FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 7 No. 2, April, 2023, pp 121 - 124
DOI: https://doi.org/10.33003/fjs-2023-0702-1718

PROGRESS IN NICKEL TARGET DESIGNS FOR DEUTERON IRRADIATION: A MILESTONE IN RADIOISOTOPE PRODUCTION OPTIMIZATION

***Ahmed Rufai Usman, and Ibrahim Abdullahi Lawal**

Department of Physics, Umaru Musa Yar'adua University, Katsina, Nigeria

*Corresponding authors' email: ahmedrufai.usman@umyu.edu.ng Phone: +2348038681477

ABSTRACT

Medical radioisotopes play significant roles in nuclear medicine, particularly in tumor diagnosis and its therapy. Optimization in production of these important isotopes is very essential for the overall health of the target patients. In this work, we analyzed general trends in the use of various forms of nickel metal as target for radioisotopes production in nuclear accelerators. A careful study of all previously used forms of nickel metal in the literature up to 2016 indicate that different physical forms of the metal, such as its very high purity and impure forms, alloys, compounds and powdered forms have, over the years, been used for various radioisotope productions under deuteron irradiation route, each providing different production effect. The excitation functions of several useful radioisotopes could be studied under deuteron irradiation of nickel. In a recent experimental work by the authors, some very pure, thin nickel foils of natural isotopic composition were also used in form of stacked arrangement for deuteron irradiation. The study found that most of the recent studies on radioisotopes production cross sections use very high purity and solid nickel forms.

Keywords: Nickel, targets, deuteron, cross section, radioisotopes

INTRODUCTION

Since the early days of nuclear physics, variety of targets have been used for radioisotopes production in different bombarding machines such as the nuclear reactors, linear accelerators and cyclotrons. For the production of medical radioisotopes from charged particle-induced reactions, cyclotron is usually preferred over the linear accelerator (linac), although the linac and other accelerators may also be efficient with the development of smaller, more reliable machines (IAEA, 2008). In general, charged-particle accelerators produce hundreds of radioisotopes which found variety of applications, ranging from multitude industrial usage to several in nuclear medicine.

Several radioisotopes production routes are available and each have been making tremendous progress over the years. Since proton is the most commonly used projectile for the radioisotopes production and is well established(Usman et al., 2016b), many advanced hospitals have proton-only cyclotron for diagnosis and treatment of patients. Targets used in proton-only cyclotrons and other radioisotopes production machines are more optimized relative to deuteron irradiated target for obvious reasons. The use of deuteron as irradiation tool has gradually been progressing. Various experimentalist used varieties of targets in different machines for production of radioisotopes of interest. The major purpose is to optimize the radioisotope production or to produce varieties ofradioisotopes for multiple applications from the same facility.

On the other hand, Ni has been in use as a very good irradiation target material for the production of radioisotopes in nuclear accelerators (or cyclotrons), leading to medical and industrial applications. Many radioisotopes including those of Co, Cu, Cr, Mn, and Ni have been produced via Ni irradiation (Usman et al., 2016a). The productions are under optimum irradiations and measurements conditions since some of these radioisotopes have very short half-lives. Co radioisotopes such as ^{55,56,57}Co found potential applications in medicine and other basic research fields due to their suitable decay characteristics (Heinle et al., 1952; Lagunas-Solar and Jungerman, 1979). In general, there are large number of potential applications of produced radionuclides from nickel target bombardment.

In any irradiation technique, one of the major challenges is to put the target at the best possible position for the optimized production. This is owing to the fact that radioisotope production facilities are not the same design. A designed target for one cyclotron may thus not be suitable to another. Target design is thus an important factor in linac and cyclotron. The purpose of this manuscript is thus to review and highlight the major progress in the targets design for deuteron irradiation of nickel targets from the early days of measurable nuclear reactions to 2016. The forms of nickel targets used in a facility may be an influential factor to the produced or measured yields of radioisotopes in that facility. Furthermore, nickel plays important role not only as a source of radioisotopes of medical importance, but also in nuclear technology and has thus recently been given a priority over some other metals by IAEA coordinated project on Nuclear Data Library (for Advanced Systems - Fusion Devices) (FENDL-3) (Amjed et al., 2013).

