Target needs for neutron-induced charged-particle reactions at LANSCE

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In general: Isotope production and/or separation, target fabrication, characterization

- For (n,z) measurements need relatively thin (typ. ~1 ug/cm^2 to 1 mg/cm^2), with uniform deposition area (or self-supported targets always ideal). Becomes more challenging when fabricating radioactive or rare isotope targets due to the need for efficient chemistry and deposition methods.
- Exploring a variety of techniques such as thermal evaporation, microjet printing, electro-spraying, electro-deposition, *etc*., with the Isotope Team at LANL (V. Mocko, C.E. Vermeulen), K. Manukyan at Notre Dame, S. Essenmacher (from MSU, now at LANL)…
- Not just fabricating the targets, but need to characterize mass, uniformity, purity, *etc*.

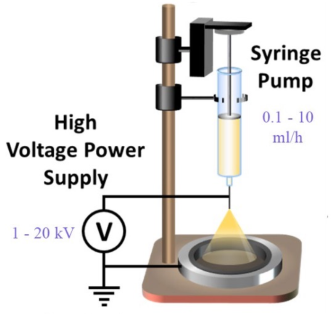
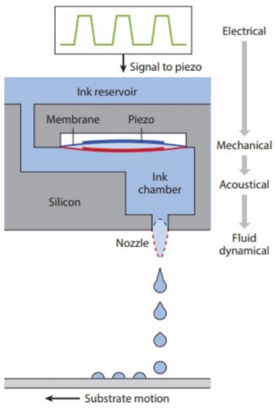
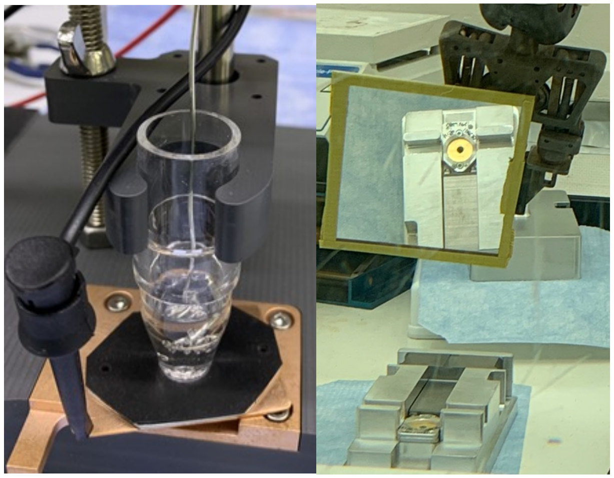


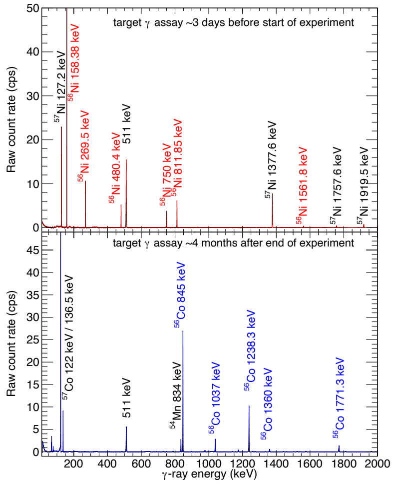
Figure 1. Schematics of the electrospraying setup

S. Dede, K. Manukyan *et al.* *Nucl inst. Methods in PR.A* Volume 1055, October 2023, 168472



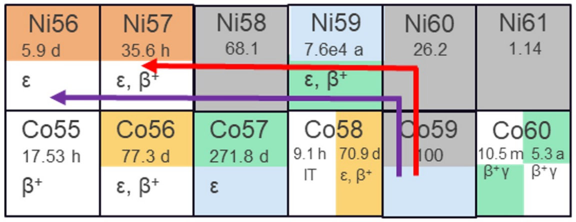
Microjet printing, included in the thesis work by S. Essenmacher (MSU), publication in preparation





Measurement of ^{56}Ni(n,z) at WNR with a radioactive target from the Isotope Production Facility (IPF) and the Hot-Cell Facility (LANL LDRD)

