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Evaluation of excitation function by TALYS code for producing ^{109}Cd with different ion beams

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Abstract TALYS code was used to calculate excitation functions for proton induced on ^{nat}Ag, ^{nat}Cd and ^{113}In, deuteron induced on ^{nat}Ag and alpha induced on ^{nat}Pd that lead to produce ^{109}Cd radioisotope using low and medium energy accelerators; calculates was performed out up to 50 MeV. Recommended thickness of the targets according to SRIM code was premeditated. Theoretical integral yields for any reaction were computed. TALYS 1.0 code predicts that production of a few curries of ^{109}Cd is feasible using a target of high isotopically enriched ^{110}Cd, proton energy of 15 to 27 MeV, however high cost of the enriched target seems to be not a practical economic alternative to produce ^{109}Cd. The Ag+p and Ag+d processes can be an efficient route and economic for the production of millicurries of the radioisotope with incident beam energy less 15 MeV using low energy accelerator.

Key words ^{109}Cd, Radioisotope production, Excitation functions, Target thickness, Yield

1 Introduction

Cd-109, with a half-life of 462.6 day, decays by electron capture to ^{109m}Ag, which becomes (39.6 s) ^{109}Ag by emitting 88 keV γ-ray[1]. It is used as a calibration source of X-ray and γ-ray detectors, a radioactive tracer to study environmental pollutant, etc. It is also used in nuclear medicine with a ^{109}Cd/^{109m}Ag generator system[2–6].

To find out feasibility of producing ^{109}Cd by ion beam bombardment of various targets, excitation functions were measured by the stacked foil activation technique. Natural silver were used in Refs.[7,8], and enriched silver foils were used in Refs.[9–13], to measure cross section of the ^{109}Cd(p,n)^{109}Ag reaction in 4–43 MeV region. Cross sections of ^{109}Cd(d,2n)^{109}Ag were measured with ^{nat}Ag targets in Refs.[14–19] using 0.44–50 MeV deuterons. Tarkanyi F, *et al*[20] measured cross sections of proton induced on ^{nat}Cd up to 80 MeV. Nortier F M, *et al*[21] measured cross sections of proton induced on ^{nat}In in the 36.3–199.6 MeV region.

The present study is to make comparison of cross sections to produce ^{109}Cd *via* different reactions with incident ion beams of up to 50 MeV.

2 Methods

Excitation function of ^{109}Cd production *via* (^{nat}Ag+p), (^{nat}Ag+d), (^{nat}In+p), (^{nat}Cd+p) and (^{nat}Pd+α) reaction was calculated by TALYS-1.0 code. An optimum energy range should be determined to avoid formation of radionuclide impurities, and to decrease production excitation function of inactive impurities. Therefore, the ^{109}Cd production began by predicting the excitation functions using TALYS-1.0 code for low energy accelerators[22]. The target thickness was determined using SRIM code[23]. Production yield was calculated using the simulation data via Simpson numerical integral.

TALYS-1.0 is developed to simulate nuclear reactions that involve n, photons, p, d, t, and He ions, in 1 keV–200 MeV energy region and for target nuclides of A≥12. Several optical potential models

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were used to protons. The cross section was calculated using the exciton model for equilibrium and pre-equilibrium emission of protons. For d, t, and ^{4}He ions, a simplification of the folding approach of Watanabe was used[24,25].

3 Results and discussion

3.1 ^{109}Cd production *via* ^{nat}Ag(p,n)^{109}Cd

According to the TALYS simulation, beneficial proton energies to produce ^{109}Cd from ^{nat}Ag target are 5–30 MeV, with a maximum cross section of 210.49 mb at 9 MeV. Radionuclide impurity of considerable half-life is not predicted in the energy range. To minimize production of inactive impurities, proton energy can be 15 MeV, at which the ^{109}Cd yield reduces negligibly, while the ^{103}Pd impurity production has a maximum cross section of 28.22 mb in 15–30 MeV energy range. Incident protons can be 8 MeV to avoid producing any isotopic impurity.