Nickel Targets for Deuteron Irradiation

An extensive survey of literature on previous experimental data shows that several works(Amjed et al., 2013; Baron and Cohen, 1963; Blann and Merkel, 1963; Brinkman et al., 1977; Budzanowski et al., 1963; Cline, 1971; Coetzee and Peisach, 1972; Cogneau et al., 1967; Fuying et al., 1983; Hermanne et al., 2013; Hermanne et al., 2007; Jung, 1992; Ochiai et al., 2007; Takács et al., 1997; Takács et al., 2001; Takács et al., 2007; Usman et al., 2016a; Zweit et al., 1991)in the past have used various forms of nickel (powder, metallic oxide or solid metals) as targets for deuteron irradiation to produce radioisotopes of interest. Tracing the earliest works in EXFOR database, 3 sets of independent studies were reported in 1963 on cross section measurement from nickel bombardment by deuteron beam.

The work of Blann and Merkel(1963) was the first to report the experimental cross sections of ^{57}Ni, $^{55\text{-}57}$Co and ^{55}Fe radioisotopes from deuteron irradiation of nickel. A closer look on the experimental details of Blann's group revealed that the authors measured the activities of the reported radioisotopes using, among other detectors, sodium iodide crystal detector (NaICR). It has been observed that the decay data of the investigated radioisotopes have been going through several updates over the years, in contrast to the data used by the group as at that time, even though the literature data found in Exfor database (Otuka et al., 2014) did not explicitly state the decay data used by the group.

The second observed work on this subject in the same 1963 was the reported work by Budzanowski's group (Budzanowski et al., 1963) which reported only ^{61}Cu radioisotope. The work was performed using a 120-cm cyclotron of the Institute of Nuclear Physics at Cracow, with a single metal foil and therefore a single data of cross-section at an energy of 12.8 MeV.

Similarly, Baron's group (Baron and Cohen, 1963) reported to have used deuteron beam on nickel within the same period. The available literature data indicate several metallic targets, in addition to Ni, were used as targets material for the irradiation in either powdered or solid metal form but does not clearly state the form of nickel target (powder or foil) used. The literature however clearly stated that the group employed both ^{27}Al and ^{209}Bi foils to serve as monitors. The other metals used in the experiments along with the nickel were gallium, lanthanum and indium targets.

Slowly, after 1963, the use of nickel as a target for deuteron bombardment for radioisotopes production gradually attracts greater attentions from various research groups, especially due to growing interest in the radiation technology and also due to more potential of the investigated radioisotopes. Detailed information on the application potentials of the measured radioisotopes from deuteron-induced nuclear reactions on nickel can be found in another publication (Usman et al., 2016a). Recently, especially around the year 2000 to date, more investigations using nickel as a target are observed.

A comprehensive survey of available literature data, comprising the authors and publication year, the method used, target information and other useful experimental details have been summarised and tabulated in Table 1.

Table 1. Summary of all previous studies on deuteron irradiated nickel targets and experimental details up to 2016

