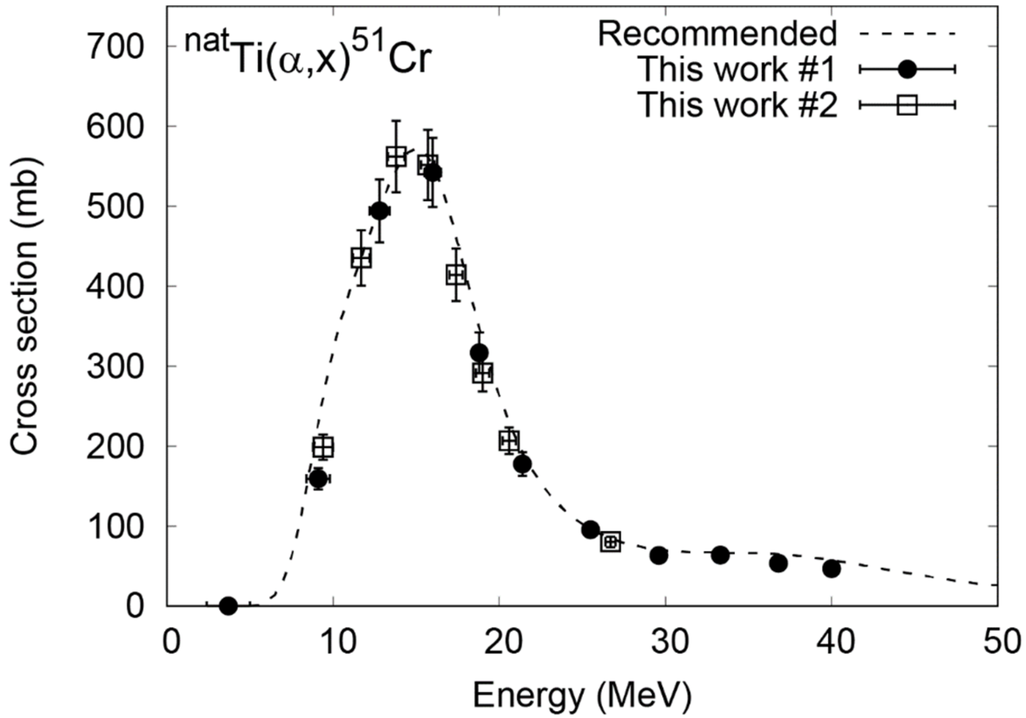
Experimental conditions

- Experimental conditions were changed in two experiments.

	#1 (2017/10)	#2 (2017/12)
Energy	**51.0 MeV**	**28.9 MeV**
Intensity	203.6 pnA	205.0 pnA
Period	7200 s	7200 s
^{nat}Zr	**13.3 mg/cm^2** **20.5 μm** 99.2 % purity	**6.75 mg/cm^2** **10.4 μm** 99.2 % purity
^{nat}Ti	2.3 mg/cm^2 5.3 μm 99.6 % purity	2.4 mg/cm^2 5.4 μm 99.6 % purity

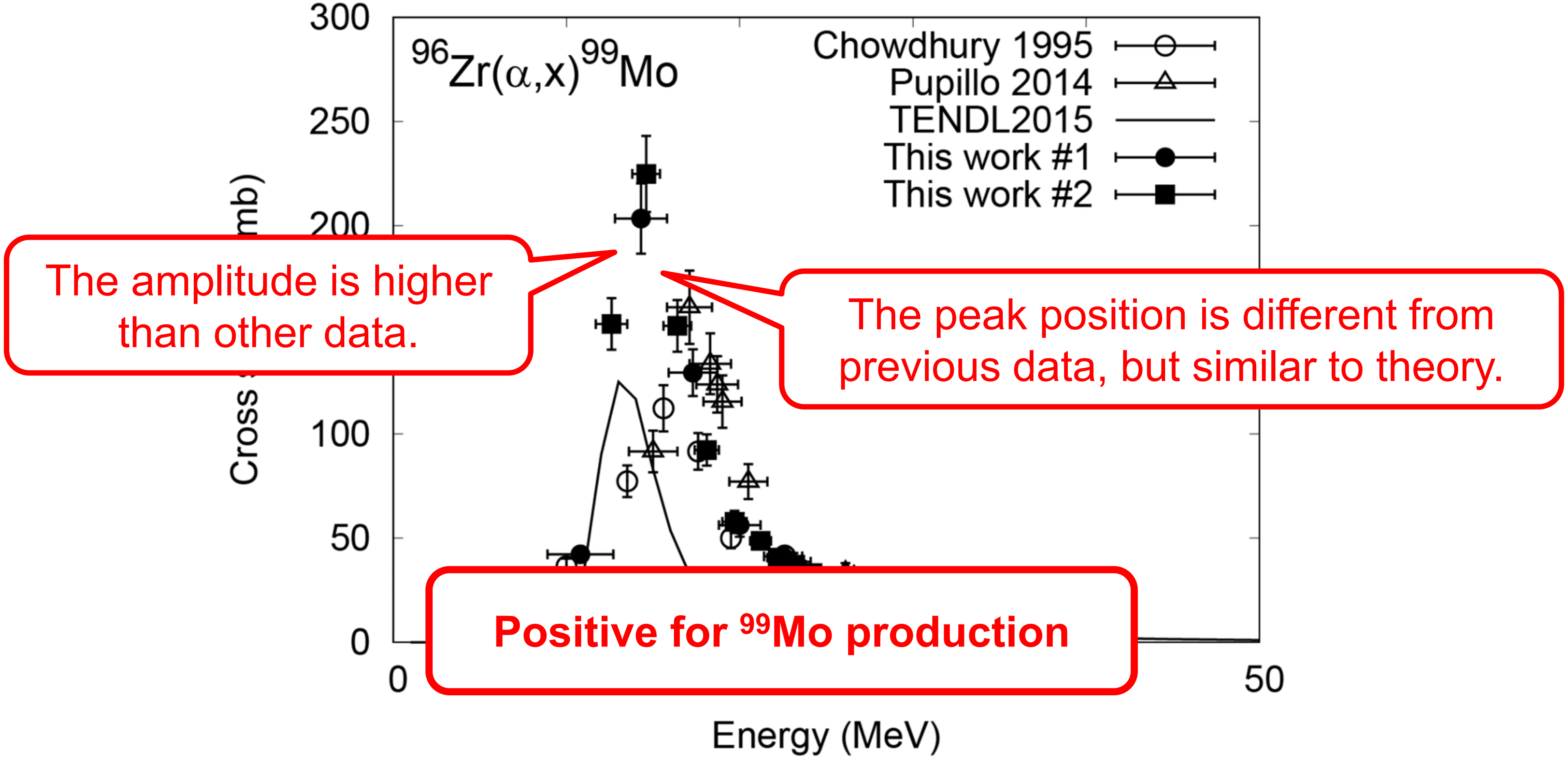
$^{nat}Ti(\alpha,x)^{51}Cr$ monitor reaction