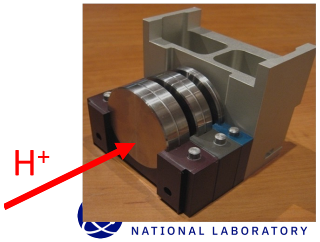
- Production of ^{56}Ni ($T_{1/2}$ ~ 6 days) tested at multiple beam energies to optimize purity
- Optimization of chemical separation and target fabrication inside hot-cell
- Significant coordination required between start of experiment (alignment and background measurements initiated at WNR, simultaneously with the start of ^{56}Ni production at IPF)
- Any time lost means less ^{56}Ni and the build up of impurities prior to neutron beam on target

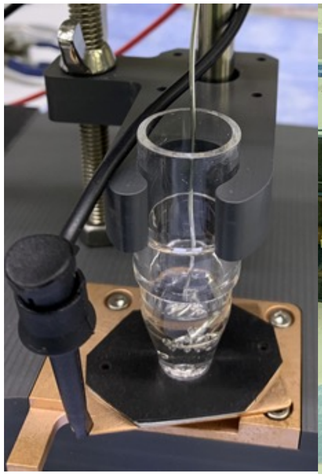


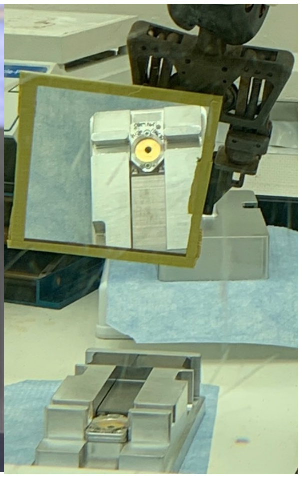
Ni56	Ni57	Ni58	Ni59	Ni60	Ni61
5.9 d ε	35.6 h ε, β⁺	68.1	7.6e4 a ε, β⁺	26.2	1.14
Co55 17.53 h β⁺	Co56 77.3 d ε, β⁺	Co57 271.8 d ε	Co58 9.1 h IT 70.9 d ε, β⁺	Co59 100	Co60 10.5 m β⁺γ 5.3 a β⁺γ