Author	Facility, Method	Target used	Beam Current, Monitor	Activity separation, Detector	Incident Energy (MeV)	RI reported, data points;
Blann+, 1963	Cyclotron,	Nat Ni	NS*	RadioChem, NaICR	24	^{57}Ni, 24; ^{55}Co, 22;
Budzanowski+, 1963.	Cyclotron,	enrich Ni	Faraday Cup	GM counter	12.8	^{61}Cu, 1
Baron+, 1963	Cyclotron, Stack	Elemental and Comp.	Faraday Cup, $^{27}Al(d,P+A)^{24}Na$, $^{209}Bi(d,p)^{210}Bi$	GM counter	18.8	^{57}Ni, 1; ^{55}Co, 1;^{59}Fe, 1
Cogneau+ ,1967	Cyclotron, NS*	From electrolysis of NiCl, NiN03	NS*, NS*	GM counter	12	^{61}Cu, 25; ^{57}Ni, 20
Cline., 1971	Cyclotron, Stack	enriched Ni electroplated on Au	Faraday Cup	NaICR, Ge(Li)	40	Several
Coetzee+, 1972	VDG (3SAFSUN)	enriched Ni electroplated onTa	Faraday Cup	NaICR, Ge(Li)	5.5	^{61}Cu
Brinkman+, 1977	Synchrocylo, stack foils	Ni foils	Faraday Cup	Ge(Li)	50.6	
Zhu Fuying, 1981	Cyclotron, stacked foils	Ni foils	Faraday cup	Ge(Li) det.	14.7	$^{55,56}Co$, ^{57}Ni
P.P Dmitriev+, 1983	Cyclotron, TTY*Measurement.	Thick Ni	$^{27}Al(d,PA)^{24}Na$	Ge(Li) det.	22	TTY for ^{55}Fe
Jung., 1987	Cyclotron, soldered foils on Cu bar	Ni foils andAlloy	Heating power on Cu bar	NS*	14 and 9	$^{56\text{-}58}Co$
Zwait +, 1991	Cyclotron, stacked foils	Ni foils, Enriched powered ^{64}Ni	Charge integration	Ge(Li)	18.9	^{57}Ni, $^{55\text{-}58}Co$
Takacs+, 1997	Cyclotron, stacked foils	Ni foils	Faraday cup, $^{27}Al(d,x)^{24}Na$	HPGe Det.	20.3	$^{55\text{-}58}Co$, ^{57}Ni,$^{60,61}Cu$
Takacs+, 2001	Cyclotron, stacked foils	Ni foils	Faraday cup,$^{nat}Ti(d,x)^{23}V$, $^{27}Al(d,x)^{24}Na$	Not stated	50 and 30	$^{61,64}Cu$, $^{56,57}Ni$,$^{55\text{-}58}Co$
Hermanne+, 2007	Cyclotron, stacked foils	Ni foils	Faraday cup $^{nat}Ti(d,x)^{48}V$	No Chemical separation γ, HPGe Det.	20.4	$^{61,64}Cu$;
Ochiai+, 2007	Cyclotron, NS*	Ni foils	Faraday cup, $^{27}Al(d,x)^{24}Na$	HPGe Det.	47.8	$^{55\text{-}57}Co$, $^{60,61}Cu$
Amjed+, 2013,	Cyclotron, stacked foils	Ni foils, NiBSi alloy	Faraday cup, $^{27}Al(d,x)^{24}Na$	HPGe Det.	40	$^{56,57}Ni$, $^{55\text{-}58}Co$ etc
Hermanne+, 2013	Cyclotron, stacked foils	Ni foils and Ga-Ni Alloy electroplated on Au	$^{nat}Ti(d,x)^{23}V$, $^{27}Al(d,x)^{24}Na$	HPGe Det.	50 and 20	$^{52,56}Mn$,$^{55\text{-}58}Co$ etc
Usman+, 2016	Cyclotron, stacked foils	Ni foils	Faraday cup,$^{nat}Ti(d,x)^{48}V$	HPGe Det.	24	^{57}Ni, $^{55\text{-}58,60}Co$ and ^{61}Cu

TTY* – Thick Target Yield, NS* – Not Stated in Exfor database.

CONCLUSION

This work studied and reviewed the various forms of nickel targets used by several researchers under deuteron irradiation route for the production of radioisotopes of medical and industrial applications. The present work shows detailed experimental parameters, measurement procedures as well as the radioisotopes measured by the previous studies. It is evident that over the years, there has been increasing interest in targets designs following the corresponding gradual improvements in the generations of irradiating beams as well as enhanced designs of linear accelerators and cyclotrons. Using very extremely pure targets for irradiation, the yield of the produced radioisotopes would greatly be optimized. This would reduce the observed discrepancies in cross sections and in turn, a better understanding of excitation functions.

REFERENCES

Amjed, N., Tarkanyi, F., Ditroi, F., Takacs, S., Yuki, H., 2013. Activation cross-sections of deuteron induced reaction of natural Ni up to 40 MeV. Applied Radiation and Isotopes 82, 87-99.

Baron, N., Cohen, B.L., 1963. Activation cross-section survey of deuteron-induced reactions. Physical Review 129, 263-2642.

Blann, M., Merkel, G., 1963. Reactions Induced in Ni 58 with 0-24 MeV Deuterons: Statistical Model Analysis. Physical Review 131, 764.

Brinkman, G.A., Helmer, J., Lindner, L., 1977. Nickel and copper foils as monitors for cyclotron beam intensities. Radiochim. Radioanal. Letters 28, 9 – 20.

Budzanowski, A., Freindl, L., Grotowski, K., Rzeszutko, M.M., Slapa, M., Szmider, J., Hodgson, P.E., 1963. Elastic scattering and total reaction cross-sections for the interaction of 12.8 MeV deuterons with 12C, 58Ni, 60 Ni and 209Bi nuclei. Nuclear Physics 49, 144-160.

Cline, C.K., 1971. Reaction mechanisms and shell structure effects in 54Fe+6Li and 58Ni+d reactions at medium energies. Nuclear Physics A 174, 73-96.

Coetzee, P.P., Peisach, M., 1972. Activation cross sections for deuteron-induced reactions on some elements of the first transition series, up to 5.5 MeV. Radiochimca Acta 17, 1-6.

Cogneau, M., Gilly, L.J., Cara, J., 1967. Absolute cross sections and excitation functions for deuteron-induced reactions on the nickel isotopes between 2 and 12 MeV. Nuclear Physics A 99, 686-694.

