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Nuclear excitation functions for medical isotope production: Targeted radionuclide therapy via $^{nat}\text{Ir}(\text{d},\text{x})^{193\text{m}}\text{Pt}$

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Abstract

$^{193\text{m}}\text{Pt}$ is an Auger emitting radionuclide which may have therapeutic potential, particularly when labeled to the chemotherapeutic drug cisplatin. One challenge to broader explorations of its clinical potential is the need for production routes with high specific activity. As part of a larger campaign to address gaps in reaction data for emerging medical radionuclides, this work seeks to characterize the $^{nat}\text{Ir}(\text{d},\text{x})$ reactions as a potential production pathway for $^{193\text{m}}\text{Pt}$. A stacked target irradiation, consisting of natural iridium, iron, nickel, and copper foils, was performed using a 33 MeV deuteron beam at the Lawrence Berkeley National Laboratory 88-Inch Cyclotron. This measurement, along with previous experimental data, suggests an energy window between 11 to 18 MeV to maximize the production and radiopurity of $^{193\text{m}}\text{Pt}$. This experiment has yielded cross sections for 43 channels of deuteron-induced reactions from threshold to 30 MeV, including the first experimental results of $^{nat}\text{Ir}(\text{d},\text{x})^{188\text{m}}\text{Ir} + ^{190\text{m}}\text{Ir}$ (cumulative), $^{nat}\text{Ni}(\text{d},\text{x})^{56}\text{Ni}, ^{57}\text{Ni}, ^{58}\text{Ni}$ (independent), $^{nat}\text{Cu}(\text{d},\text{x})^{61}\text{Cu}$ (cumulative) and $^{nat}\text{Fe}(\text{d},\text{x})^{53}\text{Fe}, ^{48}\text{V}$ (cumulative). The results were compared with literature data, the TENDL-2023 database, and default theoretical calculations from the TALYS-2.04, CoH-3.6.0, EMPIRE-3.2.3, and ALICE-2020 reaction modeling codes. This work presents another example of the lack of predictive capabilities for this set of modern nuclear-reaction modeling codes, and highlights the unsatisfactory modeling of experimental cross sections. Experimental data are important to improve the codes in general, and new experimental results can be used to improve the models. Finally, this measurement has revealed the need for an updated evaluation of the $^{nat}\text{Cu}(\text{d},\text{x})^{63}\text{Zn}$ deuteron monitor reaction.

Keywords: *Medical isotope production; Therapeutics; Nuclear medicine; Radionuclides; Ir + d; Iridium; ^{193}mPt ; Nuclear cross sections; Nuclear reactions; Stacked target activation; Deuterons; High-spin isomers*

Dataset link: <https://doi.org/10.5281/zenodo.6584051>

1. Introduction

Use of radioactive isotopes for in vivo applications within the medical field has had a transformative impact on global health. Medical practitioners make use of single-photon emission computed tomography (SPECT) and positron emission tomography (PET) imaging agents — like ^{99m}Tc and ^{18}F — to routinely diagnose diseased tissue in millions of patients per year worldwide. Use of low-energy β -emitting radionuclides — such as ^{177}Lu (Lutathera®), ^{90}Y (Zevalin®), and ^{131}I (Bexxar®) — and α -emitting radionuclides — like ^{223}Ra (Xofigo®) — as therapeutic agents have similar potential for positively redefining the medical field. Although it has yet to be fully realized, widespread use of radiotheranostic agents combining a matched pair of a therapeutic radionuclide with an imaging surrogate has potential for even larger impact than any singular diagnostic or therapeutic agent (Filippi et al., 2020; Langbein et al., 2019). Unfortunately, large-scale production of emerging radionuclides, particularly those whose decay-properties enable therapeutic applications, has not been realized to date. In selecting candidates for targeted radionuclide therapy, a vital figure-of-merit is the linear energy transfer (LET, typically reported in $\text{keV}/\mu\text{m}$) of decay radiation, which measures energy deposition per unit length. High-LET radiation produces a high density of ionization events, damaging cells and their DNA. As LET is inversely proportional to the radius over which this energy is deposited, high-LET radionuclides are prized for therapeutic potential, as their decay radiation produces high cellular lethality over a narrow region (Qaim, 2017).

The future of radionuclide therapy appears to feature two major groups: those which decay by emission of an alpha particle (“alpha emitters”), and those which emit a cascade of Auger electrons in their decay (“Auger emitters”) (Müller et al., 2017; Bolcaen et al., 2023). These are examples of the increasing trend in nuclear medicine towards using targeted therapies developed

for individual cases, which require short-range, accurately delivered doses. Alpha emitters feature high LET giving them a short range (on the order of a single cell) and significantly reducing the dose delivered to surrounding healthy tissue, and have demonstrated significant early clinical success, particularly for the case of ^{225}Ac (Kratochwil et al., 2016, 2017, 2018). In a complementary fashion, Auger emitters produce a cascade of 5–40 low-energy (10 eV–10 keV) electrons with a LET of 5–25 keV/ μm (which corresponds to a range of 2–500 nm in tissue), leading to a massive dose in a volume comparable to the nucleus of a single cell. This energy transfer induces double-strand breaks in the DNA of a cancerous cell from which it is nearly impossible for the cell to survive, while sparing surrounding healthy cells (Howell, 2023). In addition to the shorter range facilitating highly selective treatment modalities, Auger emitters avoid the common challenges of alpha emitters: a chain of multiple radioactive decays prior to reaching a stable nuclide (which will likely dissociate the daughters away from the targeting site and increase non-useful patient dose), and the location of many alpha-emitters far from stability (which often limits production paths and constrains potential target options) (Filosofov et al., 2021). However, this extreme dose localization has created challenges in matching radionuclides with suitable targeting biomolecules.

Despite tremendous potential, transitioning Auger-emitting therapeutics from the realm of R&D to an actual drug used by medical practitioners has yet to be demonstrated beyond scarce investigational and dosimetry studies. One of the most daunting problems facing the development of Auger-based medical applications is associated with limited radionuclide access and production routes with low specific activity. Auger therapy is far more sensitive to low specific activity than most α - or β --radiopharmaceuticals, as much greater quantities of the keV-scale electrons per decay must be accumulated within a finite volume to induce the desired therapeutic dose

(Filosofov et al., 2021). One interesting class of radiometals with high-spin isomeric states (Müller et al., 2017), such as $^{117\text{m}}\text{Sn}$ ($t_{1/2} = 14.00 \pm 0.05$ d (Stevenson et al., 2015; Blachot, 2002)) and $^{193\text{m}}\text{Pt}$ ($t_{1/2} = 4.33 \pm 0.03$ d (Howell et al., 1986; Shamsuzzoha Basunia, 2017)), have gained increasing interest for use in conversion- and Auger-electron therapy, respectively. These long-lived isomers result from a large difference in angular momentum from their low-lying ground state, inhibiting their ability to de-excite by isomeric transition or β/ϵ decay.

Radioplatinums, $^{193\text{m}}\text{Pt}$ in particular, have significant potential for targeted radionuclide therapy (Tárkányi et al., 2006), especially in conjunction with the platinum-based chemotherapeutic drug cisplatin. Cisplatin has been commonly used since the 1970s for treatment of a wide variety of cancers, as it binds to the DNA bases of rapidly-dividing cancer cells. Conventional cisplatin therapy is limited by its chemical toxicity, with the severe long-term side effects including irreversible hearing loss, and nerve and renal damage (Anderson et al., 1979). However, it has been suggested that for $^{193\text{m}}\text{Pt}$ -labeled cisplatin, the added radiotoxicity may significantly reduce the amount of cisplatin required, and the chemotoxicity limitations may thus be reduced (Howell et al., 1986, 1994; Azure et al., 1992). The long half-life of the $^{193\text{m}}\text{Pt}$ isomer allows for binding to the cellular DNA, facilitates the use of large biomolecules for targeting disease, and offers the possibility for large-scale regional production and shipment. The cascade of Auger electrons emitted in each decay are expected to have excellent clinical efficacy, with ranges less than the cell diameter, minimizing dose to surrounding tissue (Howell, 1992).

However, as with many Auger emitters, a dearth of production pathways with high specific activity has prevented wider clinical investigations of $^{193\text{m}}\text{Pt}$. As the isomer ($J^\pi = 13/2^+$) has a high spin state, transfer of large amounts of angular momentum is needed for reaction pathways to preferentially populate the medically-valuable isomer instead of its long-lived ground state (J^π

$= 1/2-$) (Shamsuzzoha Basunia, 2017). The typical production mechanism for ^{193m}Pt currently used is via the $^{192}\text{Os}(\alpha,3n)$ reaction at ≈ 30 MeV, which yields high specific activity, but the ^{192}Os target is highly toxic, chemically volatile, and mechanically brittle (Uddin et al., 2010). There are alternatives involving slightly heavier beams and potentially simpler targetry such as the $^{186}\text{W}(9\text{Be},2n)$ reaction, but these severely limit the number of accelerators for potential production. Proton-induced reactions on iridium have been considered for the production of radioplatinum (Tárkányi, 2005; Obata et al., 2019), but since (p,xn) reaction channels preferentially populate nuclear states closer in J Π to the target, they are less favorable for selective production of the ^{193m}Pt isomer (Qaim et al., 2018; Skobelev, 2015; Vandenbosch and Huizenga, 1960; Tárkányi et al., 2015). Likewise, reactor production is not expected to yield high specific activity ^{193m}Pt , due to the low spin transfer for thermal neutrons (Tóth, 1980). Recent work by Tarkanyi et al. (Tárkányi et al., 2006, 2019) has proposed the use of $\text{Ir}(d,xn)$ as a viable pathway for high specific activity ^{193m}Pt , with more preferential isomer population than $\text{Ir}(p,xn)$, and without the need for 30 MeV α -particles for $^{192}\text{Os}(\alpha,3n)$. The $\text{natIr}(d,x)^{193m}\text{Pt}$ production route explored in this work seeks to improve upon the earlier work by Tarkanyi et al., resolve disagreements in these previously reported channels, and provide the most complete characterization of reaction channels to date in this mass region. In this work, our stacked-target activation method was applied to measure multiple cross sections from threshold to 33 MeV. Finally, this measurement serves as the first extension of our variance minimization technique to deuteron beams.

2. Experimental methods and materials

Preliminary discussion of this measurement was reported in H. Ekeberg’s Master thesis (Ekeberg, 2020); here we present the final report of that work. Unless otherwise stated, all values are presented herein as mean $\pm$ SD (standard deviation), or as the calculated result $\pm$ half the width of a 68% confidence interval.

2.1. Stacked-target design

In this work, we used the stacked target activation technique to measure cross sections using an incident deuteron beam up to 33 MeV on a stack of well-characterized thin targets. This approach has been well-established in our recent work for the measurement of (p,x) reactions (Voyles et al., 2018; Morrell et al., 2020; Fox et al., 2021a,b; Voyles et al., 2021); this work serves as our first extension of these methods for energetic deuteron beams. The stack consisted of ten natIr (99.9%, lot #LS510228) target foils, and ten natNi (99.9%, lot #LS471921), ten natCu (99.95%, lot #LS471698) and three natFe (99.5%, lot #LS470411) monitor foils, (all nominal 25 μ m thickness, from Goodfellow Corporation, Coraopolis, PA 15108, USA).

The iridium foils were obtained as pre-cut in 25 $\times$ 25 mm squares, the nickel, copper, and iron foils were cut down to match, and all foils were cleaned with isopropanol. All foils were spatially characterized at four different locations using a digital caliper and micrometer (Mitutoyo America Corp.) and four mass measurements were performed using an analytical balance (Mettler Toledo) in order to determine their areal density. Unlike in our previous work, no beam energy degraders were needed for this stack—due to the increased stopping power of deuterons (relative to protons), the target and monitor foils served to sufficiently degrade the beam to cover our energy range of interest. Likewise, no Kapton tape was used for sealing the stack foils, due to a combination of significant ablation and scorch marks, as well as low levels of dispersible ^{13}N

contamination, found previously for $E_d < 10$ MeV on Kapton tape. Instead, the foils were mounted by their edges over the hollow aperture of 1.5875 mm-thick acrylic frames, with all Kapton tape remaining out of the beam strike area. The mounted foils can be seen in Fig. 1. The specifications of the target stack are detailed in Table A.1 of Appendix A.

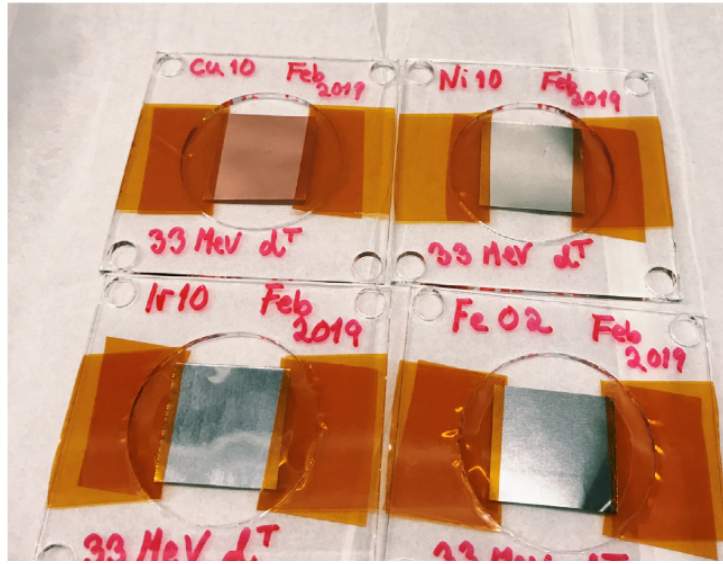


Fig. 1. Each target material mounted on acrylic frames with a hollow center. Kapton tape is attached along the edges of the foils, outside of the beam strike area.

The foils were placed in a target holder (made from 6061 aluminum alloy) with a hollow upstream aperture to provide an unobstructed path between the foils and the beam, as in our prior work (Voyles et al., 2018; Morrell et al., 2020; Fox et al., 2021a,b; Voyles et al., 2021). The target stack was irradiated with 33 MeV deuterons at the Lawrence Berkeley National Laboratory (LBNL) 88-Inch Cyclotron (Covo et al., 2017), for one hour at a nominal current of 125 nA, measured using a current integrator on the electrically-isolated beamline. The beam current remained stable under these conditions for the duration of the irradiation. The approximately 1.2 cm-diameter deuteron beam incident upon the stack’s upstream stainless steel profile monitor had an approximately 2% energy width due to multi-turn extraction—this energy profile was used for all later analysis. Following end of irradiation, the stack was removed from the beamline and

disassembled, with each mounted foil individually sealed into plastic bags for containment. All activated foils were transported to a counting lab for gamma spectrometry, which started approximately 15 minutes following the end of the irradiation.

2.2. Quantification of induced activities

One ORTEC GMX Series (model #GMX-50220-S) and six ORTEC IDM-200-V High-Purity Germanium (HPGe) detectors were used to determine the activities in each target. Samples were counted at fixed positions ranging 10–60 cm (5% maximum permissible dead-time) from the front face of the detector. The foils were counted for 5 weeks following irradiation. Net peak areas were fitted using the code FitzPeaks (Fitzgerald, 2009), which utilizes the SAMPO fitting algorithms for gamma-ray spectra (Aarnio et al., 2001). Activities for all products observed in the collected γ -ray spectra, along with all calculations of measured cross sections reported in this work, were calculated using half-lives and gamma-ray branching ratios from the most recent edition of Nuclear Data Sheets for each mass chain, with the exception of ^{61}Cu (Hermanne et al., 2025), with all utilized data tabulated in Appendix B. Corrections (typically $<0.2\%$) for gamma-ray self-attenuation within each foil were made, using photon attenuation coefficients from the XCOM photon cross sections database (Berger et al., 2010), and assuming attenuation through half the thickness of each foil. End-of-Beam (EoB) activities were determined by χ^2 -fitting of all observed decay gammas for a product to the decay curve. The total uncertainty in activity is the propagated sum of the uncertainty in fitted peak areas, uncertainty in detector efficiency calibration, uncertainty in the gamma-ray branching ratio data, and uncertainty in photon attenuation coefficients (taken as 5%). Where the decay of any precursors could be measured and the in-growth contribution separated, or where no decay precursors exist, independent cross sections for direct production of a nucleus are reported. Where the in-growth due to parent decay could not be

deconvolved, due to timing or decay-property limitations, cumulative cross sections are reported. Further details on this spectroscopy may be found in Ref. Ekeberg (2020), Voyles et al. (2018).

2.3. Deuteron energy and fluence assignments

Thin natNi, natFe, and natCu foils were co-irradiated to measure beam current at each position within the stack. The International Atomic Energy Agency (IAEA)-recommended natNi(d,x)61Cu, 56,58Co, natFe(d,x)56Co, and natCu(d,x)62,63,65Zn monitor reactions were used (Hermanne et al., 2018). Using the formalism outlined in our previous work, the integral form of the well-known activation equation was used to determine deuteron current (I), in order to account for energy loss across each monitor foil (Voyles et al., 2018). The propagated uncertainty in beam current is calculated as the quadrature sum of (1) the uncertainty in quantified EOB activity, (2) uncertainty in the duration of irradiation, (conservatively estimated at 10 s, to account for any transient changes in beam current), (3) uncertainty in foil areal density, (4) uncertainty in monitor product half-life (included, but normally negligible), (5) uncertainty in IAEA recommended cross section (using values from the 2018 IAEA re-evaluation (Hermanne et al., 2018)), and (6) uncertainty in differential deuteron fluence (from transport simulations).