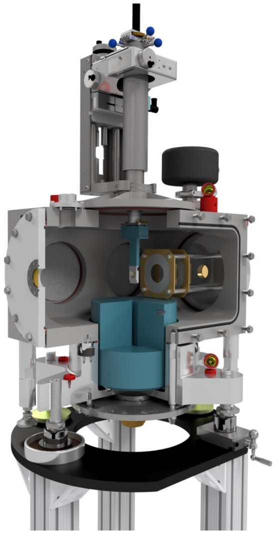
^{59}Co (p, 4n) ^{56}Ni

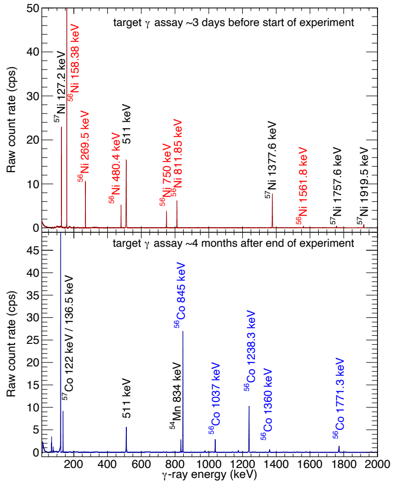
^{59}Co (p, 3n) ^{57}Ni





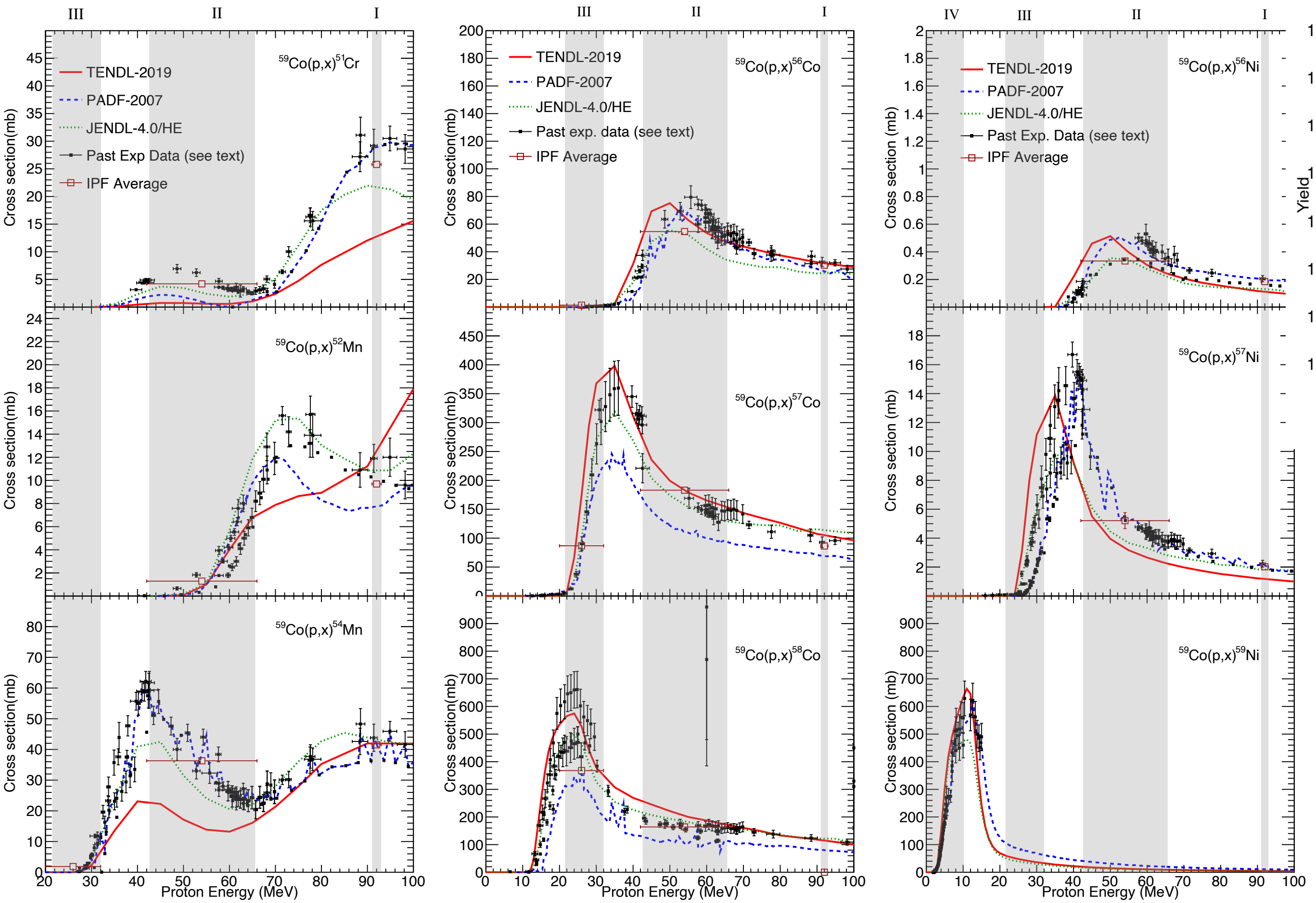


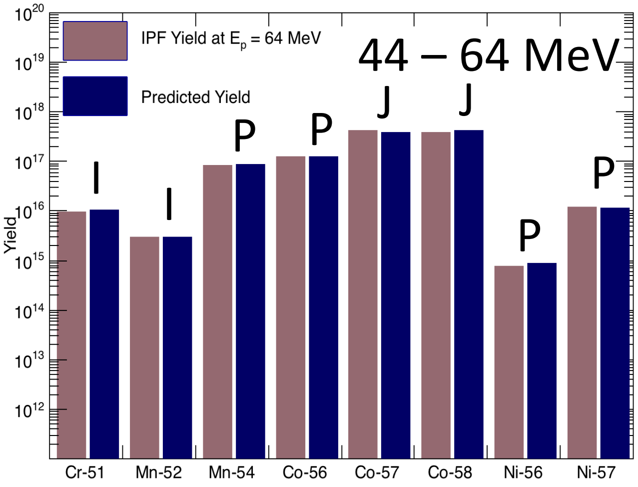




Test Production of ^{56}Ni and ^{59}Ni at IPF and UW Madison:

I: 92 MeV, II: 44-64 MeV, III: 22-31 MeV, IV: 0-10 MeV

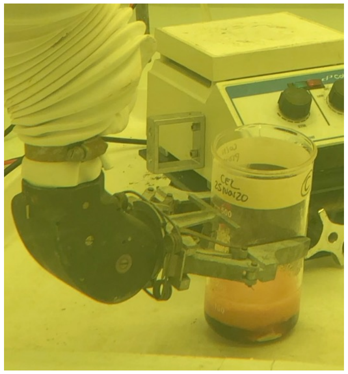




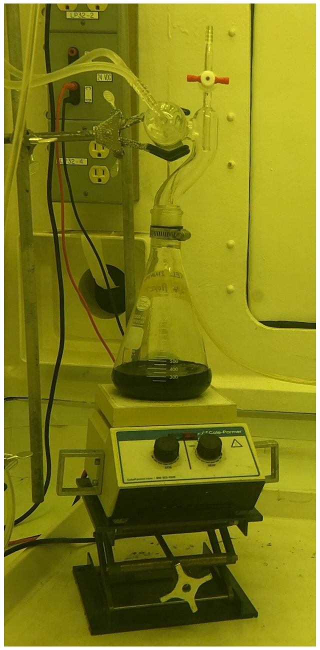
- Integral validation of charged particle evaluations and
- Optimize production of ^{56}Ni relative to other isotopes.
- Baseline for chemical separation studies.

Isolation of ^{56}Ni from irradiated Cobalt Targets

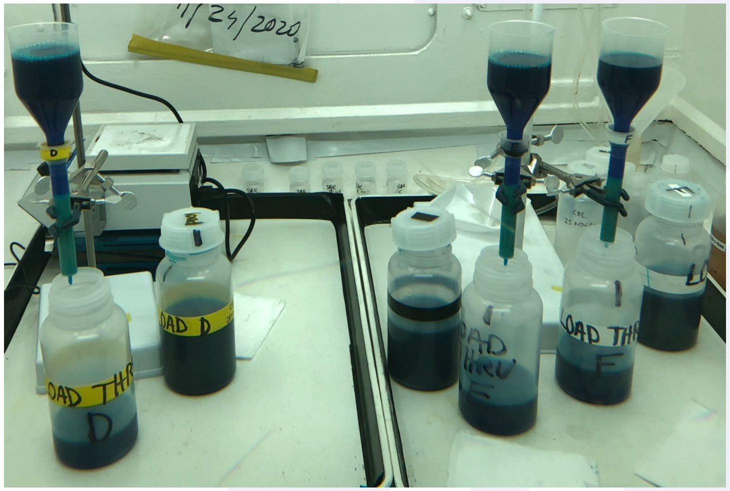
^{59}Co(p, 4n) ^{56}Ni, $t_{1/2}$ = 6.075 days
45.8 g Co metal