Fuying, Z., Zhenlan, T., Zhenxia, W., 1983. Measurements of Excitation Functions for ^{56}Ni (d, α), ^{58}Ni (d, αn) and ^{58}Ni (d, t). Chin. J. Nucl. Phys. 5, 166.

Heinle, R.W., Welch, A.D., Scharf, V., Meacham, G.C., Prusoff, W.H., 1952. Studies of excretion (and absorption) of ^{60}Co labeled vitamin B12 in pernicious anemia. Transactions of the Association of American Physicians 65, 214-222.

Hermanne, A., Takács, S., Adam-Rebeles, R., Tárkányi, F., Takács, M.P., 2013. New measurements and evaluation of database for deuteron induced reaction on Ni up to 50 MeV. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 299, 8-23.

Hermanne, A., Tárkányi, F., Takács, S., Kovalev, S.F., Ignatyuk, A., 2007. Activation cross sections of the ^{64}Ni(d,2n) reaction for the production of the medical radionuclide ^{64}Cu. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 258, 308-312.

IAEA, 2008. Cyclotron Produced Radionuclides: Principles and Practice. International Atomic Energy Agency, Vienna, Austria.

Jung, P., 1992. Cross sections for the production of helium and long-living radioactive isotopes by protons and deuterons, Nuclear data for science and technology. Springer, pp. 352-354.

Lagunas-Solar, M.C., Jungerman, J.A., 1979. Cyclotron production of carrier-free cobalt-55, a new positron-emitting label for bleomycin. The International Journal of Applied Radiation and Isotopes 30, 25-32.

Ochiai, K., Nakao, M., Kubota, N., Sato, S., Yamauchi, M., Ishioka, N., Nishitani, T., Konno, C., 2007. Deuteron induced activation cross section measurement for IFMIF, International Conference on Nuclear Data for Science and Technology. EDP Sciences, pp. 1011-1014.

Otuka, N., Dupont, E., Semkova, V., Pritychenko, B., Blokhin, A.I., Aikawa, M., Babykina, S., Bossant, M., Chen, G., Dunaeva, S., Forrest, R.A., Fukahori, T., Furutachi, N., Ganesan, S., Ge, Z., Gritzay, O.O., Herman, M., Hlavac, S., Kato, K., Lalremruata, B., Lee, Y.O., Makinaga, A., Matsumoto, K., Mikhaylyukova, M., Pikulina, G., Pronyaev, V.G., Saxena, A., Schwerer, O., Simakov, S.P., Soppera, N., Suzuki, R., Takacs, S., Tao, X., Taova, S., Tarkanyi, F., Varlamov, V.V., Wang, J., Yang, S.C., Zerkin, V., Zhuang, Y., 2014. Towards a More Complete and Accurate Experimental Nuclear Reaction Data Library (EXFOR): International Collaboration Between Nuclear Reaction Data Centres (NRDC). Nuclear Data Sheets 120, 272-276.

Takács, S., Sonck, M., Azzam, A., Hermanne, A., Tárkányi, F., 1997. Activation Gross Section Measurements of Deuteron Induced Reactions on nat Ni with Special Reference to Beam Monitoring and Production of for 61Cu Medical Purpose. Radiochimica Acta 76, 15 - 24.

Takács, S., Szelecsényi, F., Tárkányi, F., Sonck, M., Hermanne, A., Shubin, Y., Dityuk, A., Mustafa, M.G., Youxiang, Z., 2001. New cross-sections and intercomparison of deuteron monitor reactions on Al, Ti, Fe, Ni and Cu. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 174, 235-258.

Takács, S., Tárkányi, F., Király, B., Hermanne, A., Sonck, M., 2007. Evaluated activation cross sections of longer-lived radionuclides produced by deuteron induced reactions on natural nickel. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 260, 495-507.

Usman, A.R., Khandaker, M.U., Haba, H., Murakami, M., Otuka, N., 2016a. Measurements of deuteron-induced reaction cross-sections on natural nickel up to 24 MeV. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 368, 112-119.

Usman, A.R., Khandaker, M.U., Haba, H., Otuka, N., Murakami, M., Komori, Y., 2016b. Production cross-sections of radionuclides from α-induced reactions on natural copper up to 50MeV. Applied Radiation and Isotopes 114, 104-113.

Zweit, J., Smith, A.M., Downey, S., Sharma, H.L., 1991. Excitation functions for deuteron induced reactions in natural nickel: Production of no-carrier-added ^{64}Cu from enriched ^{64}Ni targets for positron emission tomography. International Journal of Radiation Applications and Instrumentation. Part A. Applied Radiation and Isotopes 42, 193-197.