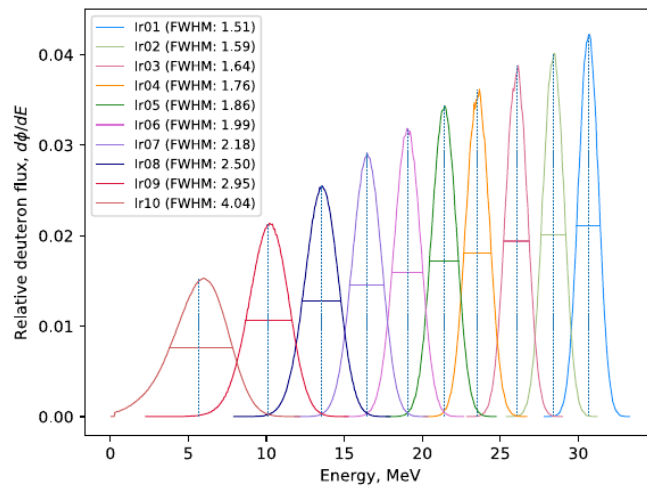


Fig. 2. Visualization of the NPAT-calculated deuteron energy spectrum for each of the 10 iridium foils. As the beam energy degrades, the distribution becomes progressively more skewed, and the full width half maximum (FWHM) becomes progressively larger.

Particle transport calculations for the target stack were performed using the Andersen & Ziegler stopping power formalism, as implemented in NPAT (now superseded by Curie) (Morrell, 2019, 2020). The calculated energy spectrum for the iridium foils in the target stack is shown in Fig. 2 as an example. As detailed in our previous work (Voyles et al., 2018; Morrell et al., 2020; Fox et al., 2021a,b; Voyles et al., 2021), the “variance minimization” technique is used here to calculate the deuteron energy spectrum and current in each foil, as well as reduce the overall systematic uncertainties in these calculations. Our earlier work has established that a poor characterization of particle transport for the degraded beam leads to compounding disagreement in beam current towards the rear of the stack, and that the variance minimization technique is successful as a corrective tool for this discrepancy. Most of our prior work has used the effective density of energy degrader foils as a free parameter in variance minimization, as they account for the overwhelming majority of stopping power for the stack. However, when no degraders are present, or if the stack foils themselves constitute the majority of the total stopping power, a global scaling of the effective areal density of all stack components and a minor ($<5\%$) scaling of the incident beam energy serve as better free parameters for this technique (Morrell et al., 2020). Applying changes in the areal density and beam energy does not imply that the nominal values are incorrect, but act as surrogate corrections for improperly characterized deuteron stopping power and systematic uncertainties in beam characterization to best reproduce the IAEA monitor cross section data (Morrell et al., 2020; Voyles et al., 2021). In this work, the stack components’ effective areal densities were varied uniformly in the stopping power simulations by a factor of up to $\pm 25\%$ of nominal values, and the incident beam energy was simultaneously varied up to $\pm 5\%$ of the

nominal 33 MeV. The resulting reduced χ^2 for all monitor channels in a compartment (e.g., Ni06/Ir06/Cu06) was minimized simultaneously for compartments 6 and 9. Compartments further back in the stack, or right above the energetic threshold for a monitor reaction, provide the greatest sensitivity to incorrect stopping powers during variance minimization—#6 was chosen as the first compartment above the $\text{natCu(d,x)}^{62}\text{Zn}$ threshold, and #9 was chosen as the first compartment above the $\text{natCu(d,x)}^{63}\text{Zn}$ threshold.

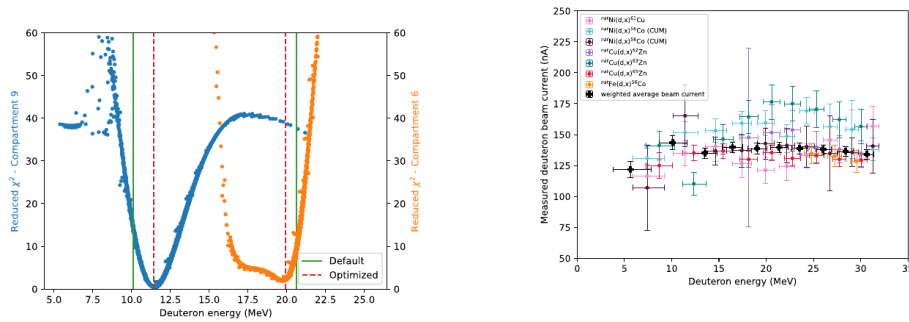


Fig. 3. (a) Result of χ^2 analysis used in the variance minimization technique to determine the required adjustment (“Optimized”) to stopping power within the deuteron energy spectrum calculations. These corrections (with the red and green lines denoting the average energy of the beam entering each of the two listed compartments) show marked improvement in monitor reaction agreement (“Optimized” calculations) over the “Default” calculations. (b) Monitor reaction beam currents following the “Optimized” stopping power adjustments.

The results of the minimization technique, seen in Fig. 3, indicate a clear minimum in the deuteron current χ^2 values, for both compartments 6 and 9. This minimum occurs for a 2% increase in incident beam energy (33.7 MeV) and a 4.25% increase in effective areal density. This implies that the monitor data are best reproduced if the average energy from the cyclotron tune (which includes multi-turn extraction) was slightly higher than 33 MeV, or if the deuteron stopping power calculations were underestimated. Since the positive enhancements to both beam energy and the areal density have compensating effects on the transport calculation, the net change in stopping power is well within the range seen in our earlier work (Voyles et al., 2018; Morrell et al., 2020; Fox et al., 2021a,b; Voyles et al., 2021). The variance minimization led to a clear improvement in

agreement for the monitor beam currents over the default transport calculations, where the $\text{natNi(d,x)}^{56}\text{Co}$ and $\text{natCu(d,x)}^{62}\text{Zn}$ monitor reactions improved the most. $\text{natCu(d,x)}^{63}\text{Zn}$ and, to a lesser degree, $\text{natNi(d,x)}^{61}\text{Cu}$ yield beam currents which were completely insensitive to variance minimization and consistently $\approx 1.5\text{--}2\sigma$ larger in magnitude than the average beam current above approximately 15 MeV, discussed further in Section 3.9. The changes in the beam current for the remaining monitor reactions were minor as a result of the variance minimization, confirming that the overall physical impact of applying this technique on the transport calculations was minimal.

In each compartment, the correlated uncertainty-weighted mean for the natCu(d,x) , natFe(d,x) , and natNi(d,x) monitor channels were calculated at each energy position, to determine the final fluence assignments for each monitor foil, respectively. The correlated uncertainty-weighted mean for all observed monitor channels was used to determine the final fluence assignments for the Ir foils. As in our recent work (Voyles et al., 2021), this correlated uncertainty-weighted mean beam current was calculated as:

$$\langle I \rangle = \sum_{i,j} I_j (V^{-1})_{ij} / \sum_{i,j} (V^{-1})_{ij} \quad (1)$$

Uncertainty in each final deuteron fluence is calculated by error propagation of the individual monitor channel fluence values at each energy position:

$$\delta \langle I \rangle = [\sum_{i,j} (V^{-1})_{ij}]^{-1/2} \quad (2)$$

Each element ij of the covariance matrix, V_{ij} is calculated using the robust sandwich estimator (Huber, 1967):

$$V_{ij} = \text{Cov}[I_i, I_j] = \Sigma \beta (\partial I / \partial \beta_i) \delta \beta_i \text{Corr}[\beta_i, \beta_j] \delta \beta_j (\partial I / \partial \beta_j) \quad (3)$$

where i and j are the monitor reactions in a given compartment, and $\beta \in [A0, \rho\Delta r, \lambda, \Delta t_{irr}, \int \sigma(E)(d\phi/dE)dE]$. Here, $A0$ is the EoB-activity for the given product, $\rho\Delta r$ is the foil areal density, λ is the decay constant for the given product, Δt_{irr} is the duration of irradiation, and $\int \sigma(E)(d\phi/dE)dE$ is the flux-averaged monitor cross section for the given reaction. $A0$ is assumed to be 30% correlated for all reactions, $\rho\Delta r$ is assumed to be 100% correlated for reactions from the same monitor foil, λ is assumed to be uncorrelated, Δt_{irr} is assumed to be 100% correlated, and $\int \sigma(E)(d\phi/dE)dE$ is assumed to be 30% correlated for reactions from the same monitor foil.

2.4. Cross sections

As in our recent work (Voyles et al., 2021), this variance-minimized deuteron current $\langle I \rangle$ in each foil is used to calculate cross sections. The reported asymmetric uncertainty in beam energy corresponds to the full width at half maximum (FWHM) for the flux distribution in each foil. Using the weighted average beam current over each compartment determined from the monitor cross sections and fluence assignments, the reported cross sections were calculated as:

$$\sigma = A0 / [\rho\Delta r \cdot \langle I \rangle \cdot (1 - e^{-\lambda\Delta t_{irr}})] \quad (4)$$

The propagated uncertainty in cross sections are reported as the quadrature sum of the uncertainty in (1) EoB-activities, (2) beam current, (3) foil areal density, and (4) the decay constant of the product.

The measured data are compared to previous experimental data from the EXFOR database (Zerkin, 2020), recommended data from the TENDL-2023 library (Koning et al., 2019), along with calculations from the nuclear reaction modeling codes TALYS-2.04, ALICE-2020, CoH-3.6.0, and EMPIRE-3.2.3 (Herman et al., 2007; Kawano et al., 2010; Blann, 1996; Koning and Rochman,

2012). The codes were run similarly to Voyles et al. (2021), using all default parameters, and energies from 0-40 MeV.

3. Results and discussion

This work presents the first extension of our variance minimization methods, performed for a deuteron beam irradiation, where small changes in the incident deuteron energy and the monitor foils were applied rather than to the beam degraders. A total of 50 reaction channels (including 7 measurements in the monitor foils) for deuteron-induced reactions on natural iridium, iron, nickel, and copper are reported in this work. This includes the first experimental measurements of $\text{natIr}(d,x)188\text{m1}+\text{gIr}$ (independent), $\text{natIr}(d,x)190\text{m1}+\text{gIr}$ (cumulative), $\text{natFe}(d,x)48\text{V}$ (cumulative), 53Fe (cumulative), $\text{natNi}(d,x)59\text{Fe}$ (cumulative), $\text{natNi}(d,x)56,57,58\text{m},58\text{gCo}$ (independent). In addition, the measurement of $\text{natIr}(d,x)189\text{Ir}$ revealed a potential error in the absolute intensity of the decay gammas. The decay data used in analysis are listed in Appendix B. Plots of the excitation functions for reactions in the monitor foils are attached in Appendix C. All reported cross section data are tabulated in Appendix D.

The measured $\text{natIr}(d,x)$ cross sections in this work are compared to prior experimental data from Tárkányi et al. (Tárkányi et al., 2006, 2019) and Obata et al. (Obata et al., 2019) who have performed similar experiments with deuteron energies in the ranges 1.7–38.0 MeV, 17.09–49.50 MeV, and 40.3–23.8 MeV, respectively.

3.1. Excitation function for $\text{natIr}(d,x)193\text{mPt}$

193mPt was observed in all foils (Fig. 4). The lack of strong gamma lines makes it challenging to make precise measurements. 193mPt was first identified exclusively using the weakly fed gamma-line ($E_\gamma = 135.5$ keV, intensity = 0.11%). Including the characteristic X-ray after internal conversion ($K\alpha_1 = 66.831$ keV, intensity = 7.21%) improved the statistics significantly. This work presents a far more precise measurement than prior work, likely due to

this inclusion. As shown in the figure, there is good agreement with the experimental data, with a predicted peak in the excitation function between 12–14 MeV. Additional future measurements near this compound peak would be useful to resolve its sharpness, as well as the amplitude. TENDL-2023 and CoH-3.6.0 match the experimental data around the peak. TALYS-2.04 and TENDL-2023 best reproduce the pre-equilibrium tail. ALICE-2020 underpredicts the peak, while overpredicting the pre-equilibrium tail. EMPIRE-3.2.3 overpredicts the entire excitation function.

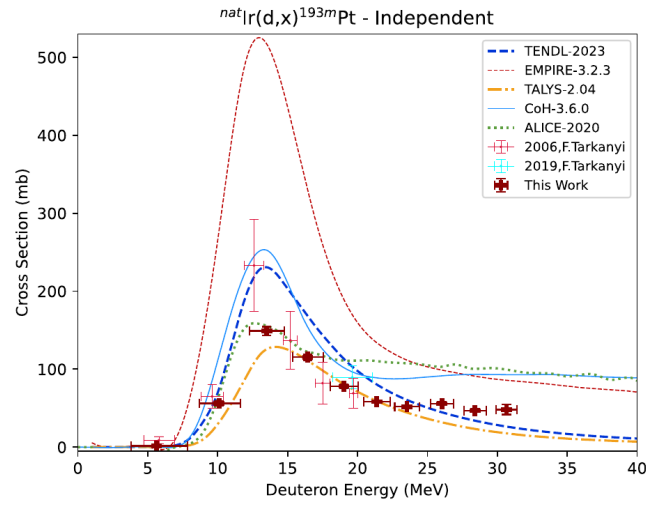


Fig. 4. Excitation function for $\text{natIr}(d,x)^{193\text{m}}\text{Pt}$, visibly peaking between approximately 11-13 MeV.

3.2. Excitation function for $\text{natIr}(d,x)^{188,189,191}\text{Pt}$

^{188}Pt (Fig. 5) is produced by $^{191}\text{Ir}(d,5n)$, and is energetically possible with deuterons of approximately 26 MeV and higher. The measured cross sections in this work are near threshold, and, beyond our measured energies, we can see a rapid increase in this channel as the deuteron energy increases. As the prior data were measured above the energies of this work, it is difficult to make a direct comparison, though the trend appears to be consistent. TENDL-2023 and CoH-3.6.0 appear to agree best with the experimental data for this channel. ALICE-2020 predicts a steeper increase. ^{189}Pt (Fig. 6) is produced through $^{191}\text{Ir}(d,4n)$, opening at approximately 19 MeV. EMPIRE-3.2.3, CoH-3.6.0 and TENDL-2023 all agree with the previously measured data. The

excitation function predicted by ALICE-2020 is shifted slightly toward a lower deuteron energy. TALYS-2.04 predicts the peak location, but disagrees in magnitude. The results obtained in this analysis tend to estimate slightly higher cross sections than previous experimental data, in particular on the rise of the compound peak. The data however agree within uncertainties, in addition to the shape of the excitation function. Given that our results agree in magnitude with previous experimental data in all other reaction channels, systematic factors such as beam current determination likely do not explain the minor discrepancies seen in this one channel, particularly for the two highest energy datapoints. A more likely explanation is the difference in adopted nuclear data for gamma branching ratios in this channel. This can be seen in the difference in magnitude between the 2006 and 2019 Tárkányi et al. measurements (Tárkányi et al., 2006, 2019), whose difference in branching ratios lead to the difference in magnitude in their results. As both Obata (Obata et al., 2019) and Tárkányi measurements use the two most intense gammas for ^{189}Pt , whereas we use an average of five of its decay gammas, this may explain the minor differences observed. ^{191}Pt (Fig. 7) is produced from both stable ^{191}Ir and ^{193}Ir isotopes, and the excitation function visibly peaks around 12 MeV and 30 MeV for both reactions, respectively. The results are in good agreement with previous experimental data. The reaction modeling codes all generally show good performance in predicting the shape. For the first peak, ALICE-2020 best predicts the magnitude of the experimental data, whereas TENDL-2023 and CoH-3.6.0 best predict its shape. For the second peak, there is some disagreement of peak location, but overall, the codes predict the experimental data fairly well.

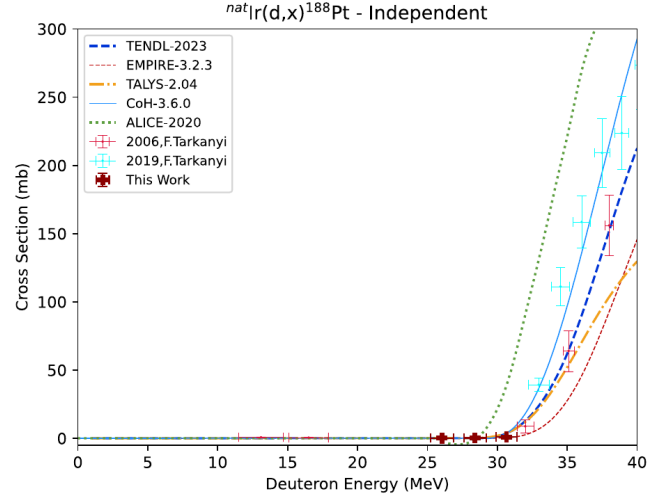


Fig. 5. Excitation function for $\text{natIr}(d,x)^{188}\text{Pt}$. The $^{191}\text{Ir}(d, 5n)^{188}\text{Pt}$ channel opens at approximately $E_d = 26$ MeV.