Using an enriched target increases the cross sections by a factor of 2 (431.16 mb) with 4–15 MeV protons.

The SRIM results indicated that the target thickness of 42.95 μm and a geometry 6° of beam incidence agreed with the optimum energy range of 4–15 MeV (Fig.1).

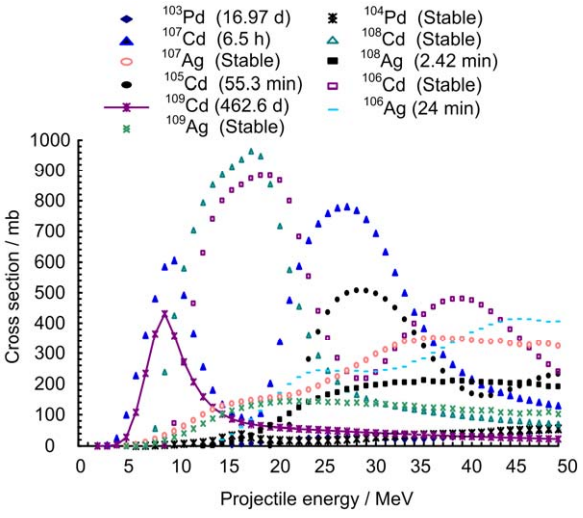

Fig.1 Excitation function of ^{109}Ag(p,n)^{109}Cd (TALYS 1.0).

3.2 ^{109}Cd production *via* ^{nat}Ag(d,2n)^{109}Cd

Usable incident deuteron energy range to produce ^{109}Cd *via* bombardment of a natural silver target is 7 to 50 MeV. Cd isotopic impurities occur in all the energy range. At 13 MeV of incident energy, the impurity is just ^{110}Cd, while deuterons of >15 MeV produces ^{106}Ag, which decays to ^{106}Pd ($t_{1/2}$= 24 min). The ^{105}Cd ($t_{1/2}$=55 min) impurity, decaying to ^{105}Ag ($t_{1/2}$=41.6 d), is produced by deuterons of >30 MeV. Maximum isomeric cross section of ^{110m}Ag ($t_{1/2}$=249.76 d) is ~14 mb at 12 MeV. The cross section of ^{106m}Ag ($t_{1/2}$=8.46 d) is of 100 mb at 30 MeV and 180 mb at 50 MeV[14]. To avoid production of ^{106m}Ag and ^{108}Cd impurities, an optimum energy range of 5–13 MeV is suggested. Using an enriched target increases the cross sections by a factor of 2. Maximum cross section of ^{109}Cd production is 589.09 mb in 5–13 MeV (Fig.2). Target thickness of 30.20 μm is suggested for the above mentioned beam geometry according to the SRIM simulation.

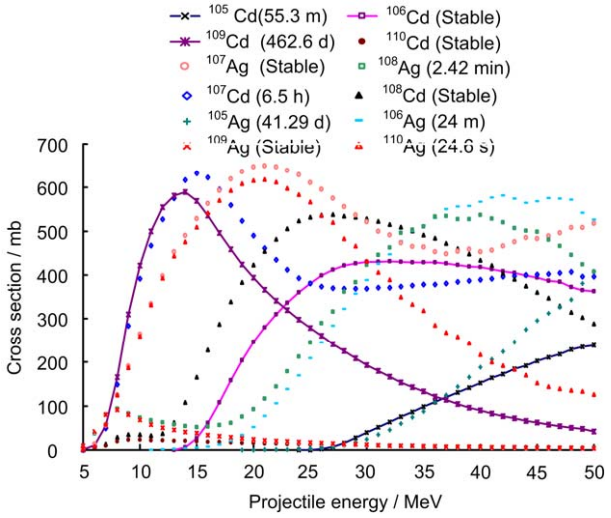

Fig.2 Excitation function of ^{109}Ag(d,2n)^{109}Cd (TALYS 1.0).