- Cross sections derived in our experiments were compared with the IAEA recommended values.
- The monitor cross sections could be reproduced.
- No corrections are required for the beam and targets.



Result: $^{96}Zr(\alpha,n)^{99}Mo$ reaction

- The two results are very similar to each other, but different from the previous studies.



Paper and entry

- The paper was published and compiled into EXFOR.

Applied Radiation and Isotopes 144 (2019) 47–53

Contents lists available at ScienceDirect

ELSEVIER

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Production cross sections of Mo, Nb and Zr radioisotopes from α-induced reaction on ^{nat}Zr

Check for updates

T. Murata[a,1], M. Aikawa[b,c,*], M. Saito[c], N. Ukon[d], Y. Komori[e], H. Haba[e], S. Takács[f]

[a] School of Science, Hokkaido University, Sapporo 060-0810, Japan
[b] Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan
[c] Graduate School of Biomedical Science and Engineering, Hokkaido University, Sapporo 060-8638, Japan
[d] Advanced Clinical Research Center, Fukushima Medical University, Fukushima City 960-1295, Japan
[e] Nishina Center for Accelerator-Based Science, RIKEN, Wako 351-0198, Japan
[f] Institute for Nuclear Research, Hungarian Academy of Sciences (ATOMKI), 4026 Debrecen, Hungary

```
ENTRY            E2592   20190117                               E259200000001
SUBENT        E2592001   20190117   20190223                    E259200100001
BIB                 12         34                               E259200100002
TITLE      Production cross sections of Mo, Nb and Zr           E259200100003
           radioisotopes from alpha-induced reaction on natZr   E259200100004
AUTHOR     (T.Murata, M.Aikawa, M.Saito, N.Ukon, Y.Komori, H.Haba, E259200100005
            S.Takacs)                                           E259200100006
INSTITUTE  (2JPNHOK) School of Science                          E259200100007
           (2JPNHOK) Faculty of Science                         E259200100008
           (2JPNHOK) Graduate School of Biomedical Science and  E259200100009
                     Engineering                                E259200100010
           (2JPNJPN) Advanced Clinical Research Center, Fukushima E259200100011
                     Medical University, Fukushima              E259200100012
           (2JPNIPC) Nishina Center for Accelerator-Based Science E259200100013
           (3HUNDEB)                                            E259200100014
REFERENCE  (J,ARI,144,47,2019)                                  E259200100015
           Main reference. See also TITLE and AUTHOR.           E259200100016
           (S,JAEA-C-2018-001,181,2018) 002 data in Fig.        E259200100017
```

^{44}Ti/^{44}Sc generator

- ^{44g}Sc ($T_{1/2}$ = 3.97 h, β^+: 94.3%) can be used for PET.
- Its parent ^{44}Ti ($T_{1/2}$ = 59.1 y, ε: 100%) is expected to be a generator.