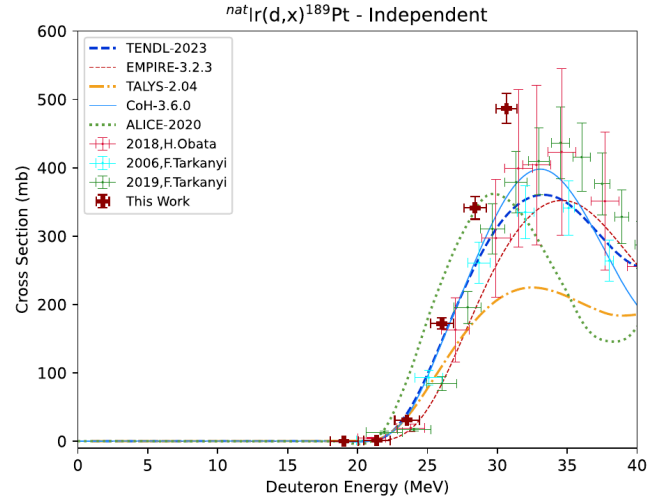


Fig. 6. Excitation function for $\text{natIr}(d,x)^{189}\text{Pt}$. Reaction $^{191}\text{Ir}(d, 4n)^{189}\text{Pt}$ opens at approximately $E_d = 19$ MeV.

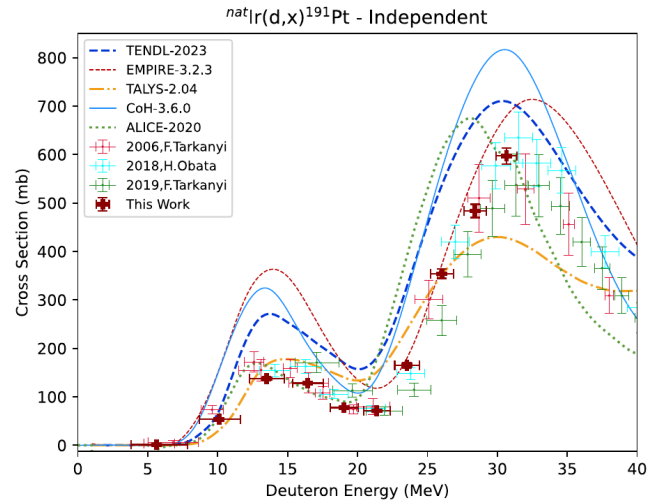


Fig. 7. Excitation function for $\text{natIr}(d,x)\text{191Pt}$. Both reaction channels contributions via $\text{191Ir}(d,2n)$ and $\text{193Ir}(d,4n)$ can be seen, where the former peaks at approximately 12 MeV and the latter peaks at approximately 30 MeV.

3.3. Excitation function for $\text{natIr}(d,x)\text{188Ir}$ – independent and cumulative

188Ir is produced directly via $\text{191Ir}(d,p4n)$ and via β^+ decay from 188Pt (ϵ : 100%). Both total cumulative (Fig. 8), and the independent (Fig. 9) are reported, where the independent measurements were obtained by subtracting the independent contribution from 188Pt . The energetic threshold for this reaction is approximately 16 MeV, and there is a rapid increase when the reaction channel for 188Pt opens at approximately 26 MeV. For the total cumulative cross sections, the experimental data in this work suggest a more rapid increase above threshold, which is generally matched in shape by EMPIRE-3.2.3, TALYS-2.04, and TENDL-2023. However, given the paucity of existing experimental data, as well as the weakly-fed nature of this channel, it is no surprise that all codes seem to be performing poorly here, with additional measurements needed to better tune predictive capabilities. However, our independent results for this channel are well-reproduced by TALYS-2.04 and TENDL-2023, suggesting that the overly sharp rise of the cumulative prediction lies with overestimation of the feeding of 188Pt , as seen previously in Fig. 5.

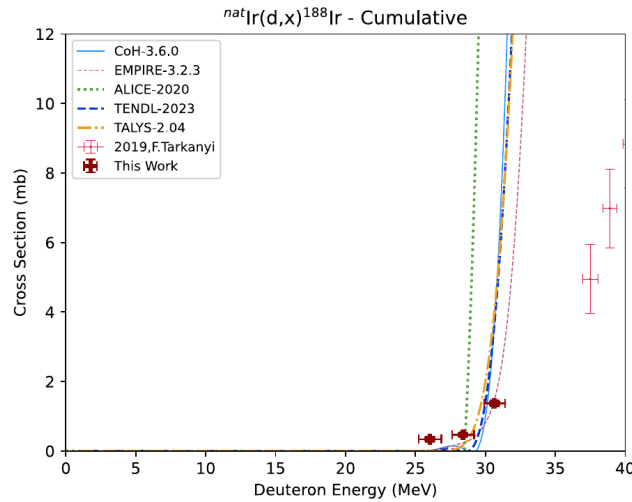


Fig. 8. Excitation function for $\text{natIr}(d,x)^{188}\text{Ir}$. This is the total cumulative cross section, including feeding from ^{188}Pt .

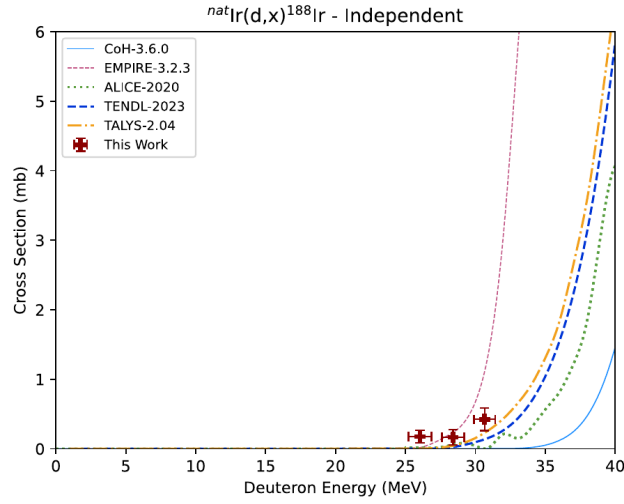


Fig. 9. Excitation function for $\text{natIr}(d,x)^{188}\text{Ir}$. The green points show the total cumulative cross section with feeding from ^{188}Pt , while the red points show the independent measurements of ^{188}Ir production.

3.4. Excitation function for $\text{natIr}(d,x)^{189}\text{Ir}$

^{189}Ir (Fig. 10) is produced directly via $^{191}\text{Ir}(d,p3n)$ and via β^+ decay ($\epsilon : 100\%$) from ^{189}Pt . The total cumulative cross section for ^{189}Ir should therefore be greater than the independent measurements of ^{189}Pt . As shown in Table D.7, the independent measurements of ^{189}Pt provide higher cross section measurements, resulting in a nonphysical behavior. This becomes evident when attempting to subtract feeding from ^{189}Pt , resulting in negative measurements of the independent cross sections for ^{189}Ir . This may imply that the absolute intensity normalization of the decay-gammas may be wrong in the current mass chain evaluation of $A = 189$ (Johnson and Singh, 2017). Therefore, to obtain the cumulative ^{189}Ir cross sections, spectra taken more than 4-5 days after EoB were used, assuming that ^{189}Pt had decayed completely after ten half-lives. There is disagreement with the measured cross sections of Tárkányi et al. (2019) (Tárkányi et al., 2019), suggesting a 10 MeV shift toward higher energy for the compound peak. However, the measured cross sections in this work agree with the experimental

data of Tárkányi et al. (2006) (Tárkányi et al., 2006) and Obata et al. (2018) (Obata et al., 2019), as well as the reaction modeling codes build confidence in the location of the peak. While no clear cause for this discrepancy in their 2006 results can be found, neither do the authors present an explanation in their more recent 2019 manuscript. This particular reaction requires further investigation.

3.5. Excitation functions for $natIr(d,x)190,190m1+g,190m2Ir$

$190Ir$ has two isomers, both of which decay by isomeric transition ($m2$: 8.6%, $m1$: 100%). A total cumulative cross section (Fig. 11), an independent measurement of the $m2$ isomer (Fig. 12), and the subtracted measurement of $190m1+gIr$ (Fig. 13) are reported. The total cumulative cross section is consistent with the existing experimental data. TENDL-2023 and TALYS-2.04 agree with the experimental data from approximately 20 MeV to 30 MeV. CoH-3.6.0 and ALICE-2020 consistently underestimate the excitation function, while EMPIRE-3.2.3 consistently overestimates the shape above 20 MeV. The contribution from the $m2$ isomer to the ground state is minimal, given that cross sections and the branching ratio are low. CoH-3.6.0, ALICE-2020 and EMPIRE-3.2.3 reproduce the shape of the excitation function of $190m2Ir$, where CoH-3.6.3 in particular follows the shape of the experimental data accurately. TENDL-2023 predicts a lower effective energetic threshold, as well as a more rapid rise of the excitation function, compared to both experimental data as well as the other codes. For $190m1+gIr$, TENDL-2023 and TALYS-2.04 reproduce the shape above 20 MeV. ALICE-2020 and CoH-3.6.0, as for the total cumulative cross section, consistently underestimate the excitation function. It was not possible to model $190m1+gIr$ with EMPIRE-3.2.3 or $190m2Ir$ with TALYS-2.04, as both codes lacked these isomers in their structure tables.

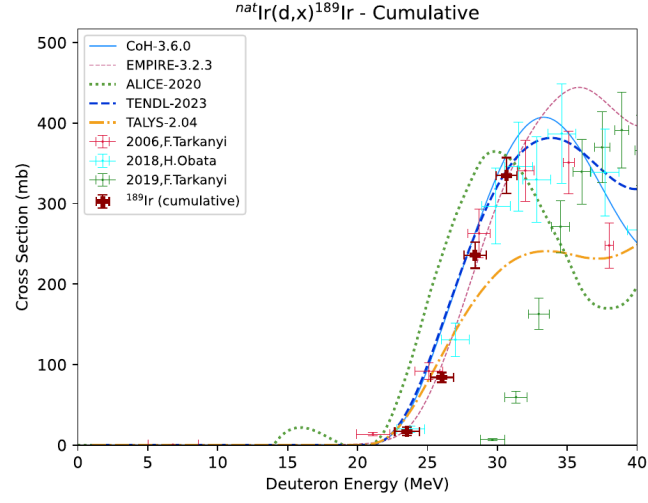


Fig. 10. Excitation function for $^{nat}\text{Ir}(d,x)^{189}\text{Ir}$.

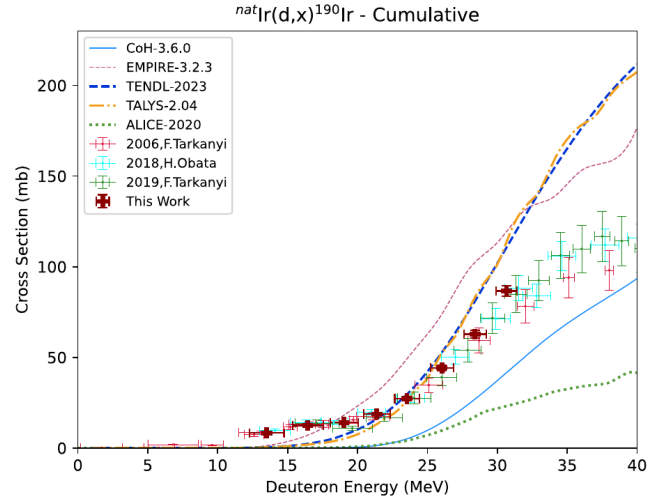


Fig. 11. Excitation function for ^{190}Ir (cumulative), including feeding of the ground state and from decay of its two isomers.

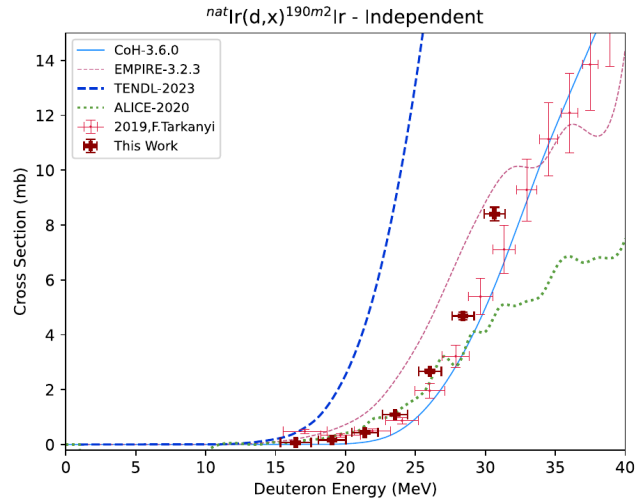


Fig. 12. Excitation function for $^{190m2}\text{Ir}$.

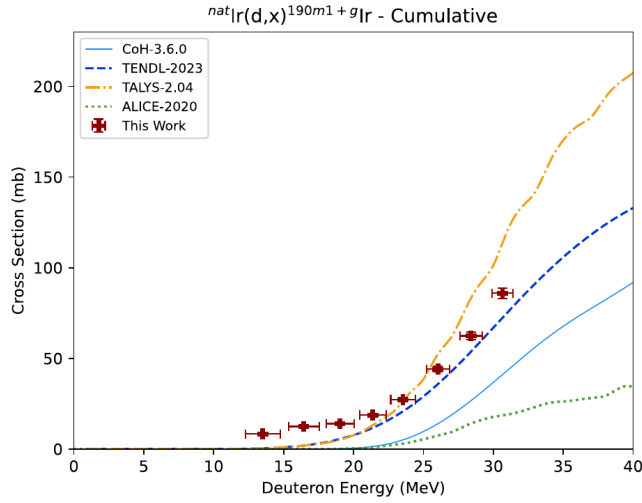


Fig. 13. Excitation function for $^{190m1}+g\text{Ir}$.

3.6. Excitation functions for $\text{natIr}(d,x)^{192}\text{Ir}$

^{192}Ir (Fig. 14) is produced via both target isotopes, and the excitation function visibly peaks around 10 MeV, increasing towards the second peak near 40 MeV. In addition, ^{192}Ir has two isomers, both of which decay by isomeric transition (m2: 100%, m1: 99.9825%). Neither were able to be directly measured in this work, due to their half-lives. The experimental data in this work are consistent with previous experimental data, though slightly higher. ALICE-2020 underestimates the excitation function. TENDL-2023 and TALYS-2.04 accurately predict the shape, but underestimate in magnitude. Neither EMPIRE-3.2.3 and CoH-3.6.0 reproduce the shape of the excitation function well.

3.7. Excitation functions for $\text{natIr}(d,x)^{194m1}+g\text{Ir}$

The cumulative cross sections for the ground state and m1 isomer (Fig. 15) are reported. The measurements agree well with previous experimental data. Both TALYS-2.04 and TENDL-2023 predict the shape of the excitation function, but suggest a peak maximum shifted slightly

towards a lower deuteron energy. CoH-3.6.0, ALICE-2020 and EMPIRE-3.2.3 disagree in shape and magnitude of the excitation function.

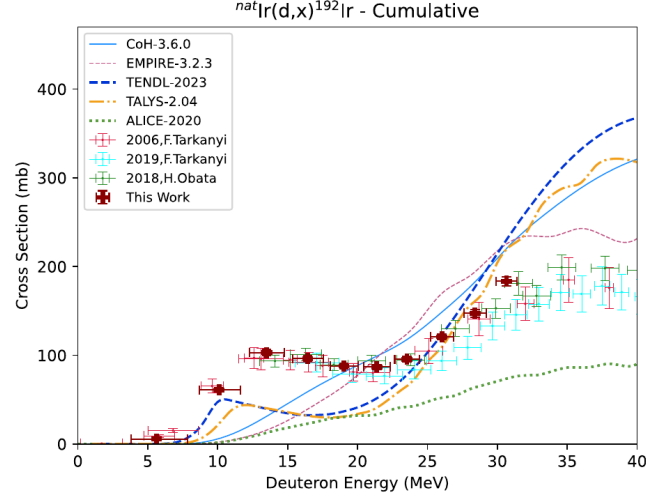


Fig. 14. Excitation function for $\text{natIr}(d,x)^{192}\text{Ir}$. Both reaction channels via $^{191}\text{Ir}(d,p)$ and $^{193}\text{Ir}(d,2np)$ can be seen, where the former peaks at approximately 14 MeV and the latter begins to peak at approximately 35–40 MeV.

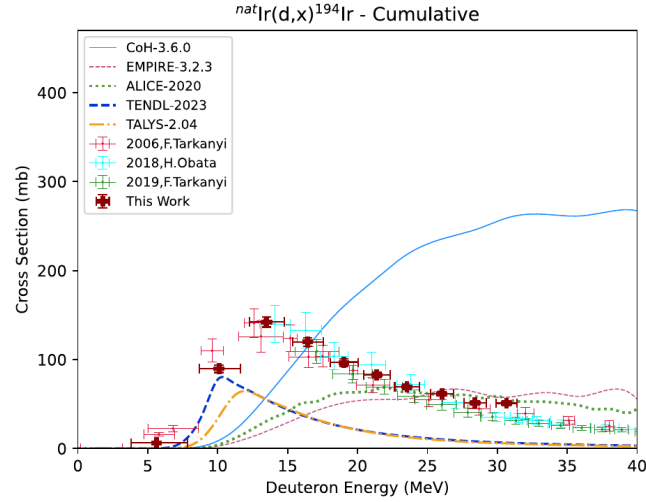


Fig. 15. Excitation function for $\text{natIr}(d,x)^{194}\text{Ir}$.

3.8. Physical thick target yield

In this work, physical yields were calculated for the observed iridium products. The physical thick target yield is defined here as the yield at the beginning of the irradiation (at $\Delta t_{\text{irr}} = 0$) per unit current (MBq/C) (Otuka and Takács, 2015):

$$\alpha_{\text{phys}} = \lambda \int_{E_L}^{E_0} (1/\rho \cdot dE/dx)^{-1} \cdot \sigma(E)/(Z \cdot e) dE \quad (5)$$

where λ represents the decay constant for a product with cross section $\sigma(E)$. The deuteron energy window is integrated from incident beam energy, E_0 , to the energy at the desired depth in the material E_L (typically to $E = 0$ or threshold of the desired reaction). ρ is the mass density of the target, dE/dx is the beam stopping power in the target, and $Z \cdot e$ is the charge of the particle beam, here +1 for deuterons.