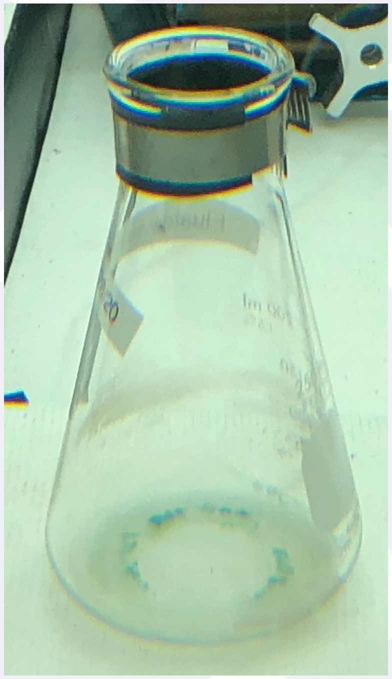
Dissolution



Distillation



Co removal – 6 column in parallel in 2 hot cells

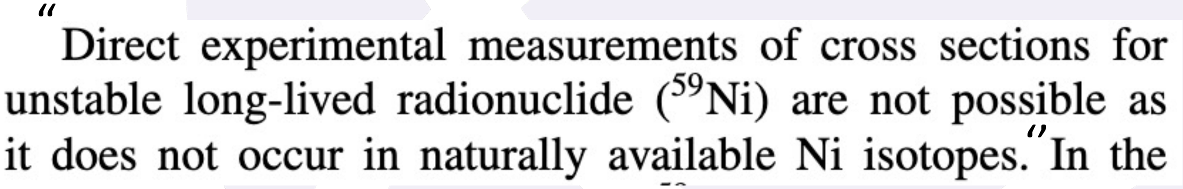


Residue after first separation

Slide reproduced from V. Mocko (LANL) WANDA 2022

Gas production on long-lived radioactive ^{59}Ni

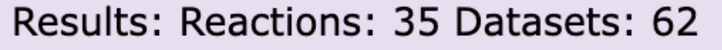
- A well-known case of a long-lived radioisotope of nickel that can build up from ^{58}Ni(n,g) in typ. reactors and from ^{60}Ni(n,2n) in fusion environments
- Long half-life (~100k years) and large positive Q-values (+ 5.1 MeV for ^{59}Ni(n,a) and +1.9 MeV for ^{59}Ni(n,p)) can make it a sig. driver of further energy production
- Background reaction for our study of ^{56}Ni but reported ^{59}Ni(n,p) and ^{59}Ni(n,a) cross sections up to ~ 10 MeV: https://doi.org/10.1103/PhysRevC.105.044608
- Only other available data in EXFOR at fusion energies of interest was derived using an indirect surrogate ratio method, for which the authors stated:



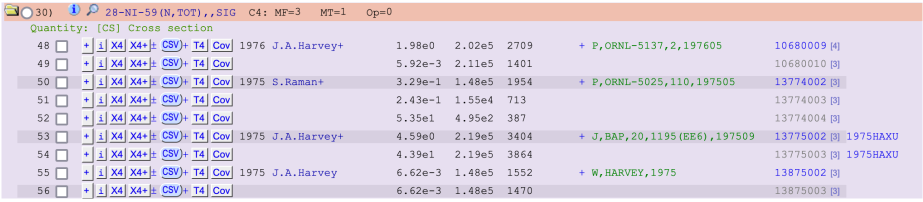
“Direct experimental measurements of cross sections for unstable long-lived radionuclide (^{59}Ni) are not possible as it does not occur in naturally available Ni isotopes.”In the

J. Pandey Phys. Rev. C 99, 014611

A search for ^{59}Ni(n,*) on EXFOR:



Results: Reactions: 35 Datasets: 62



○ 30) 28-NI-59(N,TOT),,SIG C4: MF=3 MT=1 Op=0

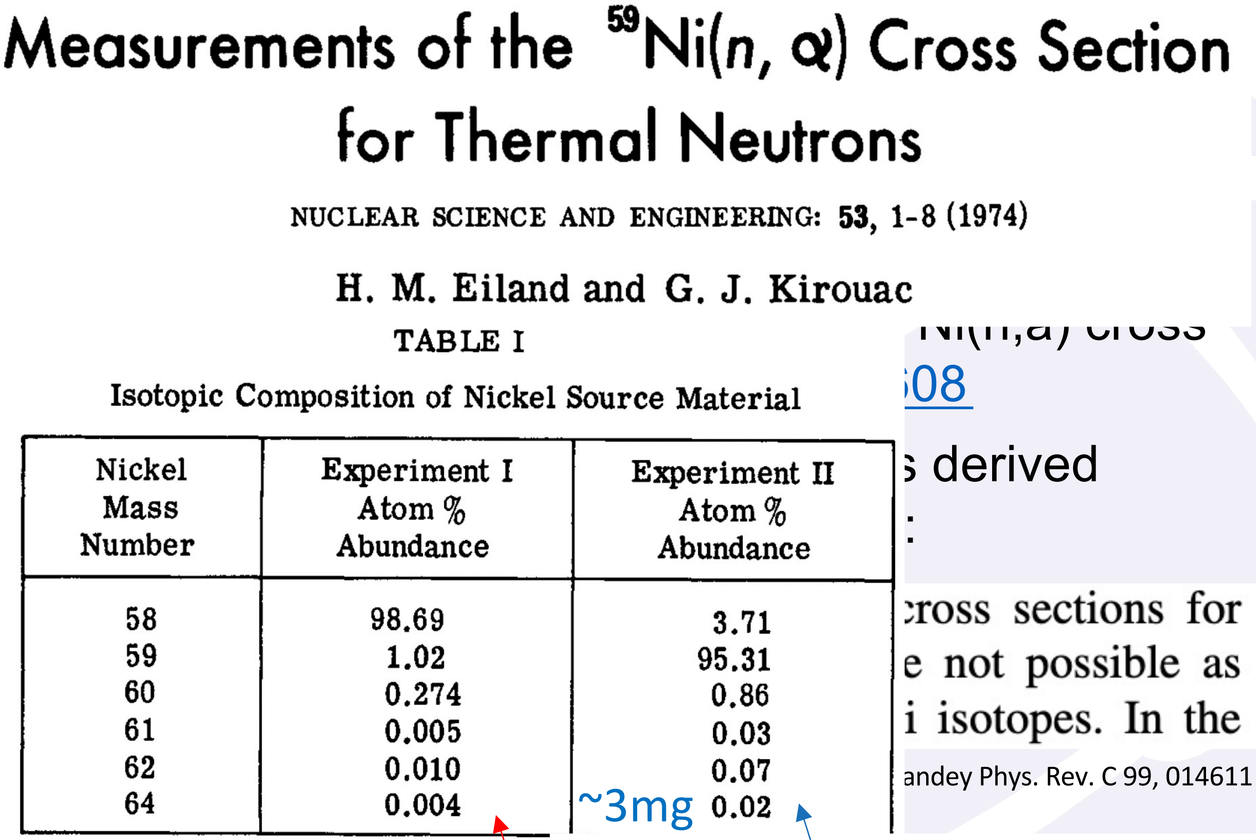
Quantity: [CS] Cross section

48	☐	+ i X4 X4+ ± CSV + T4 Cov	1976	J.A.Harvey+	1.98e0	2.02e5	2709	+ P,ORNL-5137,2,197605	10680009 [4]	
49	☐	+ i X4 X4+ ± CSV + T4 Cov			5.92e-3	2.11e5	1401		10680010 [3]	
50	☐	+ i X4 X4+ ± CSV + T4 Cov	1975	S.Raman+	3.29e-1	1.48e5	1954	+ P,ORNL-5025,110,197505	13774002 [3]	
51	☐	+ i X4 X4+ ± CSV + T4 Cov			2.43e-1	1.55e4	713		13774003 [3]	
52	☐	+ i X4 X4+ ± CSV + T4 Cov			5.35e1	4.95e2	387		13774004 [3]	
53	☐	+ i X4 X4+ ± CSV + T4 Cov	1975	J.A.Harvey+	4.59e0	2.19e5	3404	+ J,BAP,20,1195(EE6),197509	13775002 [3]	1975HAXU
54	☐	+ i X4 X4+ ± CSV + T4 Cov			4.39e1	2.19e5	3864		13775003 [3]	1975HAXU
55	☐	+ i X4 X4+ ± CSV + T4 Cov	1975	J.A.Harvey	6.62e-3	1.48e5	1552	+ W,HARVEY,1975	13875002 [3]	
56	☐	+ i X4 X4+ ± CSV + T4 Cov			6.62e-3	1.48e5	1470		13875003 [3]	

Direct measurements at LANSCE, n_TOF, ORELA over the past 50 years

Gas production on long-lived radioactive ^{59}Ni

- A well-known case of a long ^{58}Ni(n,g) in typ. reactors an
- Long half-life (~100k years) and +1.9 MeV for ^{59}Ni(n,p))
- Background reaction for our sections up to ~ 10 MeV: htt
- Only other available data in using an indirect surrogate r



Measurements of the ^{59}Ni(n, α) Cross Section for Thermal Neutrons

NUCLEAR SCIENCE AND ENGINEERING: **53**, 1-8 (1974)

H. M. Eiland and G. J. Kirouac

TABLE I

Isotopic Composition of Nickel Source Material

Nickel Mass Number	Experiment I Atom % Abundance	Experiment II Atom % Abundance
58	98.69	3.71
59	1.02	95.31
60	0.274	0.86
61	0.005	0.03
62	0.010	0.07
64	0.004	0.02