Radiochim. Acta **98**, 149–156 (2010) / **DOI** 10.1524/ract.2010.1701

A ^{44}Ti/^{44}Sc radionuclide generator for potential application of ^{44}Sc-based PET-radiopharmaceuticals

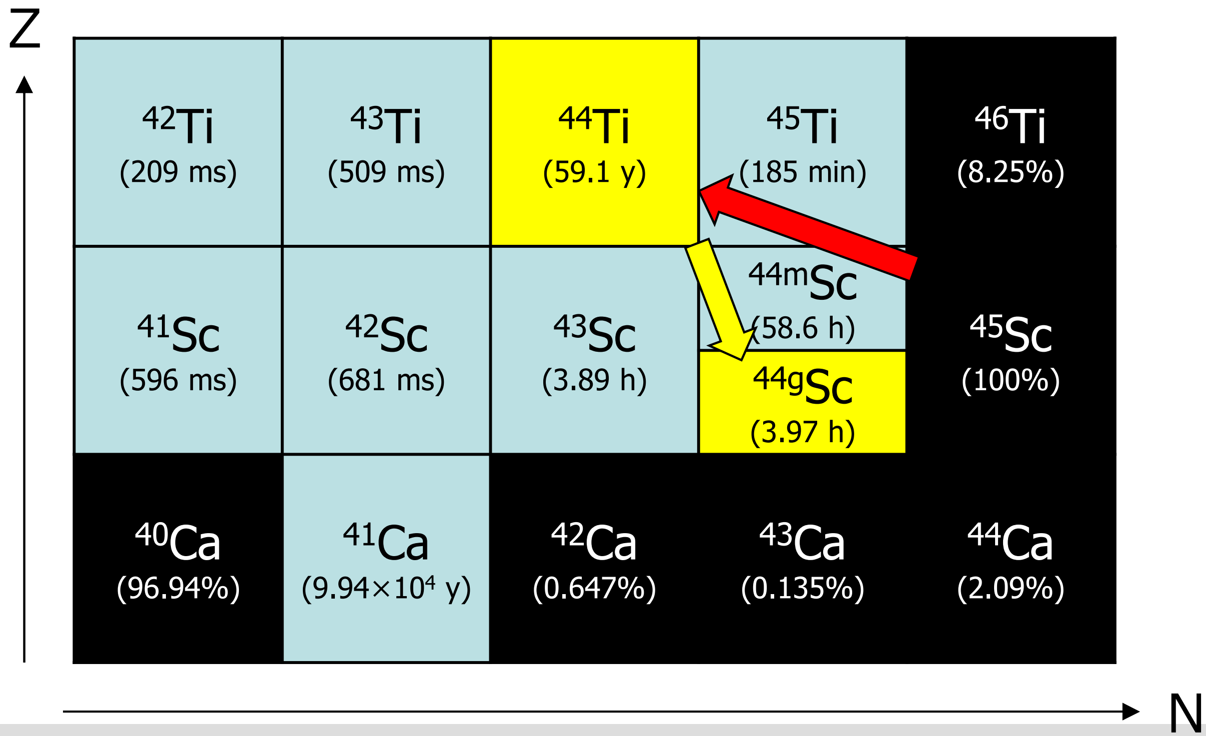
By D. V. Filosofov[1], N. S. Loktionova[2] and F. Rösch[2,*]

[1] Joint Institute of Nuclear Research, DLNP, 141980 Dubna, Russian Federation
[2] Institute of Nuclear Chemistry, University of Mainz, 55128 Mainz, Germany

(Received April 27, 2009; accepted in revised form October 21, 2009)