For medical applications, the primary competing measurable reaction channels for ^{193}mPt in the energy region are from $^{191}\text{Ir}(d,2n)^{191}\text{Pt}$, $^{191}\text{Ir}(d,p)^{192}\text{Ir}$ and $^{193}\text{Ir}(d,p)^{194}\text{Ir}$, as shown in Fig. 16. Radiocontamination from $^{188,189}\text{Pt}$ appears above deuteron energies of approximately 19 MeV, well above the threshold for ^{193}mPt production. Contamination from other radioplatinums is not desired due to the inability to separate them via radiochemical methods. For a natural Ir target, the energy window yielding the highest cross sections is between 8–18 MeV, where the only competing radioplatinum is formed via $^{191}\text{Ir}(d,2n)^{191}\text{Pt}$. Beyond 18 MeV, not only does ^{189}Pt (along with ^{191}Pt from $^{193}\text{Ir}(d,4n)$) rise rapidly, but very little additional ^{193}mPt is produced, making higher energies useless for production. By using an enriched target of ^{193}Ir , contaminants of radioplatinums can likely be significantly reduced. In addition, production of stable ^{192}Pt will be reduced, which is preferable as production of “cold” platinum will compete with ^{193}mPt during labeling, reducing its specific activity and, thus, clinical potency. The stable/long-lived platinum contaminants $^{193,194}\text{Pt}$ will be produced in this energy window, which will reduce the specific activity of the final product, though ^{193}mPt production should still dominate on a mass basis. Additionally, both ^{192}Ir and ^{194}Ir decay to stable ^{192}Pt and ^{194}Pt . To reduce further increase of stable platinum contaminants, separation of ^{193}mPt should take place shortly after end of beam, to minimize this stable platinum feeding from ^{194}Ir in particular, with

a half-life of 19.28 h. Further measurements of both cross sections and derived thick-target yields should be performed using an enriched ^{193}Ir target, to further optimize production conditions if $^{193\text{m}}\text{Pt}$ gains widespread clinical interest.

As mentioned in the introduction, deuterons are expected to more strongly populate $^{193\text{m}}\text{Pt}$ due to their increased spin transfer, relative to protons. As there are currently no experimental data on $\text{natIr}(p,x)^{193\text{m}}\text{Pt}$, TENDL-2023 was used to compare the production cross sections of protons and deuterons for both the ground state and isomer (Fig. 17(a)), as well as their thick target yields (Fig. 17(b)). We can see that the production cross section for $^{193\text{m}}\text{Pt}$ is about 12 times higher for deuterons than protons. The thick target yield emphasizes this. We can clearly see that both the isomer to ground state ratio is highest using deuterons, and that deuterons will provide a higher physical thick target yield than protons.

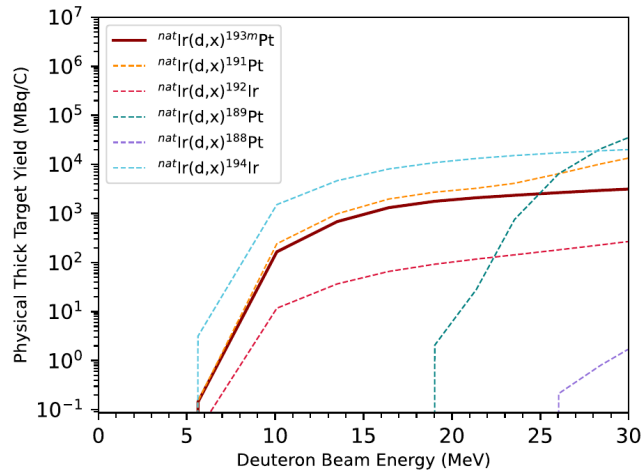


Fig. 16. The physical thick target yield for various competing reactions for deuterons on natural iridium.

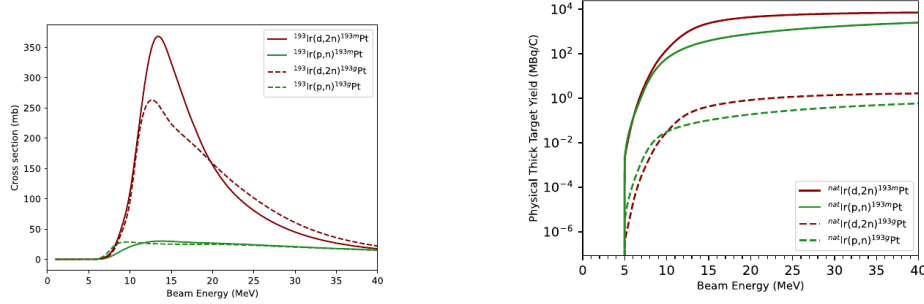


Fig. 17. (a) The excitation functions of the ground state and isomer production of ^{193}Pt , produced with protons and deuterons. Deuteron production yields higher cross sections than protons. (b) Thick target yield calculated using the TENDL-2023 cross sections. This indicates that the population of the isomer using deuterons will provide the higher yield. For both routes, the isomer yield is significantly larger than the yields of the ^{193}Pt ground state due to both larger cross sections as well as a significantly shorter half life.

3.9. Status of deuteron monitor reactions

The current state of datasets used to obtain the IAEA-recommended cross section data for deuteron-induced monitor reactions is significantly more limited compared to proton-induced reactions. For instance, the reaction $\text{natCu}(p,x)^{63}\text{Zn}$ has 3.7 times more experimental datasets than $\text{natCu}(d,x)^{63}\text{Zn}$. More experimental data will improve the monitor reactions, yielding more precise beam currents, and better cross section results. The particular monitor reaction of $\text{natCu}(d,x)^{63}\text{Zn}$ (Fig. 18) is a good example of opportunities for improvement in deuteron monitor reactions. While our apparent $\text{natCu}(d,x)^{63}\text{Zn}$ cross sections (calculated using the final beam currents in the same fashion as with all other reactions on copper), agree with the IAEA evaluation up to approximately 15 MeV, we yield higher values beyond this energy and in the pre-equilibrium tail than the recommended IAEA data. Notably, relatively few measurements (with significant spread) exist in this region, with the current evaluation essentially fitting the Ochiai data (Ochiai et al., 2007) beyond 30 MeV, and approximately interpolating between the average of the lower-energy Lebeda data (Lebeda and Červenák, 2019) and the high-energy Ochiai data from 20–30 MeV. This is also apparent in the beam current plot from earlier (Fig. 3), where this particular reaction consistently yielded higher beam currents, without significant improvement after variance

minimization. If the beam current solely relied upon this monitor reaction, all the measured cross sections would have resulted in systematically being offset above 15 MeV, paving a cautionary tale for those measuring cross sections without the use of multiple monitor reactions to build confidence. For this reaction, we recommend to perform additional measurements, in particular for deuteron energies from 15-30 MeV, to build confidence in the location of the compound peak and the pre-equilibrium tail, and to perform an updated evaluation based on this future work. Comparisons for the remaining monitor reactions are plotted in Fig. C.20 of Appendix C.

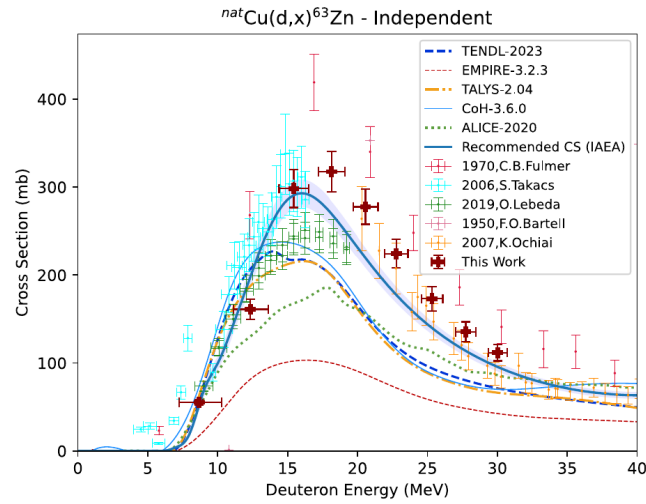


Fig. 18. The excitation function of $^{nat}\text{Cu}(d,x)^{63}\text{Zn}$. Experimental data are retrieved from the EXFOR database (Fulmer and Williams, 1970; Takács et al., 2006; Lebeda and Červenák, 2019; Bartell et al., 1950; Ochiai et al., 2007).

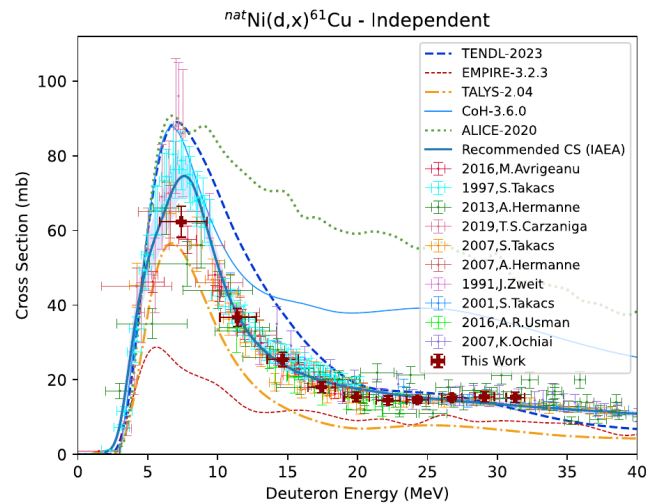


Fig. 19. The excitation function of $\text{natNi(d,x)}^{61}\text{Cu}$. Experimental data are retrieved from the EXFOR database (Avriganu et al., 2016; Takács et al., 1997; Hermanne et al., 2013; Carzaniga et al., 2019; Takács et al., 2007; Hermanne et al., 2007; Zweit et al., 1991; Takács et al., 2001; Usman et al., 2016; Ochiai et al., 2007).

Similarly, in light of our recently-reported relative γ -ray intensities for the decay of ^{61}Cu (Bleuel et al., 2021), we have adopted the decay data from the IAEA-proposed re-evaluation based upon our measurements (Hermanne et al., 2025). Using these decay data, we report here new independent cross sections for the $\text{natNi(d,x)}^{61}\text{Cu}$ monitor reaction, seen in Fig. 19. The re-evaluation uses these decay data to report corrected cross sections for the $\text{natNi(d,x)}^{61}\text{Cu}$ monitor reaction, but as the pointwise data are not yet publicly available, we can only compare to the existing evaluation. Overall, the changes in decay data have only minor impact, with less than approximately 5% changes in cross section seen as a result. These changes also are consistent with the systematics seen in the re-evaluation, particularly for the inflection point seen near 20 MeV (Hermanne et al., 2025). While the impact in these results is minor/modest, due to our use of multiple gamma lines in spectroscopy, these new results will be valuable for future evaluations of this monitor reaction.

This observation indicates the need for the development and evaluation of new monitor reactions for deuteron-induced reactions. A good monitor reaction product should have the following properties: high intensity, distinct gamma lines without background contamination, sufficiently long half-life to allow for multiple observations with good statistics, no production possible through secondary neutrons, and preferably no decay feeding by other radionuclides. In addition, monitor targets should be available and inexpensive. Currently, the only deuteron monitor reaction for a natFe target is the $\text{natFe(d,x)}^{56}\text{Co}$ reaction. Both $\text{natFe(d,x)}^{57}\text{Co}$ and $\text{natFe(d,x)}^{58}\text{Co}$ are candidate reactions that should perhaps be considered in the future, given the fairly modest amount of experimental data currently available for both reactions natNi(d,x) has a

limited number of monitor reactions that meet the criteria, as the current reactions $\text{natNi(d,x)}^{56,58}\text{Co}$ are both subject to decay feeding and can be produced through secondary neutrons. $\text{natNi(d,x)}^{64}\text{Cu}$ may be considered, but its lack of intense gamma lines make it challenging to use as a monitor channel. natIr(d,x) is not practically suitable as a monitor foil due to the high cost of the target material.

4. Conclusions

This work presents 43 cross-section measurements, in the beam-energy range between threshold and 33 MeV, for the natIr(d,x) , natFe(d,x) , natNi(d,x) , and natCu(d,x) reactions. Most of these results provide the best precision for the respective reactions to date. We report the first measurements of experimental measurements of $\text{natIr(d,x)}188\text{m1}+\text{gIr}$ (independent), $\text{natIr(d,x)}190\text{m1}+\text{gIr}$ (cumulative), $\text{natFe(d,x)}48\text{V},53\text{Fe}$ (cumulative), $\text{natFe(d,x)}61\text{Co}$ (cumulative), $\text{natNi(d,x)}59\text{Fe}$ (cumulative), $\text{natNi(d,x)}56,57,58\text{ m},58\text{gCo}$ (independent). In this work, the energy window which optimizes the production of 193mPt was investigated. In addition, other medically valuable radionuclides such as 191Pt and $192,194\text{Ir}$ were also investigated. Physical thick target yield proves an optimized production window from threshold to 18 MeV. The physical thick target yield of protons and deuterons were compared both for the ground state and the isomer of 193Pt using TENDL-2023. This emphasized the isomer-to-ground state ratio being higher using deuterons, as well as a higher yield for 193mPt in total.

Modeling of deuteron-induced reactions on iridium, in particular, has provided yet another example of the poor predictive capability of modern reaction codes, particularly for the range of high-spin isomers populated in these reactions. Developing a framework for parameter optimization similar to that in our recent work for proton-induced reactions (Fox et al., 2021b,a) is an obvious next step, given the performance seen here. However, such an optimization would benefit from reaction data collected for deuteron irradiations of a naturally mono-isotopic or enriched target, to significantly constrain the parameter space involved. Likewise, choosing a spherical or nearly spherical target nucleus as a first step will provide an important probe to optimize the nuclear level density model. In particular, our results suggest that these codes would benefit from improvements in the deuteron optical model, the role of angular momentum transfer

in these reactions, and the competition between compound reaction mechanisms and deuteron breakup. While such an optimization is beyond the scope of the current work, these results nonetheless play a valuable role in highlighting the need for future work in proving the predictive performance of deuteron-induced reaction modeling. This work has also identified a potential error in the branching ratio of ^{189}Ir . Finally, this work has revealed weaknesses with the $\text{natCu(d,x)}^{63}\text{Zn}$ and $\text{natNi(d,x)}^{61}\text{Cu}$ monitor reaction evaluations, further emphasizing the importance of high-fidelity experimental data, and the dangers of reliance upon a single monitor reaction, in particular for deuterons.

CRedit authorship contribution statement

H.L.O. Ekeberg: Writing – original draft, Formal analysis, Data curation. A.S. Voyles: Writing – review & editing, Formal analysis, Data curation. M.S. Basunia: Writing – review & editing. J.C. Batchelder: Writing – review & editing. L.A. Bernstein: Writing – review & editing. D.L. Bleuel: Writing – review & editing. K.C.W. Li: Writing – review & editing. E.M. Martinsen: Writing – review & editing. E.F. Matthews: Writing – review & editing. J.T. Morrell: Writing – review & editing. N.I.J. Pettersen: Writing – review & editing. S. Siem: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors have shared the data: <https://doi.org/10.5281/zenodo.6584051>

Appendix C. Excitation functions for monitor reactions and additional reaction channels

Excitation functions for the monitor reactions $\text{natFe}(d,x)^{56}\text{Co}$, $\text{natNi}(d,x)^{56,58}\text{Co}$, ^{61}Cu and $\text{natCu}(d,x)^{62,65}\text{Zn}$ are presented in Fig. C.20, and ^{63}Zn is presented in Fig. 18. Excitation functions for reactions induced in iron are presented in Figs. C.21 and C.22. Excitation functions for reactions induced in nickel are presented in Figs. C.23, C.24 and C.25. Excitation functions for reactions induced in copper are presented in Fig. C.26. All excitation functions are compared to experimental data retrieved from the EXFOR database.