3.3 ^{109}Cd production *via* ^{nat}Cd(p,x)^{109}Cd

Cross section for the ^{nat}Cd(p,x)^{109}Cd in 25–50 MeV showed that this reaction is not suitable, due to high cross sections of impurities, even though a maximum of ^{109}Cd cross section is 272.94 mb. An enriched target of ^{110}Cd achieves a higher production yield within a projectile energy boundary. The proton energy can be 15–50 MeV to produce ^{109}Cd. As the cross section does not change noticeably after 30 MeV, an optimum range of 15–27 MeV to decrease cross section of the impurities is suggested, with a maximum cross section to produce ^{109}Cd of 282.88 mb at ~27 MeV. There are Cd isotopic impurities in 15–27 MeV with similar

cross sections of ^{109}Cd (Fig.3).

This reaction has an advantage of simultaneous production of ^{109}In parent nuclei that decay ($t_{1/2}$=4.2 h) to ^{109}Cd. The recommended target thickness is of 100.54 μm, conforming to the SRIM results.

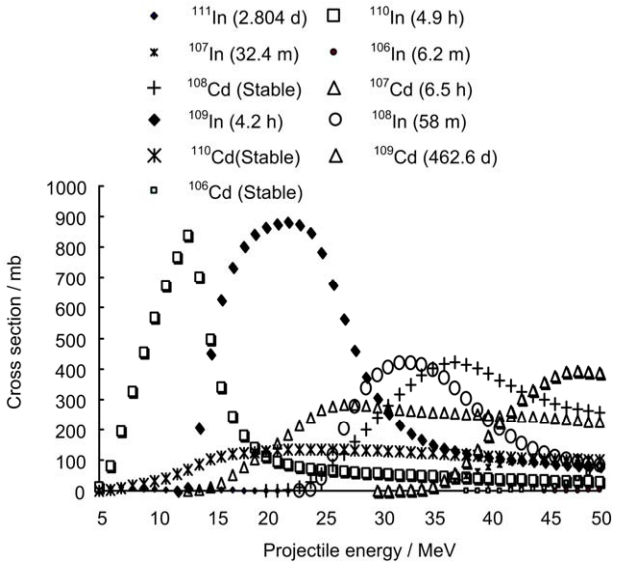

Fig.3 Excitation function of ^{110}Cd(p,pn)^{109}Cd (TALYS 1.0).

3.4 ^{109}Cd production *via* ^{nat}Pd(α,x)^{109}Cd

The excitation function data from TALYS simulation show that bombarding ^{nat}Pd with alpha particles leads to production of isotopic and non-isotopic impurities of equal or higher cross sections comparing with other ^{109}Cd-producing reactions. ^{109}Cd can be produce from two channels of ^{106}Pd and ^{108}Pd of full benefit alpha induced cross section in natural target. Maximum ^{109}Cd production excitation function of α particle on ^{nat}Pd is 283.87 mb at 38 MeV.

Using ^{106}Pd-enriched target causes to produce ^{109}Cd with only impurity of ^{108}Cd in 12–30 MeV regions. To decrease the impurity production, incident energy of 17 MeV can be selected. Maximum cross section of ^{109}Cd production *via* ^{106}Pd(α,x)^{109}Cd is 368.949 mb at 18 MeV (Fig.4).

Also ^{108}Pd-enriched target can be used with full benefit energy range of 26–50 MeV and very high cross sections of up to 1059.98 mb (Fig.5). However, Cd isotopic impurities are produced in all the energy range.

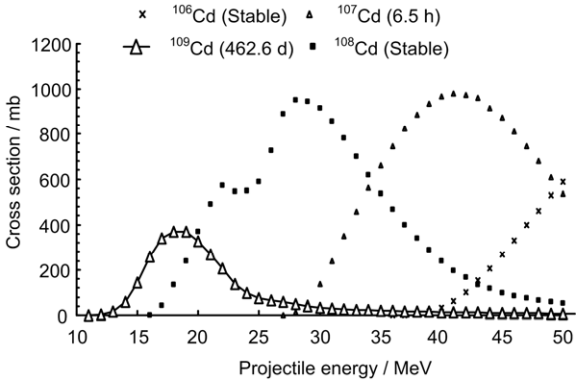

Fig.4 Excitation function of ^{106}Pd(α,n)^{109}Cd (TALYS 1.0).