Ni(n,a) cross

608

s derived

:

cross sections for
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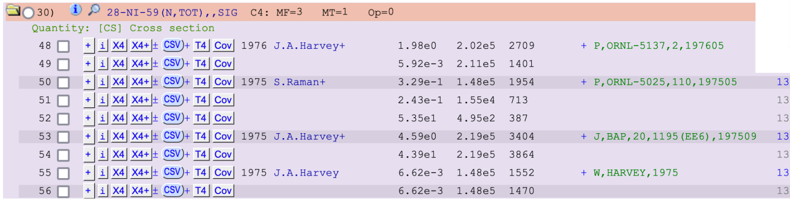
i isotopes. In the

andey Phys. Rev. C 99, 014611

A search for ^{59}Ni(n,*) on EXFOR:

Results: Reactions: 35 Datasets: 62



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○30)    28-NI-59(N,TOT),,SIG   C4: MF=3    MT=1    Op=0
   Quantity: [CS] Cross section
   48 ☐  + i X4 X4+± CSV + T4 Cov 1976 J.A.Harvey+       1.98e0   2.02e5  2709      + P,ORNL-5137,2,197605
   49 ☐  + i X4 X4+± CSV + T4 Cov                        5.92e-3  2.11e5  1401
   50 ☐  + i X4 X4+± CSV + T4 Cov 1975 S.Raman+          3.29e-1  1.48e5  1954      + P,ORNL-5025,110,197505       137
   51 ☐  + i X4 X4+± CSV + T4 Cov                        2.43e-1  1.55e4  713                                     137
   52 ☐  + i X4 X4+± CSV + T4 Cov                        5.35e1   4.95e2  387                                     137
   53 ☐  + i X4 X4+± CSV + T4 Cov 1975 J.A.Harvey+       4.59e0   2.19e5  3404      + J,BAP,20,1195(EE6),197509    13775002 [3] 1975HAXU
   54 ☐  + i X4 X4+± CSV + T4 Cov                        4.39e1   2.19e5  3864                                     13775003 [3] 1975HAXU
   55 ☐  + i X4 X4+± CSV + T4 Cov 1975 J.A.Harvey        6.62e-3  1.48e5  1552      + W,HARVEY,1975                13875002 [3]
   56 ☐  + i X4 X4+± CSV + T4 Cov                        6.62e-3  1.48e5  1470                                    13875003 [3]
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~3mg

ca. 1974: Commercial

Oak Ridge

over the past 50 y

(w. isotope separation/Leon Love)

An incomplete list of rare/radioactive samples of interest to be fabricated into thin targets for use in (n,z) measurements:

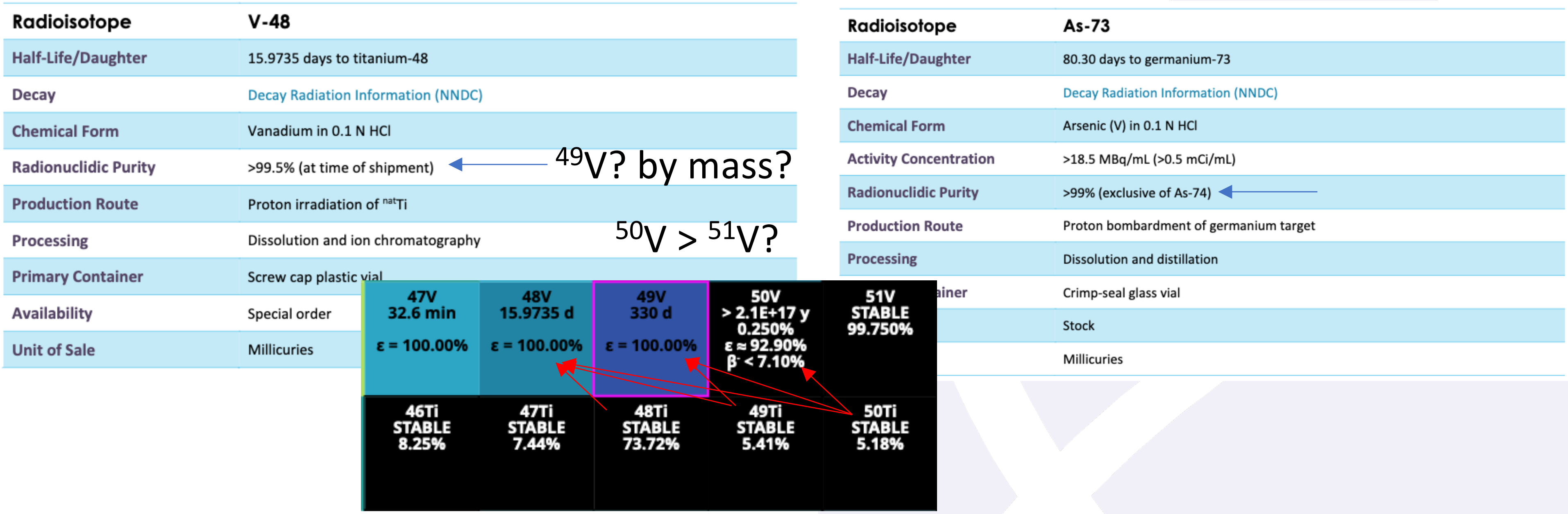
^{7}Be ($T_{1/2}$ ~ 53 d)
^{26}Al ($T_{1/2}$ ~ 720 ky)
^{36}Cl ($T_{1/2}$ ~ 300 ky)
^{44}Ti ($T_{1/2}$ ~ 60 y)
^{48}V ($T_{1/2}$ ~ 16 d), ^{49}V ($T_{1/2}$ ~ 330 d), ^{50}V
^{55}Fe ($T_{1/2}$~2.7 y)
^{56}Co ($T_{1/2}$ ~ 77 d), ^{57}Co ($T_{1/2}$ ~ 270 d)
^{56}Ni ($T_{1/2}$ ~ 6 d), ^{57}Ni ($T_{1/2}$ ~ 36 h), ^{59}Ni ($T_{1/2}$ ~ 100K years)
^{73}As ($T_{1/2}$ ~ 80 d), ^{74}As ($T_{1/2}$ ~ 18 d)