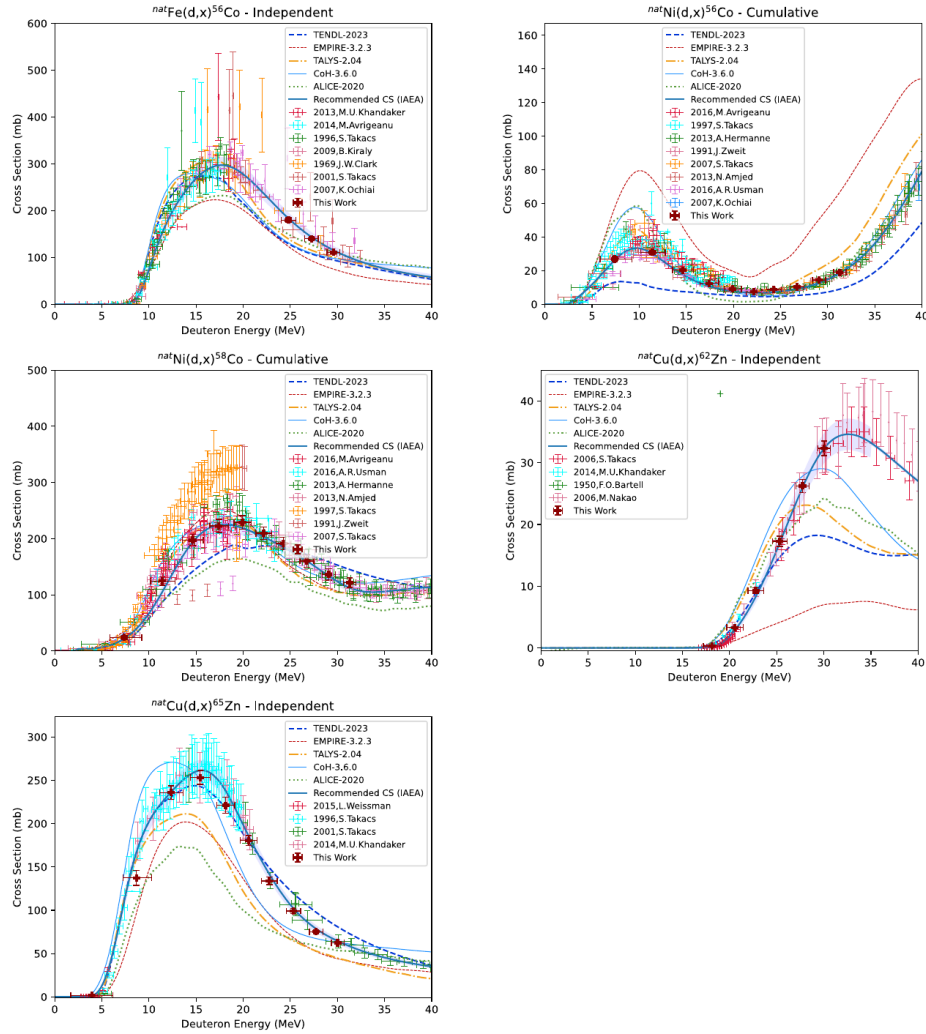


Fig. C.20. Excitation functions for the monitor reactions (except for $\text{natCu(d,x)}^{63}\text{Zn}$ and $\text{natNi(d,x)}^{61}\text{Cu}$, seen in Figs. 18 and 19).

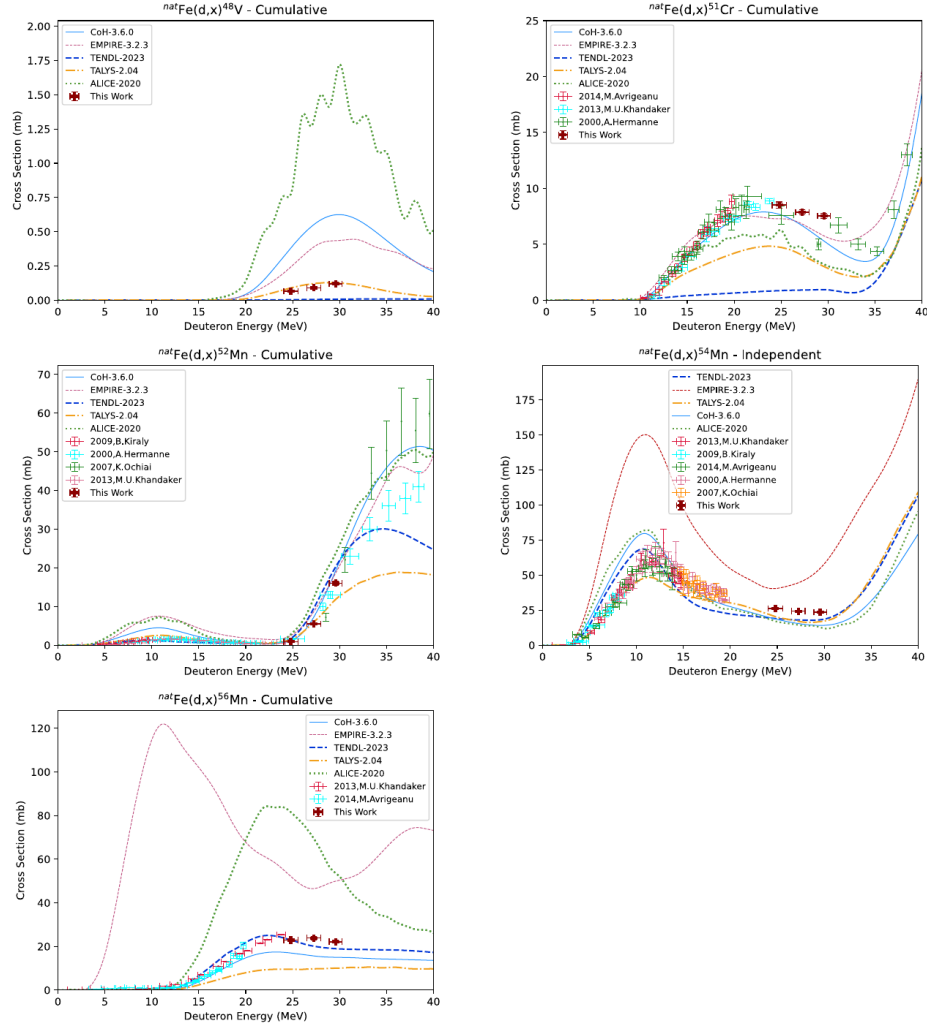


Fig. C.21. Excitation functions for reactions on natural iron.

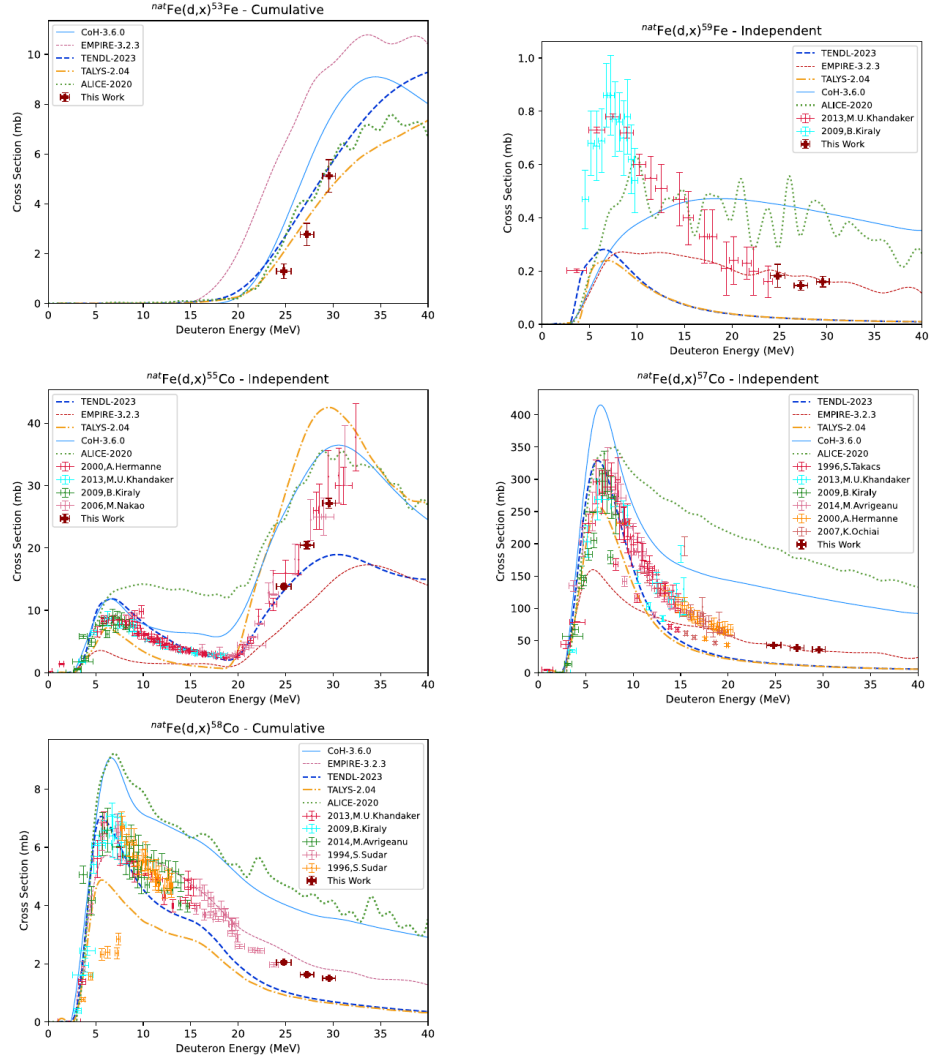


Fig. C.22. Excitation functions for reactions on natural iron.

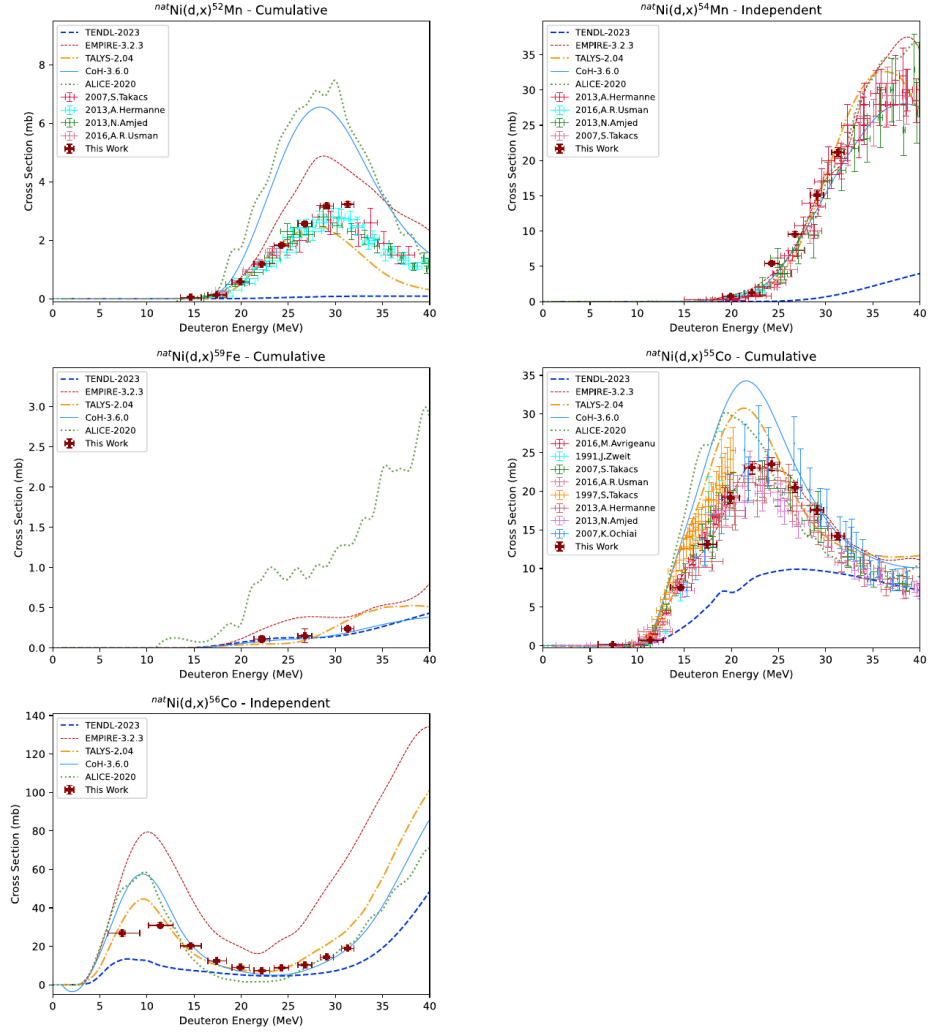


Fig. C.23. Excitation functions for reactions on natural nickel.

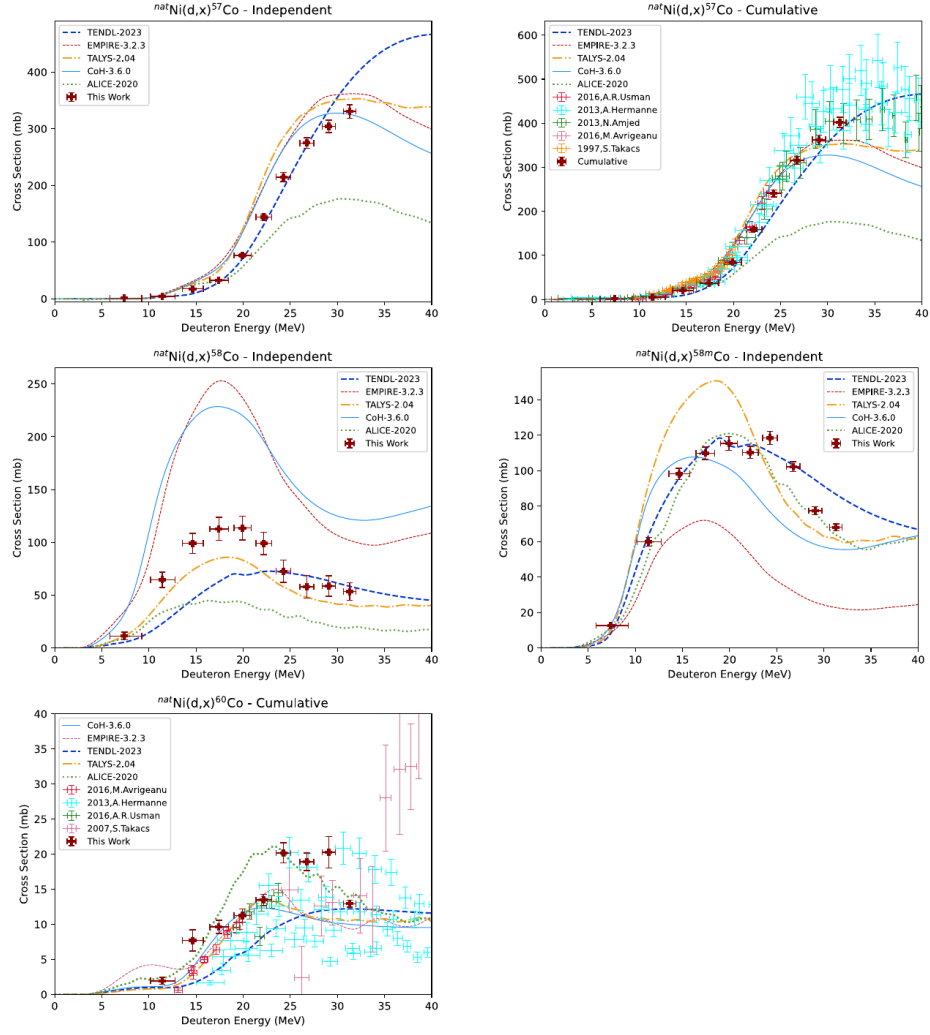


Fig. C.24. Excitation functions for reactions on natural nickel.

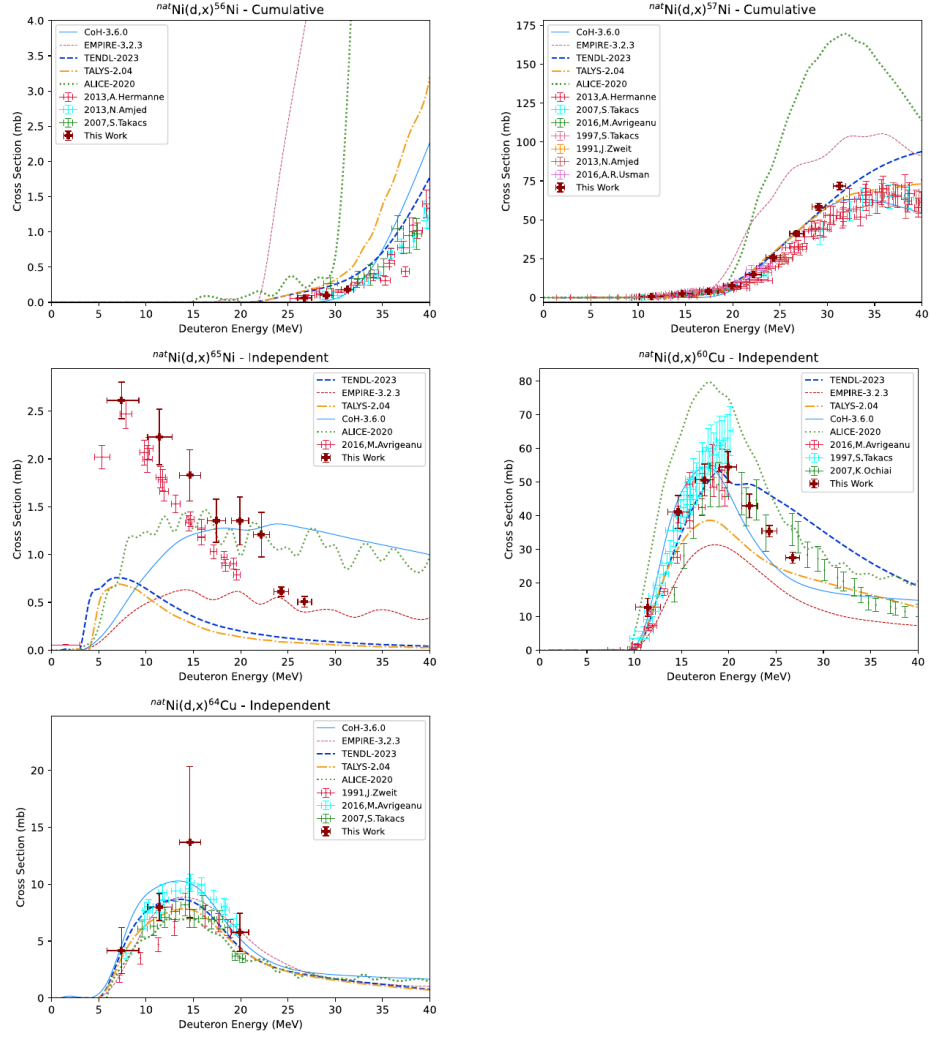
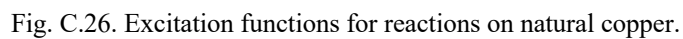


Fig. C.25. Excitation functions for reactions on natural nickel.