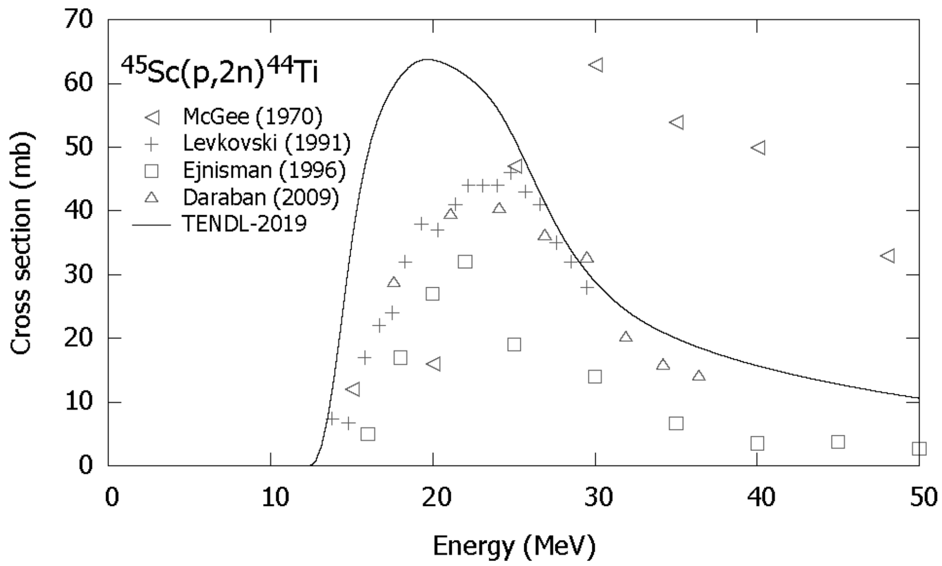
Scandium and titanium radioisotopes

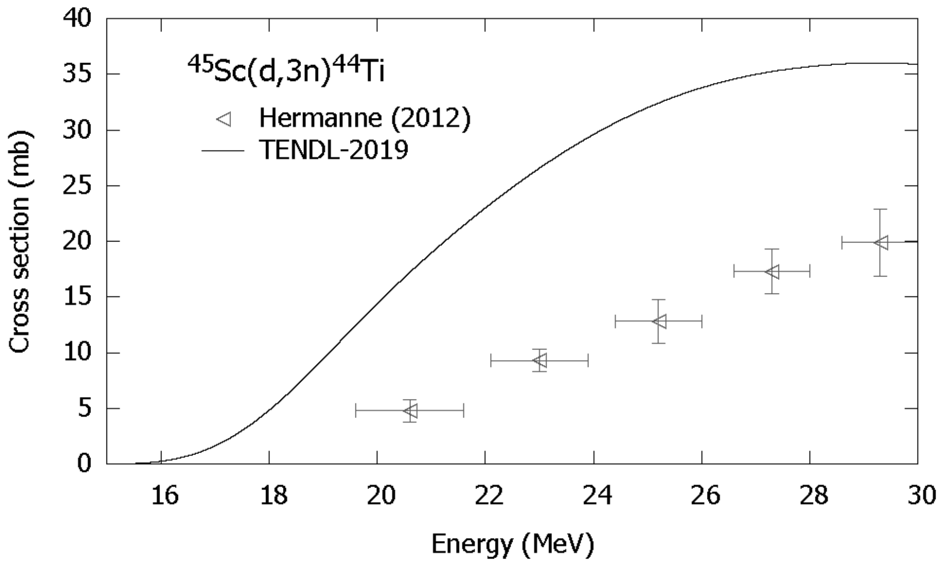
- ^{44g}Sc ($T_{1/2}$ = 3.97 h, β^+: 94.3%)
  - Emitted positrons (E_{ave}: 632 keV) can be used for PET.
- ^{44}Ti ($T_{1/2}$ = 59.1 y, ε: 100%)
  - Generator of ^{44g}Sc.



Proton- and deuteron-induced reactions on ^{45}Sc

- The literature data of proton- and deuteron-induced reactions found in the EXFOR library were scattered or few.

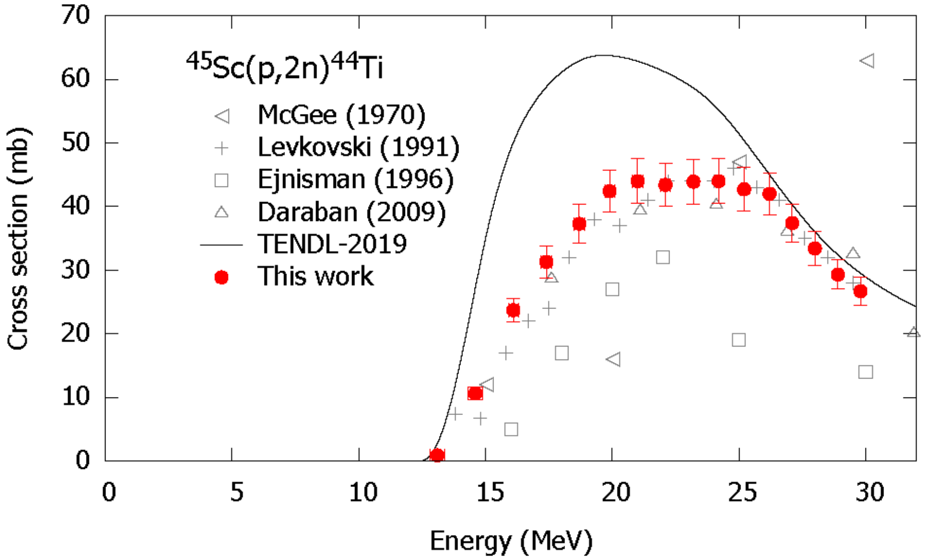


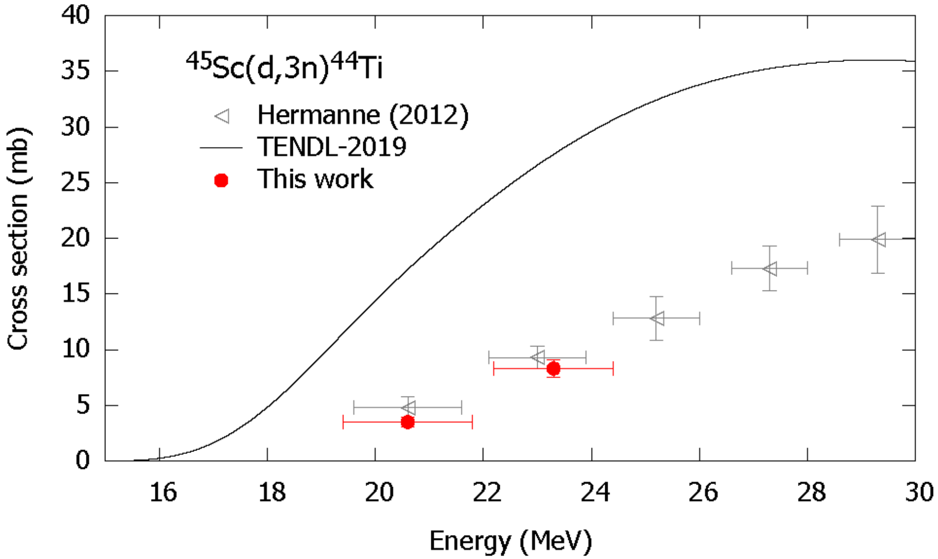


Our experimental results

- We performed two experiments to measure the cross sections.