~ug quantities needed -> typ. 100s of mCis – Ci activities for isotopes with ~day long half lives

Commercial options sometimes exist for rare isotopes or very long-lived radioisotopes, including on the NIDC website

However, options for purity of sample may be limited and could require further processing. Each case is different, no standard minimum purity.

NIDC:



Radioisotope	**V-48**
Half-Life/Daughter	15.9735 days to titanium-48
Decay	Decay Radiation Information (NNDC)
Chemical Form	Vanadium in 0.1 N HCl
Radionuclidic Purity	>99.5% (at time of shipment)
Production Route	Proton irradiation of ^{nat}Ti
Processing	Dissolution and ion chromatography
Primary Container	Screw cap plastic vial
Availability	Special order
Unit of Sale	Millicuries

^{49}V? by mass?

^{50}V > ^{51}V?

Radioisotope	**As-73**
Half-Life/Daughter	80.30 days to germanium-73
Decay	Decay Radiation Information (NNDC)
Chemical Form	Arsenic (V) in 0.1 N HCl
Activity Concentration	>18.5 MBq/mL (>0.5 mCi/mL)
Radionuclidic Purity	>99% (exclusive of As-74)
Production Route	Proton bombardment of germanium target
Processing	Dissolution and distillation
ainer	Crimp-seal glass vial
	Stock
	Millicuries

- To understand the isotope production/target fab. R&D needs for a given experiment, it would be very beneficial to have references provided about the production route and the expected processing that is considered “state of the art”
- This would allow for a better estimate and more confidence in not just the quoted radionuclidic purity but to be able to estimate and assess expected stable contaminants.
- For short-lived radionuclides, need to streamline and optimize the process to the final target form factor

Summary

- LANSCE with WNR/Lujan neutron sources and the Isotope Production Facility provides a world-unique capability to perform neutron-induced nuclear reaction studies directly over a broad energy range on “short-lived” radioactive nuclei.

- Opportunities for collaboration that benefit multiple programs:
  - Direct measurements on [radioactive, rare, or isotopically enriched] nuclei, at neutron energies where no data exists
  - Validation of charged particle evaluations and models for isotope production
  - Advancing chemistry and target fabrication techniques and training for versatility in producing different final products for a broad scientific community.

- Improved interdisciplinary training (and recruitment/retention) in isotope production and target fabrication, neutron transport, and in nuclear science measurements are key in progressing these capabilities.

- Customer vs Collaborator