Appendix A. Stack design

The stack design is tabulated in Table A.1. The deuteron beam enters the stack upstream of the SS1 profile monitor, and travels through the stack in the order presented here. A 316 stainless steel foil is inserted at both the front and rear of the target stack as a monitor of the beam's spatial profile by developing radiochromic film (Gafchromic EBT3) after end-of-bombardment. Unlike in recent work with proton irradiations, no degrader foils or Kapton tape were included between the foils listed here, due to the increased stopping power of deuterons.

Foil	Measured thickness (μm)	Measured areal density (mg/cm^2)
SS1	124.5 ± 1.0	100.199 ± 0.091
Ni01	28.5 ± 1.0	22.77 ± 0.14
Ir01	29.5 ± 1.3	55.174 ± 0.053
Cu01	34.1 ± 3.0	22.338 ± 0.048
Fe01	27.8 ± 1.0	20.03 ± 0.11
Ni02	29.5 ± 1.0	23.118 ± 0.096
Ir02	27.8 ± 1.5	55.60 ± 0.24
Cu02	34.8 ± 2.0	22.325 ± 0.028
Fe02	27.4 ± 4.0	20.017 ± 0.034
Ni03	27.0 ± 1.0	22.338 ± 0.066
Ir03	24.3 ± 1.7	55.64 ± 0.12
Cu03	34.3 ± 3.0	22.313 ± 0.043
Fe03	31.0 ± 4.0	19.95 ± 0.11
Ni04	27.3 ± 1.0	20.704 ± 0.068
Ir04	26.1 ± 2.9	56.00 ± 0.11
Cu04	33.3 ± 1.0	22.284 ± 0.027
Ni05	26.3 ± 1.0	21.768 ± 0.045
Ir05	25.6 ± 2.4	55.161 ± 0.081
Cu05	33.4 ± 3.0	22.443 ± 0.028
Ni06	28.5 ± 2.0	22.86 ± 0.12
Ir06	24.0 ± 1.2	55.731 ± 0.088
Cu06	34.0 ± 2.0	22.396 ± 0.012
Ni07	26.8 ± 2.0	23.092 ± 0.078
Ir07	27.8 ± 2.2	56.685 ± 0.085
Cu07	32.6 ± 2.0	22.320 ± 0.014
Ni08	25.6 ± 3.0	22.41 ± 0.12
Ir08	28.1 ± 2.2	58.03 ± 0.13
Cu08	33.3 ± 3.0	22.401 ± 0.033
Ni09	25.7 ± 4.0	21.741 ± 0.073
Ir09	27.3 ± 1.0	56.669 ± 0.043
Cu09	33.1 ± 2.0	22.425 ± 0.041

Foil	Measured thickness (μm)	Measured areal density (mg/cm^2)
Ni10	27.1 ± 3.0	23.093 ± 0.024
Ir10	27.0 ± 1.6	55.065 ± 0.055
Cu10	35.5 ± 1.0	22.314 ± 0.047
SS2	125.2 ± 1.0	100.865 ± 0.097

Table A.1. Specifications of the target stack design in the present work.

Appendix B. Tabulated nuclear and reaction data

Accepted decay data used to calculate activities for the monitor products are listed in Table B.2, and Tables B.3–B.6 for nuclei produced from iridium, iron, nickel and copper, respectively. Decay data is retrieved from the NuDat-3.0 database.

Monitor reaction	Half-life	E_γ (keV) (I_γ %)	Useful beam-energies (MeV)
natFe(d,x)56Co	77.236 d	263.434 (0.0220 $\pm$ 0.0003); 486.55 (0.0540 $\pm$ 0.002); 733.514 (0.191 $\pm$ 0.003); 787.743 (0.311 $\pm$ 0.003); 846.77 (99.9399 $\pm$ 0.0023); 852.732 (0.049 $\pm$ 0.003); 896.51 (0.073 $\pm$ 0.003); 977.372 (1.421 $\pm$ 0.006); 996.948 (0.111 $\pm$ 0.004); 1037.843 (14.05 $\pm$ 0.04); 1140.368 (0.132 $\pm$ 0.003); 1159.944 (0.094 $\pm$ 0.006); 1175.101 (2.252 $\pm$ 0.006); 1198.888 (0.049 $\pm$ 0.005); 1238.288 (66.46 $\pm$ 0.12); 1335.4 (0.1224 $\pm$ 0.0012); 1360.212 (4.283 $\pm$ 0.012); 1771.357 (15.41 $\pm$ 0.06); 1963.741 (0.707 $\pm$ 0.004); 2015.215 (3.016 $\pm$ 0.012); 2034.791 (7.77 $\pm$ 0.03); 2212.944 (0.388 $\pm$ 0.004); 2276.131 (0.118 $\pm$ 0.004); 2598.5 (16.97 $\pm$ 0.04)	10–50
natNi(d,x)56Co (cumulative)	77.236 d	787.743 (0.3111 $\pm$ 0.003); 846.77 (99.9399 $\pm$ 0.0023); 977.372 (1.421 $\pm$ 0.006); 1175.101 (2.252 $\pm$ 0.006); 1963.741 (0.707 $\pm$ 0.004); 2015.215 (3.016 $\pm$ 0.012); 2034.791 (7.77 $\pm$ 0.03)	5–50
natNi(d,x)58Co (cumulative)	70.86 d	810.7593 (99.450 $\pm$ 0.01); 863.951 (0.686 $\pm$ 0.01); 1674.725 (0.517 $\pm$ 0.01)	5–50
natNi(d,x)61Cu (Hermanne et al., 2025)	3.339 h	282.956 (12.7 $\pm$ 2.0); 373.05 (2.14 $\pm$ 0.33); 529.169 (0.37 $\pm$ 0.06); 588.605 (1.17 $\pm$ 0.18); 625.605 (0.044 $\pm$ 0.008); 656.008 (10.07 $\pm$ 1.68); 816.692 (0.35 $\pm$ 0.05); 841.211 (0.24 $\pm$ 0.04); 902.294 (0.087 $\pm$ 0.013); 1032.162 (0.055 $\pm$ 0.012); 1073.465 (0.042 $\pm$ 0.012); 1132.351 (0.091 $\pm$ 0.014); 1185.234 (3.6 $\pm$ 0.6); 1446.492 (0.046 $\pm$ 0.007)	3–50
natCu(d,x)62Zn	9.193 h	40.85 (25.5 $\pm$ 2.4); 243.36 (2.52 $\pm$ 0.23); 246.95 (1.90 $\pm$ 1.8); 260.43 (1.35 $\pm$ 1.3); 304.88 (0.29 $\pm$ 0.03); 394.03 (2.24 $\pm$ 0.17); 548.35 (15.3 $\pm$ 1.4); 596.56 (26.0 $\pm$ 2.0); 637.41 (0.25 $\pm$ 0.03)	15–50
natCu(d,x)63Zn	38.47 min	449.93 (0.236 $\pm$ 0.019); 669.62 (8.2 $\pm$ 0.3); 962.06 (6.5 $\pm$ 0.4)	8–50
natCu(d,x)65Zn	243.93 d	1115.539 (50.04 $\pm$ 0.1)	5–50

Table B.2. Overview of the gamma-lines used to calculate monitor reaction activities in each foil at end of beam.

Products observed for reactions on Iridium foils. Iridium has two stable isotopes: ^{191}Ir (37.3%) and ^{193}Ir (62.7%).

Nuclide (level, keV)	Half-life	Decay mode	Reaction route	Q value (keV)	E_γ (keV) (I_γ %)
^{188}Ir (0.0)	41.5 h	$\epsilon = 100\%$	$^{191}\text{Ir}(\text{d},4\text{np})$	-24802.0	1209.8 (6.9 ± 0.7); 1715.67 (6.2 ± 0.6); 2059.65 (7.0 ± 0.6)
^{189}Ir (0.0)	13.2 d	$\epsilon = 100\%$	$^{191}\text{Ir}(\text{d},3\text{np})$; $^{193}\text{Ir}(\text{d},5\text{np})$	-16626.0; -30596.0	233.5 (0.30 ± 0.03); 245.1 (6.0 ± 0.6)
^{190}Ir (0.0)	11.78 d	$\epsilon = 100\%$	$^{191}\text{Ir}(\text{d},2\text{np})$; $^{193}\text{Ir}(\text{d},4\text{np})$	-10251.1; -24221.2	294.75 (6.6 ± 0.7); 380.03 (2.03 ± 0.11); 1036.05 (2.42 ± 0.16)
$^{190\text{m}}\text{Ir}$ (376.4)	3.087 h	IT=8.6%; $\epsilon=91.4\%$	$^{191}\text{Ir}(\text{d},2\text{np})$; $^{193}\text{Ir}(\text{d},4\text{np})$	-10627.5; -24597.6	361.2 (86.72 ± 0.21); 502.5 (89.38 ± 0.2)
^{192}Ir (0.0)	73.829 d	$\epsilon=4.76\%$; $\beta^-=95.24\%$	$^{191}\text{Ir}(\text{d},\text{p})$; $^{193}\text{Ir}(\text{d},2\text{np})$	3973.55; -9996.6	201.3112 (0.471 ± 0.006); 374.4852 (0.727 ± 0.007); 416.4688 (0.670 ± 0.021); 468.06885 (47.84 ± 0.03); 489.06 (0.438 ± 0.015); 612.46215 (5.34 ± 0.07); 1061.49 (0.0531 ± 0.0006)
^{194}Ir (0.0)	19.28 h	$\beta^- = 100\%$	$^{193}\text{Ir}(\text{d},\text{p})$	3842.22	293.541 (2.5 ± 0.3); 938.69 (0.60 ± 0.08); 1468.91 (0.19 ± 0.03)
^{188}Pt (0.0)	10.16 d	$\epsilon=99.999974\%$; $\alpha=0.000026\%$	$^{191}\text{Ir}(\text{d},5\text{n})$	-26109.0	195.05 (18.336 ± 0.955); 381.43 (7.3535 ± 0.382)
^{189}Pt (0.0)	10.87 h	$\epsilon = 100\%$	$^{191}\text{Ir}(\text{d},4\text{n})$	-19389.0	94.34 (6.5 ± 1.8); 113.82 (2.5 ± 0.7); 243.5 (5.9 ± 1.8); 317.65 (2.8 ± 0.7); 721.38 (7.9 ± 2.1)
^{191}Pt (0.0)	2.802 d	$\epsilon = 100\%$	$^{191}\text{Ir}(\text{d},2\text{n})$; $^{193}\text{Ir}(\text{d},4\text{n})$	-4017.0; -17988.0	178.96 (0.99 ± 0.17); 351.17 (3.4 ± 0.6); 409.44 (7.9 ± 1.4); 456.47 (3.3 ± 0.6); 538.87 (14.3 ± 2.4); 624.06 (1.46 ± 0.25)
$^{193\text{m}}\text{Pt}$ (149.783)	4.33 d	IT = 100%	$^{193}\text{Ir}(\text{d},2\text{n})$	-3063.5	66.831 (7.21 ± 0.15); 135.5 (0.1145 ± 0.03)

Table B.3. Products observed for reactions on iridium foils.

Products observed for reactions on Iron foils. Iron has four stable isotopes: ^{54}Fe (5.845%), ^{56}Fe (91.754%), ^{57}Fe (2.119%) and ^{58}Fe (0.282%).

Nuclide (level, keV)	Half-life	Decay mode	Reaction route	Q value (keV)	$E\gamma$ (keV) ($I\gamma$ %)
48V (0.0)	15.9735 d	$\epsilon = 100\%$	$^{54}\text{Fe}(d,2\alpha)$; $^{56}\text{Fe}(d,2n2\alpha)$; $^{57}\text{Fe}(d,3n2\alpha)$	-3490.9; -23986.1; -31632.2	944.13 (7.870 ± 0.007); 983.525 (99.98 ± 0.04); 1312.106 (98.2 ± 0.3)
^{51}Cr (0.0)	27.704 d	$\epsilon = 100\%$	$^{54}\text{Fe}(d,p\alpha)$; $^{56}\text{Fe}(d,2np\alpha)$; $^{57}\text{Fe}(d,3np\alpha)$; $^{58}\text{Fe}(d,4np\alpha)$	-1381.3; -21876.5; -29522.6; -39567.2	320.0824 (9.910 ± 0.01)
^{52}Mn (0.0)	5.591 d	$\epsilon = 100\%$	$^{54}\text{Fe}(d,\alpha)$; $^{54}\text{Fe}(d,2n2p)$; $^{56}\text{Fe}(d,2n\alpha)$; $^{57}\text{Fe}(d,3n\alpha)$	5163.6; -23132.1; -15331.6; -22977.7	346.02 (0.980 ± 0.014); 744.233 (90.0 ± 1.2); 848.18 (3.32 ± 0.4); 935.544 (94.5 ± 1.3); 1246.278 (4.21 ± 0.07); 1333.649 (5.07 ± 0.07); 1434.092 (100.0 ± 14.0)
^{54}Mn (0.0)	312.20 d	$\epsilon = 100\%$	$^{54}\text{Fe}(d,2p)$; $^{56}\text{Fe}(d,\alpha)$; $^{57}\text{Fe}(d,n\alpha)$; $^{58}\text{Fe}(d,2n\alpha)$	-2139.1; 5661.4; -1984.7; -12029.3	834.848 (99.9760 ± 0.001)
^{56}Mn (0.0)	2.5789 h	$\beta^- = 100\%$	$^{56}\text{Fe}(d,2p)$; $^{57}\text{Fe}(d,n2p)$; $^{58}\text{Fe}(d,\alpha)$	-5137.8; -12783.8; 5467.2	846.7638 (98.86 ± 0.03); 1810.726 (26.9 ± 0.4); 2113.092 (14.2 ± 0.3)
^{53}Fe (0.0)	8.51 min	$\epsilon = 100\%$	$^{54}\text{Fe}(d,2np)$; $^{56}\text{Fe}(d,4np)$	-15602.9; -36098.1	377.9 (42.0 ± 3.0)
^{59}Fe (0.0)	44.490 d	$\beta^- = 100\%$	$^{58}\text{Fe}(d,p)$	4356.44	1099.245 (56.5 ± 0.9); 1291.59 (43.2 ± 0.9)
^{55}Co (0.0)	17.53 h	$\epsilon = 100\%$	$^{54}\text{Fe}(d,n)$; $^{56}\text{Fe}(d,3n)$; $^{57}\text{Fe}(d,4n)$	2839.8; -17655.4; -25301.5	91.9 (1.16 ± 0.09); 477.2 (20.2 ± 1.7); 803.7 (1.87 ± 0.15); 827 (0.21 ± 0.06); 931.1 (75 ± 4.0); 1316.6 (7.1 ± 0.3); 1370 (2.9 ± 0.3); 1408.5 (16.9 ± 0.8); 2177.6 (0.29 ± 0.04); 2872.4 (0.118 ± 0.008); 2938.9 (0.057 ± 0.01)
^{57}Co (0.0)	271.74 d	$\epsilon = 100\%$	$^{56}\text{Fe}(d,n)$; $^{57}\text{Fe}(d,2n)$; $^{58}\text{Fe}(d,3n)$	3802.9; -3843.2; -13887.8	122.06065 (85.60 ± 0.17); 136.47356 (10.68 ± 0.08)
^{58}Co (0.0)	70.86 d	$\epsilon = 100\%$	$^{57}\text{Fe}(d,n)$; $^{58}\text{Fe}(d,2n)$	4729.7; -5314.9	810.7593 (99.450 ± 0.01)

Table B.4. Products observed for reactions on iron foils.

Products observed for reactions on Nickel foils. Nickel has five stable isotopes: ^{58}Ni (68.077%), ^{60}Ni (26.223%), ^{61}Ni (1.1399%), ^{62}Ni (3.6346%) and ^{64}Ni (0.9255%).