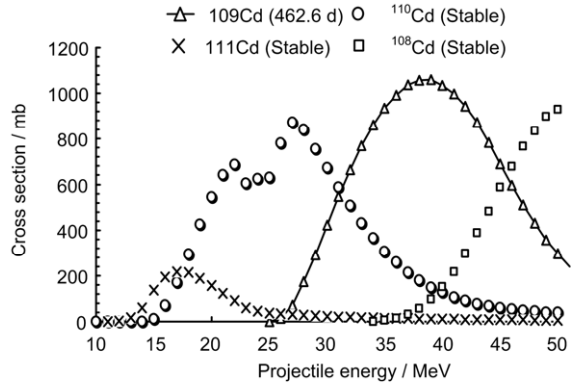

Fig.5 Excitation function of ^{108}Pd(α,3nγ)^{109}Cd (TALYS 1.0).

3.5 ^{109}Cd production *via* ^{nat}In(p,n)^{109}Cd

Natural indium has two isotopes of ^{115}In (95.7%) and ^{113}In (4.3%). By choosing proton energies between 1–50 MeV, ^{109}Cd can be produced *via* just the channel of ^{113}In during irradiation of indium target. However, ^{109}Cd production using natural indium is not possible. Maximum cross section of ^{109}Cd production *via* ^{113}In(p,x)^{109}Cd is only 30.6 mb in 18–50 MeV; whereas impurities of cross section higher than ^{109}Cd can be produced in all the energy range (Fig.6).

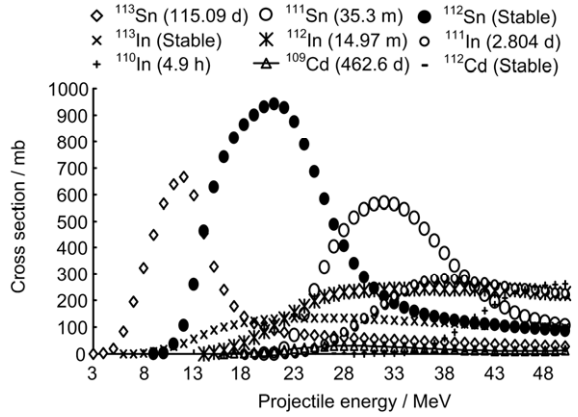

Fig.6 Excitation function of ^{113}In(p,x)^{109}Cd (TALYS 1.0).

3.6 The thick target integral yields

The thick target integral yields were deduced with the simulated cross-sections by using the numerical integral (Simpson method) from Eq.(1)

$$Y=0.102H(1-e^{-\lambda t})I/M\int[\sigma(E)/S_p(E)]dE \quad (1)$$

where Y is the yield (Bq·μA^{-1}·h^{-1}), H is isotope abundance (%), M is the target mass (g), $\sigma(E)$ is cross section (mb), S_p is stopping power (MeV·mg^{-1}·cm^{-2}), I is beam current (μA) and t is bombardment time (h) The calculations (Table 1) predicted that the most attainable yield is from proton bombardment of an enriched ^{110}Cd target (3.15×10^{9} Bq·μA^{-1}·h^{-1}). The minimum yield of ^{109}Cd production is irradiation of ^{113}In (1.30×10^{5} Bq·μA^{-1}·h^{-1}) and ^{106}Pd targets (4.07×10^{5} Bq·μA^{-1}·h^{-1}).

Table 1 ^{109}Cd production yield *via* different nuclear reactions

Reaction	^{109}Ag(p,n)^{109}Cd	^{109}Ag(d,2n)^{109}Cd	^{110}Cd(p,pn)^{109}Cd *	^{106}Pd(α,n)^{109}Cd	^{108}Pd(α,3n)^{109}Cd	^{113}In(p,x)^{109}Cd
Energy range / MeV	15→4	13→5	15→27	12→17	26→50	18→50
Target thickness / μm	42.95	30.20	100.54	2.31	28.62	461.14
Theorical yield / MBq·μA^{-1}·h^{-1}	0.225	0.218	0.229	0.011	0.377	0.129
Isotopic abundance / %	48.16	48.16	12.24	27.33	26.46	4.3

Proton irradiation of an enriched ^{110}Cd target lead to produce ^{109}In nuclei parent of 0.0032 mCi·μA^{-1}·h^{-1} yield, so total yield of ^{109}Cd *via* ^{110}Cd(p,x)^{109}Cd reaction will be 0.0113 mCi·μA^{-1}·h^{-1} (0.418 MBq·μA^{-1}·h^{-1}).