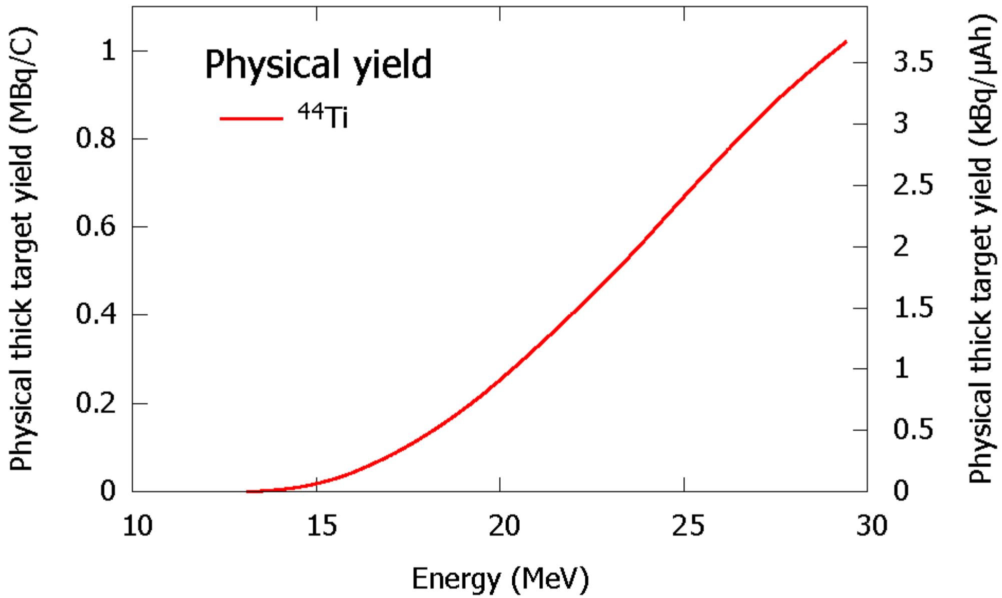
	proton	deuteron
Beam	51.0 MeV, 195 nA, 3600 s	24.3 MeV, 180 nA, 1800 s
^{45}Sc	102 μm, 99 % purity	25.8/250 μm, 99.9% purity
^{nat}Ti	4.97 μm, 99.6 % purity	20.2 μm, 99.6 % purity





Physical thick target yield

- The physical thick target yield of ^{44}Ti in the $^{45}Sc(p,2n)^{44}Ti$ reaction was derived using the measured cross sections.
- The yield was ~1 MBq/C (3.6 kBq/μAh) at the incident energy of 30 MeV.



Activity required for ^{18}F-FDG scan

- The required activity for the PET scan is 74-370 MBq, which depends on the weight of each patient.

2022年3月改訂（第1版）

貯法：室温保存 有効期間：放射能が 74MBq となるまで， 放射能減衰表参照

日本標準商品分類番号	
874300	
承認番号	21700AMZ00697000
販売開始	2005年8月

放射性医薬品・悪性腫瘍診断薬，虚血性心疾患診断薬，てんかん診断薬

放射性医薬品基準フルデオキシグルコース（^{18}F）注射液

処方箋医薬品注）

ＦＤＧスキャン®注

FDGscan® Injection

注）注意－医師等の処方箋により使用すること

®：登録商標

3. 組成・性状

3.1 組成

販売名	FDGスキャン注		
有効成分	1バイアル（1.2mL）中フルデオキシグルコース（^{18}F）（検定日時において）111MBq	1バイアル（1.6mL）中フルデオキシグルコース（^{18}F）（検定日時において）148MBq	1バイアル（2mL）中フルデオキシグルコース（^{18}F）（検定日時において）185MBq
添加剤	1バイアル（1.2mL）中日本薬局方D-	1バイアル（1.6mL）中日本薬局方D-	1バイアル（2mL）中日本薬局方D-

○虚血性心疾患（左室機能が低下している虚血性心疾患による心不全患者で，心筋組織のバイアビリティ診断が必要とされ，かつ，通常の心筋血流シンチグラフィで判定困難な場合）の診断

○難治性部分てんかんで外科切除が必要とされる場合の脳グルコース代謝異常領域の診断

○大型血管炎の診断における炎症部位の可視化

6. 用法及び用量

通常，成人には本剤1バイアルを静脈内に投与し撮像する。投与量（放射能）は，年齢，体重により適宜増減するが，最小 74MBq，最大 370MBq までとする。

Possible beam intensity at J-PARC

- The possible beam intensity of a 30-MeV proton beam at J-PARC is more than 50 mA.