Nuclide (level, keV)	Half-life	Decay mode	Reaction route	Q value (keV)	E_γ (keV) (I_γ %)
^{52}Mn (0.0)	5.591 d	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},2\alpha)$; $^{60}\text{Ni}(\text{d},2\text{n}2\alpha)$; $^{61}\text{Ni}(\text{d},3\text{n}2\alpha)$	-1235.6; -21622.6; -29442.7	744.233 (90.0 ± 1.2); 935.544 (94.5 ± 1.3); 1246.278 (4.21 ± 0.07); 1434.092 (100.0 ± 1.4)
^{54}Mn (0.0)	312.20 d	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},2\text{p}\alpha)$; $^{60}\text{Ni}(\text{d},2\alpha)$; $^{61}\text{Ni}(\text{d},\text{n}2\alpha)$; $^{62}\text{Ni}(\text{d},2\text{n}2\alpha)$	-8538.3; -629.6; -8449.7; -19045.4	834.848 (99.9760 ± 0.001)
^{59}Fe (0.0)	44.490 d	$\beta^- = 100\%$	$^{60}\text{Ni}(\text{d},3\text{p})$; $^{61}\text{Ni}(\text{d},\text{n}3\text{p})$; $^{62}\text{Ni}(\text{d},\text{p}\alpha)$; $^{64}\text{Ni}(\text{d},2\text{np}\alpha)$	-12539.5; -20359.6; -2659.7; -19154.9	1291.59 (43.2 ± 0.9)
^{55}Co (0.0)	17.53 h	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},\text{n}\alpha)$; $^{58}\text{Ni}(\text{d},3\text{n}2\text{p})$; $^{60}\text{Ni}(\text{d},3\text{n}\alpha)$; $^{61}\text{Ni}(\text{d},4\text{n}\alpha)$	-3559.4; -31855.0; -23946.4; -31766.5	385.4 (0.54 ± 0.05); 520 (0.83 ± 0.08); 803.7 (1.87 ± 0.15); 931.1 (75 ± 4.0); 1212.8 (0.26 ± 0.03); 1316.6 (7.1 ± 0.3); 1370 (2.9 ± 0.3); 2177.6 (0.29 ± 0.04)
^{57}Co (0.0)	271.74 d	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},\text{n}2\text{p})$; $^{60}\text{Ni}(\text{d},\text{n}\alpha)$; $^{60}\text{Ni}(\text{d},3\text{n}2\text{p})$; $^{61}\text{Ni}(\text{d},2\text{n}\alpha)$; $^{62}\text{Ni}(\text{d},3\text{n}\alpha)$	-10396.7; -2488.1; -30783.8; -10308.2; -20903.9	122.06065 (85.60 ± 0.17); 136.47365 (10.68 ± 0.08)
$^{58\text{m}}\text{Co}$ (24.88921)	9.10 h	IT = 100%	$^{58}\text{Ni}(\text{d},2\text{n})$; $^{60}\text{Ni}(\text{d},\alpha)$; $^{61}\text{Ni}(\text{d},\text{n}\alpha)$; $^{62}\text{Ni}(\text{d},2\text{n}\alpha)$; $^{64}\text{Ni}(\text{d},4\text{n}\alpha)$	-1848.7; 6060.0; -1760.2; -12355.9; -28851.1	—
^{60}Co (0.0)	1925.28 d	$\beta^- = 100\%$	$^{60}\text{Ni}(\text{d},2\text{p})$; $^{61}\text{Ni}(\text{d},\text{n}2\text{p})$; $^{62}\text{Ni}(\text{d},\alpha)$; $^{64}\text{Ni}(\text{d},2\text{n}\alpha)$	-4265.0; -12085.1; 5614.8; -10880.4	1173.228 (99.85 ± 0.03); 1332.492 (99.9826 ± 0.0006)
^{56}Ni (0.0)	6.075 d	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},3\text{np})$	-24688.4	158.38 (98.8 ± 1.0); 480.44 (36.5 ± 0.8); 749.95 (49.5 ± 1.2); 811.85 (86.0 ± 0.9); 1561.8 (14.0 ± 0.6)
^{57}Ni (0.0)	35.60 h	$\epsilon = 100\%$	$^{58}\text{Ni}(\text{d},2\text{np})$; $^{60}\text{Ni}(\text{d},4\text{np})$	-14440.8; -34827.8	1757.55 (5.75 ± 0.2); 1919.52 (12.3 ± 0.4); 2804.2 (0.098 ± 0.004)
^{65}Ni (0.0)	2.51719 h	$\beta^- = 100\%$	$^{64}\text{Ni}(\text{d},\text{p})$	3873.51	366.27 (4.81 ± 0.06); 1481.84 (23.59 ± 0.0014); 1623.42 (0.498 ± 0.014); 1724.92 (0.399 ± 0.012)
^{60}Cu (0.0)	23.7 min	$\epsilon = 100\%$	$^{60}\text{Ni}(\text{d},2\text{n})$; $^{61}\text{Ni}(\text{d},3\text{n})$; $^{62}\text{Ni}(\text{d},4\text{n})$	-9134.9; -16955.0; -27550.7	467.3 (3.52 ± 0.18); 497.9 (1.67 ± 0.09); 643.2 (0.97 ± 0.05); 952.4 (2.73 ± 0.18); 1035.2 (3.70 ± 0.18); 1110.5 (1.06 ± 0.18); 1293.7 (1.85 ± 0.18); 1791.6 (45.4 ± 2.3); 1861.6 (4.8 ± 0.3); 1936.9 (2.20 ± 0.09); 2061 (0.79 ± 0.04); 2158.9 (3.34 ± 0.18); 2403.3 (0.77 ± 0.08); 2687.9 (0.44 ± 0.07); 2746.1 (1.06 ± 0.09)
^{64}Cu (0.0)	12.701 h	$\epsilon=61.5\%$; $\beta^-=38.5\%$	$^{64}\text{Ni}(\text{d},2\text{n})$	-4681.3	1345.77 (0.475 ± 0.011)

Table B.5. Products observed for reactions on nickel foils.

Products observed for reactions on Copper foils. Copper has two stable isotopes: ^{63}Cu (69.15%) and ^{65}Cu (30.85%).

Nuclide (level, keV)	Half-life	Decay mode	Reaction route	Q value (keV)	E_γ (keV) (I_γ %)
^{59}Fe (0.0)	44.490 d	$\beta^- = 100\%$	$^{63}\text{Cu}(\text{d}, 2\text{p}\alpha)$; $^{65}\text{Cu}(\text{d}, 2\alpha)$	-8782.1; 1687.0	1099.245 (56.5 ± 1.8); 1291.59 (43.2 ± 1.4)
^{60}Co (0.0)	1925.28 d	$\beta^- = 100\%$	$^{63}\text{Cu}(\text{d}, \text{p}\alpha)$; $^{65}\text{Cu}(\text{d}, 2\text{np}\alpha)$	-507.6; -18334.1	1173.228 (99.85 ± 3.0); 1332.492 (99.9826 ± 0.06)
^{61}Co (0.0)	1.649 h	$\beta^- = 100\%$	$^{63}\text{Cu}(\text{d}, \text{n}3\text{p})$; $^{65}\text{Cu}(\text{d}, \text{np}\alpha)$	-19484.2; -9015.1	67.412 (84.7)
^{65}Ni (0.0)	2.51719 h	$\beta^- = 100\%$	$^{65}\text{Cu}(\text{d}, 2\text{p})$	-3580.2	1481.84 (23.59 ± 0.14)
^{61}Cu (Hermanne et al., 2025) (0.0)	3.339 h	$\epsilon = 100\%$	$^{63}\text{Cu}(\text{d}, 3\text{np})$; $^{65}\text{Cu}(\text{d}, 5\text{np})$	-21962.9; -39789.4	282.956 (12.7 ± 2.0); 656.008 (10.07 ± 1.68); 1185.234 (3.6 ± 0.6)
^{64}Cu (0.0)	12.701 h	$\epsilon=61.5\%$; $\beta^-=38.5$	$^{63}\text{Cu}(\text{d}, \text{p})$; $^{65}\text{Cu}(\text{d}, 2\text{np})$	5691.54; -12135.0	1345.77 (0.475 ± 0.011)

Table B.6. Products observed for reactions on copper foils.

Appendix D. Tabulated cross sections

The tabulated measured cross sections obtained in this work are presented in Tables D.7, D.8, D.9 and D.10 for reactions in iridium, iron, nickel and copper, respectively. Subscript i indicates an independent measurement; subscript c indicates a cumulative measurement.

Nuclide	30.65	28.40	26.03	23.54	21.38	19.03	16.43	13.51	10.09	5.63
188Pt _i	0.95 ± 0.13	0.30 ± 0.09	0.17 ± 0.05	—	—	—	—	—	—	—
189Pt _i	486.47 ± 21.86	341.24 ± 16.64	172.11 ± 8.03	30.72 ± 1.48	1.04 ± 0.07	0.09 ± 0.02	—	—	—	—
191Pt _i	597.10 ± 16.55	483.60 ± 13.79	353.99 ± 9.67	165.12 ± 5.15	71.05 ± 2.19	77.53 ± 2.57	128.24 ± 4.03	137.37 ± 4.42	53.45 ± 3.23	1.05 ± 0.06
193mPt _i	48.11 ± 6.33	46.78 ± 2.18	55.68 ± 2.17	51.79 ± 2.12	58.31 ± 1.96	77.98 ± 2.89	115.33 ± 4.09	148.98 ± 5.54	56.18 ± 2.85	1.55 ± 0.12
188Ir _c	1.37 ± 0.01	0.47 ± 0.07	0.34 ± 0.08	—	—	—	—	—	—	—
188m1+gIr _c	0.42 ± 0.16	0.17 ± 0.11	0.17 ± 0.09	—	—	—	—	—	—	—
189Ir _c	334.77 ± 22.25	235.95 ± 16.33	84.03 ± 6.03	16.81 ± 5.17	—	—	—	—	—	—
190m2Iri	8.40 ± 0.25	4.69 ± 0.14	2.67 ± 0.08	1.09 ± 0.04	0.44 ± 0.01	0.17 ± 0.01	0.07 ± 0.01	—	—	—
190Ir _c	86.65 ± 2.89	62.80 ± 2.14	44.26 ± 1.47	27.29 ± 1.02	18.73 ± 0.71	14.02 ± 0.55	12.40 ± 0.51	8.26 ± 0.43	—	—
190m1+gIr _c	85.92 ± 2.89	62.39 ± 2.14	44.03 ± 1.47	27.19 ± 1.02	18.69 ± 0.71	14.01 ± 0.55	12.39 ± 0.51	8.26 ± 0.43	—	—
192Ir _c	183.35 ± 5.18	147.35 ± 4.28	120.82 ± 3.34	95.47 ± 3.02	86.86 ± 2.70	87.91 ± 2.93	96.17 ± 3.05	103.00 ± 3.35	60.91 ± 2.44	5.54 ± 0.32
194Ir _c	50.94 ± 2.28	51.41 ± 2.29	61.39 ± 2.39	69.45 ± 2.76	82.71 ± 3.21	96.64 ± 4.15	119.84 ± 4.66	142.26 ± 5.72	89.76 ± 4.22	6.35 ± 0.43

Table D.7. Measured cross sections (mb) for natIr(d,x) reactions. Column headers give the deuteron energy (MeV) at each foil position.

Nuclide	29.57	27.25	24.80
58Coc	1.50 ± 0.05	1.62 ± 0.05	2.05 ± 0.07
57Coi	35.91 ± 1.06	38.37 ± 1.13	42.63 ± 1.27
55Coi	27.15 ± 0.80	20.44 ± 0.60	13.82 ± 0.40
59Fei	0.16 ± 0.02	0.15 ± 0.02	0.18 ± 0.04
53Fec	5.11 ± 0.65	2.77 ± 0.44	1.29 ± 0.30
56Mnc	22.14 ± 0.65	23.86 ± 0.80	22.91 ± 0.65
54Mni	23.58 ± 0.70	24.18 ± 0.72	26.12 ± 0.79
52Mnc	16.00 ± 0.46	5.48 ± 0.16	0.91 ± 0.03
51Cre	7.54 ± 0.23	7.86 ± 0.25	8.51 ± 0.29
48Vc	0.12 ± 0.01	0.09 ± 0.01	0.07 ± 0.01
56Coi (monitor)	115.74 ± 3.55	143.76 ± 4.22	183.75 ± 5.41

Table D.8. Measured cross sections (mb) for natFe(d,x) reactions. Column headers give the deuteron energy (MeV) at each foil position.

Nuclide	31.29	29.08	26.74	24.28	22.19	19.92	17.42	14.63	11.41	7.40
64Cui	—	—	—	—	—	5.78 ± 1.66	—	13.69 ± 6.64	7.99 ± 1.19	4.17 ± 2.02
60Cui	—	—	27.51 ± 1.68	35.38 ± 1.71	42.90 ± 3.55	54.43 ± 4.62	50.61 ± 4.68	41.09 ± 4.89	12.76 ± 2.64	—
65Nii	—	—	0.51 ± 0.06	0.61 ± 0.05	1.21 ± 0.23	1.35 ± 0.25	1.35 ± 0.23	1.83 ± 0.27	2.23 ± 0.29	2.61 ± 0.19
57Nic	71.67 ± 2.37	58.38 ± 2.21	41.16 ± 1.38	25.85 ± 0.95	14.79 ± 0.62	7.66 ± 0.36	4.22 ± 0.18	2.61 ± 0.15	0.65 ± 0.05	—
56Nic	0.18 ± 0.01	0.10 ± 0.01	0.06 ± 0.01	—	—	—	—	—	—	—
60Coc	12.94 ± 0.48	20.26 ± 2.23	18.91 ± 1.24	20.17 ± 1.44	13.48 ± 0.77	11.25 ± 0.95	9.64 ± 0.95	7.69 ± 1.52	1.94 ± 0.51	—
58mCoi	68.06 ± 1.92	77.42 ± 2.20	102.27 ± 2.79	118.56 ± 3.70	110.28 ± 3.40	115.36 ± 3.86	109.86 ± 3.46	98.24 ± 3.19	59.93 ± 2.38	12.66 ± 0.69
58gCoi	53.45 ± 8.36	58.67 ± 9.72	58.02 ± 10.71	72.68 ± 10.59	99.10 ± 10.52	113.57 ± 11.36	112.78 ± 10.98	99.08 ± 9.48	64.66 ± 7.30	11.36 ± 3.74
57Coc	402.12 ± 11.70	362.58 ± 10.85	315.94 ± 9.06	240.63 ± 7.74	158.92 ± 5.17	84.14 ± 3.08	36.78 ± 1.23	20.01 ± 0.75	5.03 ± 0.23	1.29 ± 0.29
57Coi	330.46 ± 11.94	304.20 ± 11.08	274.78 ± 9.16	214.79 ± 7.79	144.12 ± 5.21	76.48 ± 3.10	32.56 ± 1.25	17.40 ± 0.77	4.38 ± 0.24	1.29 ± 0.29
56Coi	18.97 ± 0.56	14.38 ± 0.46	10.33 ± 0.31	8.88 ± 0.30	7.40 ± 0.25	9.06 ± 0.33	12.43 ± 0.41	20.30 ± 0.69	30.91 ± 1.24	26.89 ± 1.50
55Coc	14.19 ± 0.48	17.59 ± 0.59	20.47 ± 0.63	23.50 ± 0.81	23.03 ± 0.82	19.13 ± 0.72	13.11 ± 0.47	7.57 ± 0.30	0.71 ± 0.04	0.18 ± 0.03
59Fec	0.24 ± 0.03	—	0.15 ± 0.09	—	0.11 ± 0.03	—	—	—	—	—
54Mni	21.17 ± 0.64	15.11 ± 0.74	9.55 ± 0.35	5.42 ± 0.29	1.23 ± 0.08	0.76 ± 0.17	—	—	—	—
52Mnc	3.22 ± 0.09	3.17 ± 0.10	2.56 ± 0.07	1.83 ± 0.06	1.19 ± 0.04	0.57 ± 0.02	0.13 ± 0.01	0.05 ± 0.02	—	—
56Coc (mon.)	18.39 ± 1.02	14.16 ± 2.10	10.08 ± 1.12	8.83 ± 0.27	7.67 ± 0.24	9.57 ± 0.31	13.22 ± 0.41	19.73 ± 0.60	31.65 ± 0.91	27.78 ± 0.96
58Coc (mon.)	116.66 ± 18.54	133.05 ± 22.35	155.58 ± 29.03	190.24 ± 28.10	217.14 ± 23.76	241.76 ± 24.98	236.83 ± 23.97	191.83 ± 18.91	127.59 ± 14.39	24.81 ± 8.13
61Cui (mon.)	15.25 ± 1.41	15.44 ± 1.41	15.20 ± 0.88	14.67 ± 0.88	14.49 ± 1.19	15.39 ± 1.23	17.98 ± 1.44	25.45 ± 1.93	36.70 ± 2.48	62.33 ± 4.18

Table D.9. Measured cross sections (mb) for natNi(d,x) reactions. Column headers give the deuteron energy (MeV) at each foil position.

Nuclide	30.03	27.74	25.32	22.77	20.57	18.14	15.43	12.34	8.68	3.94
64Cui	170.76 ± 7.76	153.78 ± 8.20	132.56 ± 6.93	121.54 ± 7.12	106.07 ± 5.81	95.92 ± 7.14	123.79 ± 6.62	156.65 ± 8.20	209.38 ± 11.27	73.54 ± 5.70
61Cuc	4.54 ± 0.87	2.07 ± 0.95	1.18 ± 0.72	—	—	—	—	—	—	—
65Nii	3.42 ± 1.76	3.84 ± 1.94	2.89 ± 1.48	1.92 ± 1.14	—	—	—	—	—	—
61Coc	1.62 ± 0.09	0.82 ± 0.07	0.29 ± 0.05	—	—	—	—	—	—	—
60Coc	9.49 ± 0.52	11.38 ± 0.51	12.02 ± 0.51	11.36 ± 0.43	9.27 ± 0.41	5.65 ± 0.26	1.53 ± 0.12	—	—	—
59Fec	0.21 ± 0.03	0.18 ± 0.02	0.17 ± 0.02	0.12 ± 0.01	0.07 ± 0.01	0.03 ± 0.01	—	—	—	—
62Zni (mon.)	32.51 ± 1.24	26.56 ± 1.09	17.24 ± 0.83	9.37 ± 0.43	3.26 ± 0.17	0.32 ± 0.13	—	—	—	—
63Zni (mon.)	112.37 ± 9.38	137.19 ± 11.41	172.92 ± 13.89	226.46 ± 16.14	273.59 ± 19.27	322.03 ± 22.76	300.45 ± 21.21	170.56 ± 12.23	60.07 ± 3.19	—
65Zni (mon.)	62.65 ± 1.90	76.11 ± 2.47	98.93 ± 2.87	135.19 ± 4.09	177.91 ± 4.97	224.29 ± 8.55	254.98 ± 7.25	249.63 ± 7.83	149.24 ± 8.45	14.79 ± 5.49

Table D.10. Measured cross sections (mb) for natCu(d,x) reactions. Column headers give the deuteron energy (MeV) at each foil position.