3.7 TALYS 1.0 code and experimental data

The TALYS 1.0 simulation results were compared with the experimental excitation functions in several channels of ^{109}Cd production. Average error between the experimental and simulated excitation functions of deuteron was about 25%. The average error of proton excitation functions of ^{109}Ag(p,n)^{109}Cd and ^{109}Ag(d,2n)^{109}Cd were less than 15% (as seen in Figs.7 and 8).

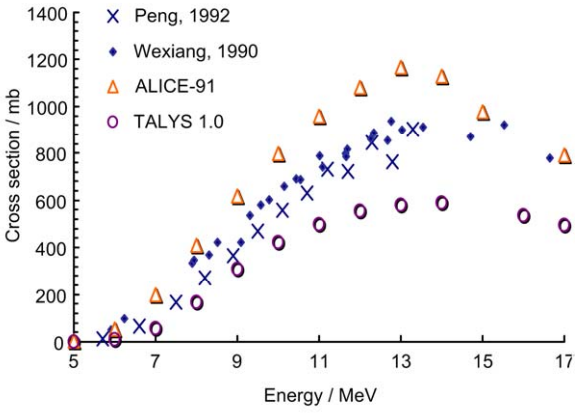

Fig.7 Excitation function of ^{109}Ag(p,n)^{109}Cd reaction from experimental data, TALYS-1.0 and ALICE-91.

The simulated production yield of 0.090 MBq·μA^{-1}·h^{-1} for 4–15 MeV proton bombardment is 27% larger than the yield in Ref.[26] (0.071 MBq·μA^{-1}·h^{-1}) measured with ^{nat}Ag target, but it is in an better agreement with the experimental result in Ref.[11], where a function had a yield of 0.077 MBq·μA^{-1}·h^{-1} with SD of 7% being fitted to the data.

Experimental data for comparing the other simulated cross sections were not available.

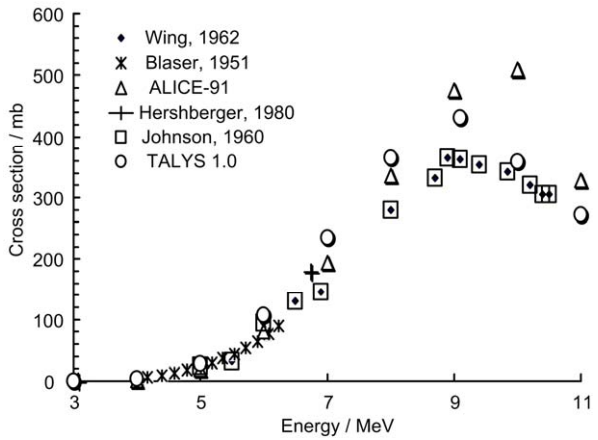

Fig.8 Excitation function of ^{109}Ag(d,2n)^{109}Cd reaction from experimental data, TALYS-1.0 and ALICE-91.

4 Conclusion

Theoretical ^{109}Cd yield *via* ^{110}Cd(p,x)^{109}Cd nuclear reaction was 0.418 MBq·μA^{-1}·h^{-1}. That is higher than

theoretical yield of ($p+^{109}Ag$), ($d+^{109}Ag$), ($\alpha+^{106}Pd$), ($\alpha+^{108}Pd$) and ($p+^{113}In$) reactions. However, utilization necessity of the enriched target suggests that this reaction is not a practical economic alternative to produce ^{109}Cd. In addition, this nuclear reaction do not provide a carrier free ^{109}Cd product. Theoretical yield of ^{109}Cd production *via* proton and deuteron bombardment of ^{109}Ag target is about 46% less than ^{110}Cd target. Nevertheless, excellent thermal conductivity of silver, easy electroplating of it and its two isotopically natural targets is of advantages that make it as a suitable reaction to routine production of ^{109}Cd. In addition, proton irradiation of an Ag target is able to produce non-carrier-added ^{109}Cd in the determined energy range.