Proceedings of IPAC2015, Richmond, VA, USA THPF039

STABILITY STUDIES FOR J-PARC LINAC UPGRADE TO 50mA/400MeV

Y. Liu, T. Maruta, K. Futatsukawa, T. Miyao KEK/J-PARC, Ibaraki-ken, Japan
M. Ikegami, FRIB, East Lansing, USA
A. Miura, JAEA/J-PARC, Tokai-mura, Japan

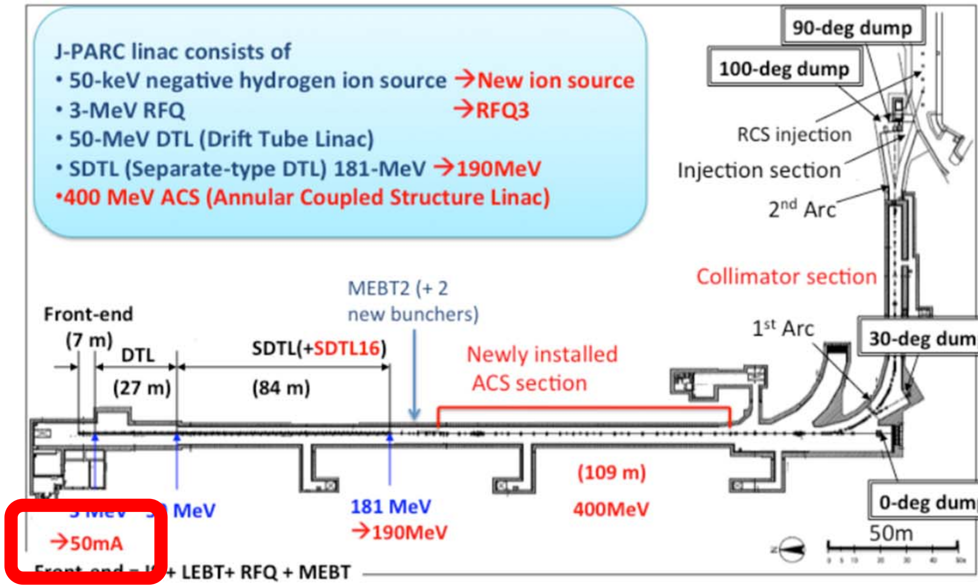
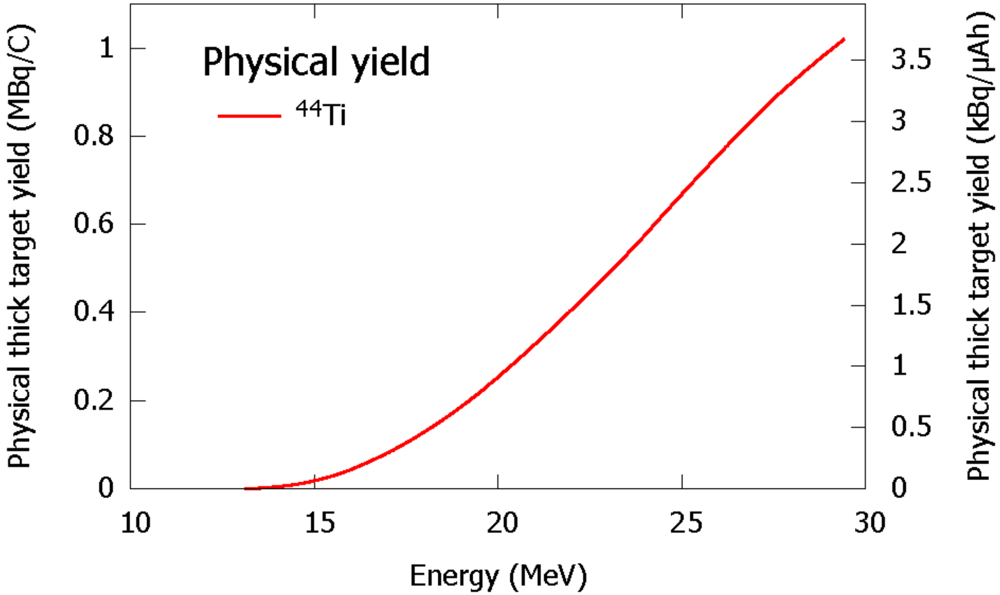


Figure 1: Layout of J-PARC linac.

Possible activity

- If we can use a 30-MeV proton beam of 50 mA for 3 h, the produced activity of ~525 MBq is expected.