References

1 Firestone R B. Table of Isotopes. Version 1.0 Wiley-Interscience, 1996.

2 Fleming D E B, Forbes T A. Appl Radiat Isot, 2001, **55:** 527–532.

3 Arfelli F, Barbiellini G, Bonvicini V, *et al.* Nucl Instrum Methods Phys Res A, 1995, **367:** 48–53.

4 Lad S M, Kane P P. Instrum Methods Phys Res B, 1988, **34:** 113–117.

5 Gupta D, Chatterjee J M, Ghosh R, *et al.* Appl Radiat Isot, 2007, **65:** 512–516.

6 Mansur M S, Mustuq A, Mohammad A. Radioanal Nucl Chem, 1995, **20:** 205–211.

7 Albert R D. Phys Rev, 1959, **115:** 925–927.

8 Goetz L, Sabbioni E, Marafanti E, *et al.* Radiochem Radioanal Letts, 1980, **45:** 51–59.

9 Hassbroek F J, Burdzik G F, Cogneau M, *et al.* Excitation functions and thick-target yields for Ga-67, Ge-68/Ga-68, Cd-109 and In-111 induced in natural zinc and silver by 100 MeV alpha particles, Rep. 91, Council of Scientific and Industrial Research, Pretoria (CSIR-FIS-91), 1976.

10 Read J B J, Miller J M. J Phys Rev B, 1965, **140:** 623–630.

11 Wing J, Huizenga J R. Phys Rev, 1962, **128:** 280–290.

12 Johnson C H, Galonsky A, Inskeep C N. Cross sections for (p,n) reactions in intermediate-weight nuclei. ORNL–2910**,** 1960, 25–28.

13 Blaser J P, Boehm F, Marmier P, *et al.* Int J Helv Phys Acta, 1951, **24:** 3–8.

14 Uddin M S, Baba M, Hagiwara M, *et al.* Appl Radiat Isot, 2006, **64:** 1013–1019.

15 Weixiang Y, Hanlin L, Wenrong Z, *et al.* The excitation functions of the ^{107}Ag(d,2n) and (d,p) reactions. Progress Report for Beijing National Tandem Accelerator Laboratory, 1989.

16 Rohm H F, Steyn J, Rautenbach W L, *et al.* Inorg Nucl Chem, 1970, **32:** 1413–1417.

17 Dmitriev P P, Krasnov M N, Molin G A. Yadernie Konstanti, 1982, **44:** 38–43 (in Russian).

18 Long X, Peng X, He F, *et al.* Appl Radiat Isot, 1991, **42:** 1234–1236.

19 Peng X, Xianguan L, He F, *et al.* Nucl Instrum Methods B, 1992, **68:** 145–148.

20 Tarkanyi F, Kiraly B, Ditroi F, *et al.* Nucl Instrum Methods B, 2006, **245:** 379–394.

21 Nortier F M, Mills S J, Steyn G F. Appl Radiat Isot, 1991, **42:** 1105–1107.

22 Koning A J, Hilarie S, Duijvestijn M. A nuclear reaction program. TALYS 1.0. NRC-Nuclear Research and Consultancy Group, 2007.

23 Ziegler J F, Biersack J P, Littmark U. The stopping and range of ions in matter. SRIM code. NY (USA): 2006.

24 Watanabe S. Nucl Phys, 1958, **8:** 484–492.

25 Madland D G. In proceedings of a specialists' meeting on pre-equilibrium nuclear reactions, Austria, 1988, 103.

26 Landini L, Osso Jr J A. J Radioanal Nucl Chem, 2001, **250:** 429–431.