Paper and entry

Applied Radiation and Isotopes 168 (2021) 109448

ELSEVIER

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: http://www.elsevier.com/locate/apradiso

Production cross sections of ^{45}Ti in the deuteron-induced reaction on ^{45}Sc up to 24 MeV

Check for updates

Zolbadral Tsoodol [a,b,*], Masayuki Aikawa [a,c], Dagvadorj Ichinkhorloo [b,c], Tegshjargal Khishigjargal [d], Erdene Norov [d], Yukiko Komori [e], Hiromitsu Haba [e], Sándor Takács [f], Ferenc Ditrói [f], Zoltán Szűcs [f]

[a] Graduate School of Biomedical Science and Engineering, Hokkaido University, Sapporo, 060-8638, Japan
[b] Nuclear Research Center, National University of Mongolia, Ulaanbaatar, 13330, Mongolia
[c] Faculty of Science, Hokkaido University, Sapporo, 060-0810, Japan
[d] School of Engineering and Applied Sciences, National University of Mongolia, Ulaanbaatar, 14201, Mongolia
[e] Nishina Center for Accelerator-Based Science, RIKEN, Wako, 351-0198, Japan
[f] Institute for Nuclear Research (ATOMKI), Debrecen, 4026, Hungary

```
ENTRY            E2682   20220621   20220819   20220819       E135
SUBENT        E2682001   20220621   20220819   20220819       E135
BIB                 14         29
TITLE      Production cross sections of 45Ti in the
           deuteron-induced reaction on 45Sc up to 24 MeV
AUTHOR     (Z.Tsoodol, M.Aikawa, D.Ichinkhorloo, T.Khishigjargal,
            E.Norov, Y.Komori, H.Haba, S.Takacs, F.Ditroi,
            Z.Szucs)
INSTITUTE  (2JPNHOK,3MGLNUM,2JPNIPC,3HUNDEB)
REFERENCE  (J,ARI,168,109448,2021)
```

III-3. Radiochemistry & Nuclear Chemistry RIKEN Accel. Prog. Rep. 55 (2022)

Production cross sections of titanium radionuclides via proton-induced reactions on scandium

M. Aikawa,[*1,*2,*3] H. Huang,[*2,*3] H. Haba,[*2] S. Takács,[*4] F. Ditrói,[*4] and Z. Szücs[*4]

^{211}Rn/^{211}At generator

- ^{211}At ($T_{1/2}$ = 7.22 h) is an alpha emitter and can be used for therapy.
- Its parent ^{211}Rn ($T_{1/2}$ = 14.6 h) can be a generator.

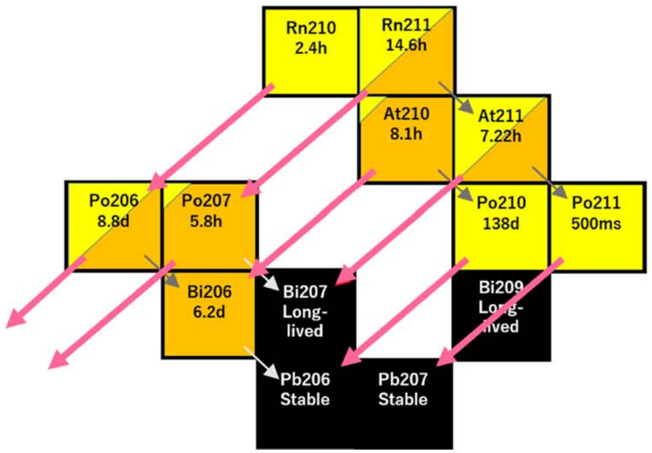
Journal of Radioanalytical and Nuclear Chemistry (2020) 323:921–926
https://doi.org/10.1007/s10967-019-06990-z

Check for updates

Measurements of the excitation functions of radon and astatine isotopes from ^{7}Li-induced reactions with ^{209}Bi for development of a ^{211}Rn–^{211}At generator

Eita Maeda[1] · Akihiko Yokoyama[2] · Takumi Taniguchi[1] · Kohshin Washiyama[3] · Ichiro Nishinaka[4]

Received: 30 September 2019 / Published online: 14 December 2019



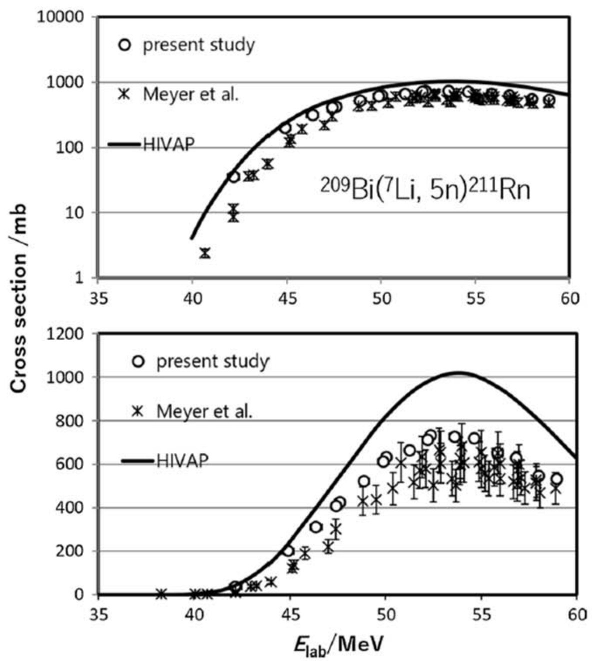
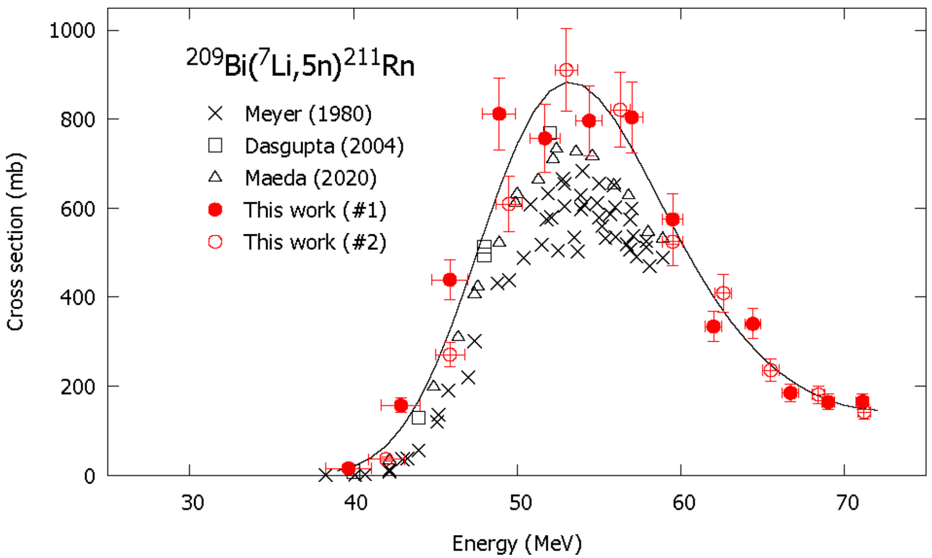
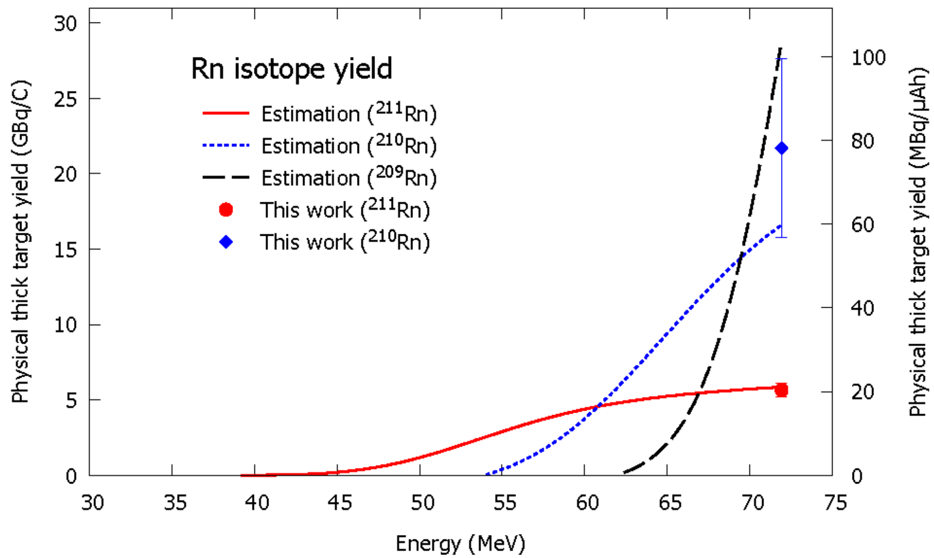


Fig. 3 Excitation function of the ^{209}Bi(^{7}Li, 5n)^{211}Rn reaction. Circle marks indicate results from the present study, whereas crosses are results from [6]. Data are compared with a solid line calculated with the use of the HIVAP code in logarithmic scale in the upper figure and in linear scale in the bottom figure

$^{209}Bi(^{7}Li,5n)^{211}Rn$ reaction

	Cross section (#1)	Cross section (#2)	Yield
Beam	71.9 MeV, 147 nA, 3600 s	71.9 MeV, 147 nA, 3420 s	71.2 MeV, 142 nA, 1200 s
^{209}Bi	7.34 mg/cm², 100 % purity	5.72 mg/cm², 100 % purity	1062 mg/cm², 100% purity
^{27}Al	8.04 µm, 99 % purity	17.7 µm, 99 % purity	10 µm, 99 % purity





Summary

- To discuss production of radioisotopes for generators, nuclear data, e.g. cross sections and yields, are necessary.
- We systematically measure experimental cross sections using stacked-foil activation technique and gamma-ray spectrometry.
- Activation cross sections for some generators were measured.
  - $^{99}Mo/^{99m}Tc$
  - $^{44}Ti/^{44}Sc$
  - $^{211}Rn/^{211}At$
  - $^{68}Ge/^{68}Ga$
  - $^{140}Nd/^{140}Pr$

Collaborators

- G. Damdinsuren, S. Goto, Y. Toyoeda (HU)
- M. Saito, T. Murata, M. Sakaguchi, H. Huang (HU→Co.)
- D. Ichinkhorloo, Z. Tsoodol (HU→NUM)
- H. Haba (RIKEN)
- Y. Komori (RIKEN→Co.)
- S. Takacs, F. Ditori, S. Zoltan (ATOMKI)
- N. Otsuka (IAEA)
- S. Ebata (HU→TIT→Saitama U)
- N. Ukon (HU→Fukushima Med. U)
- H. Yashima (Kyoto U)
- M. Hagiwara (KEK→NIST)

Thank you for your attention.