Data availability: the full dataset, including all tabulated values and associated covariance information, has been deposited at <https://doi.org/10.5281/zenodo.6584051>.

References

- Aarnio, P.A., Nikkinen, M.T., Routti, J.T., 2001. UNISAMPO, comprehensive software for gamma-spectrum processing. *J. Radioanal. Nucl. Chem.* 248 (2), 371–375.
- Amjed, N., Tárkányi, F., Ditrói, F., Takács, S., Yuki, H., 2013. Activation cross-sections of deuteron induced reaction of natural Ni up to 40 MeV. *Appl. Radiat. Isot.* 82, 87–99.
- Anderson, T., Javadpour, N., Zwelling, L., 1979. Proceedings of the National Cancer Institute Conference on cis-Platinum and Testicular Cancer. *Cancer Treatment Reports*, Vol. 63, Issues 9–12. U.S. Department of Health, Education, and Welfare, Public Health Service, National Institutes of Health.
- Avrigeanu, M., Avrigeanu, V., Bém, P., Fischer, U., Honusek, M., Katovsky, K., Mănăilescu, C., Mrázek, J., Šimečková, E., Závorka, L., 2014. Low energy deuteron-induced reactions on Fe isotopes. *Phys. Rev. C* 89, 044613.
- Avrigeanu, M., Šimečková, E., Fischer, U., Mrázek, J., Novak, J., Štéfánik, M., Costache, C., Avrigeanu, V., 2016. Deuteron-induced reactions on Ni isotopes up to 60 MeV. *Phys. Rev. C* 94, 014606.
- Azure, M.T., Sastry, K.S.R., Archer, R.D., Howell, R.W., Rao, D.V., 1992. Microscale synthesis of carboplatin labeled with the Auger emitter platinum-193m: radiotoxicity versus chemotoxicity of the antitumor drug in mammalian cells. In: *Biophysical Aspects of Auger Processes*. AAPM Symposium Proceedings No. 8, pp. 336–351.
- Baglin, C.M., 2012a. Nuclear data sheets for A=192. *Nucl. Data Sheets* 113 (8–9), 1871–2111.
- Baglin, C.M., 2012b. Nuclear data sheets for A=92. *Nucl. Data Sheets* 113 (10), 2187–2389.
- Bartell, F.O., Helmholz, A.C., Softky, S.D., Stewart, D.B., 1950. Excitation functions for spallation reactions on Cu. *Phys. Rev.* 80, 1006–1010.
- Basunia, M.S., 2017. Nuclear data sheets for A=193. *Nucl. Data Sheets* 143, 1–381.
- Basunia, M.S., 2018. Nuclear data sheets for A=59. *Nucl. Data Sheets* 151, 1–333.
- Berger, M.J., Hubbell, J.H., Seltzer, S.M., Chang, J., Coursey, J.S., Sukumar, R., Zucker, D.S., Olsen, K., 2010. XCOM: Photon Cross Section Database (version 1.5). National Institute of Standards and Technology, Gaithersburg, MD.
- Bhat, M.R., 1998. Nuclear data sheets for A=57. *Nucl. Data Sheets* 85 (3), 415–536.
- Blachot, J., 2002. Nuclear data sheets for A=117. *Nucl. Data Sheets* 95 (3), 679–836.
- Blann, M., 1996. New precompound decay model. *Phys. Rev. C* 54 (3), 1341–1349.
- Bleuel, D., Bernstein, L., Marsh, R., Morrell, J., Rusnak, B., Voyles, A., 2021. Precision measurement of relative γ -ray intensities from the decay of ^{61}Cu . *Appl. Radiat. Isot.* 170, 109625.
- Bolcaen, J., Gizawy, M.A., Terry, S.Y., Paulo, A., Cornelissen, B., Korde, A., Engle, J., Radchenko, V., Howell, R.W., 2023. Marshalling the potential of Auger electron radiopharmaceutical therapy. *J. Nucl. Med.* 64 (9), 1344–1351.
- Browne, E., Tuli, J.K., 2010. Nuclear data sheets for A=65. *Nucl. Data Sheets* 111 (9), 2425–2553.
- Browne, E., Tuli, J.K., 2013. Nuclear data sheets for A=60. *Nucl. Data Sheets* 114 (12), 1849–2022.
- Burrows, T.W., 2006. Nuclear data sheets for A=48. *Nucl. Data Sheets* 107 (7), 1747–1922.

- Carzaniga, T.S., van der Meulen, N.P., Hasler, R., Kottler, C., Peier, P., Türler, A., Vermeulen, E., Vockenhuber, C., Braccini, S., 2019. Measurement of the ^{43}Sc production cross-section with a deuteron beam. *Appl. Radiat. Isot.* 145, 205–208.
- Clark, J.W., Fulmer, C.B., Williams, I.R., 1969. Excitation functions for radioactive nuclides produced by deuteron-induced reactions in iron. *Phys. Rev.* 179, 1104–1108.
- Covo, M.K., Albright, R.A., Ninemire, B.F., Johnson, M.B., Hodgkinson, A., Loew, T., Benitez, J.Y., Todd, D.S., Xie, D.Z., Perry, T., Phair, L., Harrig, K.P., Goldblum, B.L., Brown, J.A., Laplace, T., Bevins, J., Harasty, M., Matthews, E.F., Bernstein, L.A., Bleuel, D.L., Bushmaker, A., 2017. 88-Inch cyclotron: the one-stop facility for electronics radiation testing. In: 2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace). IEEE, pp. 484–488.
- Diksic, M., Galinier, J.-L., Marshall, H., Yaffe, L., Moore, R.B., Santry, D.C., 1979. Absolute cross sections for ^{64}Cu and ^{61}Cu produced by deuteron-induced reactions in copper. *Nucl. Instrum. Methods* 159, 171–175.
- Dong, Y., Junde, H., 2014. Nuclear data sheets for $A=54$. *Nucl. Data Sheets* 121, 1–142.
- Dong, Y., Junde, H., 2015. Nuclear data sheets for $A=52$. *Nucl. Data Sheets* 128, 185–314.
- Ekeberg, H.L.O., 2020. Nuclear Excitation Functions for Medical Isotope Production: Targeted Radionuclide Therapy via $\text{natIr}(d,x)^{193}\text{mPt}$. University of Oslo (Master's thesis), p. 155.
- Erjun, B., Junde, H., 2001. Nuclear data sheets for $A=63$. *Nucl. Data Sheets* 92 (1), 147–252.
- Filippi, L., Chiaravalloti, A., Schillaci, O., Cianni, R., Bagni, O., 2020. Theranostic approaches in nuclear medicine: current status and future prospects. *Expert Rev. Med. Devices* 17 (4), 331–343.
- Filosofov, D., Kurakina, E., Radchenko, V., 2021. Potent candidates for targeted Auger therapy: production and radiochemical considerations. *Nucl. Med. Biol.* 94–95, 1–19.
- Fitzgerald, J., 2009. FitzPeaks gamma analysis and calibration software.
- Fox, M.B., Voyles, A.S., Morrell, J.T., Bernstein, L.A., Batchelder, J.C., Birnbaum, E.R., Cutler, C.S., Koning, A.J., Lewis, A.M., Medvedev, D.G., Nortier, F.M., O'Brien, E.M., Vermeulen, C., 2021a. Measurement and modeling of proton-induced reactions on arsenic from 35 to 200 MeV. *Phys. Rev. C* 104 (6), 064615.
- Fox, M.B., Voyles, A.S., Morrell, J.T., Bernstein, L.A., Lewis, A.M., Koning, A.J., Batchelder, J.C., Birnbaum, E.R., Cutler, C.S., Medvedev, D.G., Nortier, F.M., O'Brien, E.M., Vermeulen, C., 2021b. Investigating high-energy proton-induced reactions on spherical nuclei: implications for the preequilibrium exciton model. *Phys. Rev. C* 103 (3), 034601.
- Fulmer, C., Williams, I., 1970. Excitation functions for radioactive nucleides produced by deuteron-induced reactions in copper. *Nucl. Phys. A* 155, 40–48.
- Herman, M., Capote, R., Carlson, B.V., Obložinský, P., Sin, M., Trkov, A., Wienke, H., Zerkin, V., 2007. EMPIRE: nuclear reaction model code system for data evaluation. *Nucl. Data Sheets* 108 (12), 2655–2715.
- Hermanne, A., Ignatyuk, A., Capote, R., Carlson, B., Engle, J., Kellett, M., Kibédi, T., Kim, G., Kondev, F., Hussain, M., Lebeda, O., Luca, A., Nagai, Y., Naik, H., Nichols, A., Nortier, F., Suryanarayana, S., Takács, S., Tárkányi, F., Verpilli, M., 2018. Reference cross sections for charged-particle monitor reactions. *Nucl. Data Sheets* 148, 338–382.
- Hermanne, A., Sonck, M., Takács, S., Tárkányi, F., 2000. Experimental study of excitation functions for some reactions induced by deuterons (10–50 MeV) on natural Fe and Ti. *Nucl. Instrum. Methods Phys. Res. B* 161, 178–185.

- Hermanne, A., Takács, S., Adam-Rebeles, R., Tárkányi, F., Takács, M., 2013. New measurements and evaluation of database for deuteron induced reaction on Ni up to 50 MeV. Nucl. Instrum. Methods Phys. Res. B 299, 8–23.
- Hermanne, A., Tárkányi, F., Ignatyuk, A., Takacs, S., Capote, R., 2025. Critical re-evaluation of recommended excitation functions of 7 reactions for ^{61}Cu formation. Nucl. Instrum. Methods Phys. Res. B 563, 165690.
- Hermanne, A., Tárkányi, F., Takacs, S., Kovalev, S., Ignatyuk, A., 2007. Activation cross sections of the $^{64}\text{Ni}(d,2n)$ reaction for the production of the medical radionuclide ^{64}Cu . Nucl. Instrum. Methods Phys. Res. B 258 (2), 308–312.
- Howell, R.W., 1992. Radiation spectra for Auger-electron emitting radionuclides: report no. 2 of AAPM Nuclear Medicine Task Group No. 6. Med. Phys. 19 (6), 1371–1383.
- Howell, R.W., 2023. Advancements in the use of Auger electrons in science and medicine during the period 2015–2019. Int. J. Radiat. Biol. 99 (1), 2–27.
- Howell, R.W., Kassis, A.I., Adelstein, S.J., Rao, D.V., Wright, H.A., Hamm, R.N., Turner, J.E., Sastry, K.S.R., 1994. Radiotoxicity of platinum-195m-labeled trans-platinum (II) in mammalian cells. Radiat. Res. 140 (1), 55.
- Howell, R.W., Sastry, K.S.R., Hill, H.Z., Rao, D.V., 1986. Cis-platinum-193m: its microdosimetry and potential for chemo-Auger combination therapy of cancer. In: Fourth International Radiopharmaceutical Dosimetry Symposium, pp. 493–513.
- Huber, P.J., 1967. The behavior of maximum likelihood estimates under nonstandard conditions. In: Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, Vol. 1, pp. 221–234.
- Johnson, T., Singh, B., 2017. Nuclear data sheets for A=189. Nucl. Data Sheets 142, 1–330.
- Junde, H., 2008a. Nuclear data sheets for A=55. Nucl. Data Sheets 109 (4), 787–942.
- Junde, H., 2009. Nuclear data sheets for A=53. Nucl. Data Sheets 110, 2689–2814.
- Junde, H., Su, H., Dong, Y., 2011. Nuclear data sheets for A=56. Nucl. Data Sheets 112 (6), 1513–1645.
- Kawano, T., Talou, P., Chadwick, M.B., Watanabe, T., 2010. Monte Carlo simulation for particle and γ -ray emissions in statistical Hauser-Feshbach model. J. Nucl. Sci. Technol. 47 (5), 462–469.
- Khandaker, M.U., Haba, H., Kanaya, J., Otuka, N., 2013. Activation cross-sections of deuteron-induced nuclear reactions on natural iron up to 24 MeV. Nucl. Instrum. Methods Phys. Res. B 316, 33–41.
- Khandaker, M.U., Haba, H., Murakami, M., Otuka, N., Kassim, H.A., 2014. Deuteron-induced activation cross-sections on natural copper up to 24 MeV. J. Radioanal. Nucl. Chem. 302, 759–764.
- Király, B., Takács, S., Ditrói, F., Tárkányi, F., Hermanne, A., 2009. Evaluated activation cross sections of longer-lived radionuclides produced by deuteron induced reactions on natural iron up to 10 MeV. Nucl. Instrum. Methods Phys. Res. B 267, 15–22.
- Kondev, F., Juutinen, S., Hartley, D., 2018. Nuclear data sheets for A=188. Nucl. Data Sheets 150, 1–364.
- Koning, A.J., Rochman, D., 2012. Modern nuclear data evaluation with the TALYS code system. Nucl. Data Sheets 113 (12), 2841–2934.
- Koning, A., Rochman, D., Sublet, J.-C., Dzysiuk, N., Fleming, M., van der Marck, S., 2019. TENDL: complete nuclear data library for innovative nuclear science and technology. Nucl. Data Sheets 155, 1–55.

- Kratochwil, C., Bruchertseifer, F., Giesel, F.L., Weis, M., Verburg, F.A., Mottaghy, F., Kopka, K., Apostolidis, C., Haberkorn, U., Morgenstern, A., 2016. ^{225}Ac -PSMA-617 for PSMA-targeted α -radiation therapy of metastatic castration-resistant prostate cancer. *J. Nucl. Med.* 57 (12), 1941–1944.
- Kratochwil, C., Bruchertseifer, F., Rathke, H., Bronzel, M., Apostolidis, C., Weichert, W., Haberkorn, U., Giesel, F.L., Morgenstern, A., 2017. Targeted α -therapy of metastatic castration-resistant prostate cancer with ^{225}Ac -PSMA-617: dosimetry estimate and empiric dose finding. *J. Nucl. Med.* 58 (10), 1624–1631.
- Kratochwil, C., Bruchertseifer, F., Rathke, H., Hohenfellner, M., Giesel, F.L., Haberkorn, U., Morgenstern, A., 2018. Targeted α -therapy of metastatic castration-resistant prostate cancer with ^{225}Ac -PSMA-617: swimmer-plot analysis suggests efficacy regarding duration of tumor control. *J. Nucl. Med.* 59 (5), 795–802.
- Langbein, T., Weber, W.A., Eiber, M., 2019. Future of theranostics: an outlook on precision oncology in nuclear medicine. *J. Nucl. Med.* 60 (Suppl. 2), 13S–19S.
- Lebeda, O., Červenák, J., 2019. Measurement of deuteron-induced nuclear reactions cross-sections on ^{197}Au and on natCu focused on the theranostic $^{197}\text{m,gHg}$. *Nucl. Instrum. Methods Phys. Res. B* 461, 105–113.
- Morrell, J.T., 2019. NPAT: Nuclear Physics Analysis Tools.
- Morrell, J.T., 2020. Curie: A Python Toolkit to Aid in the Analysis of Experimental Nuclear Data.
- Morrell, J.T., Voyles, A.S., Basunia, M.S., Batchelder, J.C., Matthews, E.F., Bernstein, L.A., 2020. Measurement of $^{139}\text{La}(p,x)$ cross sections from 35–60 MeV by stacked-target activation. *Eur. Phys. J. A* 56 (1), 13.
- Müller, C., Van Der Meulen, N.P., Benešová, M., Schibli, R., 2017. Therapeutic radiometals beyond ^{177}Lu and ^{90}Y : production and application of promising α -particle, β -particle, and Auger electron emitters. *J. Nucl. Med.* 58 (Suppl. 2), 91S–96S.
- Nakao, M., Hori, J., Ochiai, K., Kubota, N., Sato, S., Yamauchi, M., Ishioka, N.S., Nishitani, T., 2006. Measurements of deuteron-induced activation cross-sections for IFMIF accelerator structural materials. *Nucl. Instrum. Methods Phys. Res. A* 562 (2), 785–788.
- Nesaraja, C.D., Geraedts, S.D., Singh, B., 2010. Nuclear data sheets for $A=58$. *Nucl. Data Sheets* 111 (4), 897–1092.
- Nichols, A.L., Singh, B., Tuli, J.K., 2012. Nuclear data sheets for $A=62$. *Nucl. Data Sheets* 113 (4), 973–1114.
- Obata, H., Minegishi, K., Nagatsu, K., Zhang, M.-R., Shinohara, A., 2019. Production of ^{191}Pt from an iridium target by vertical beam irradiation and simultaneous alkali fusion. *Appl. Radiat. Isot.* 149, 31–37.
- Ochiai, K., Nakao, M., Kubota, N., Sato, S., Yamauchi, M., Ishioka, N.H., Nishitani, T., Konno, C., 2007. Deuteron induced activation cross section measurement for IFMIF. In: ND2007. EDP Sciences, pp. 1011–1014.
- Otuka, N., Takács, S., 2015. Definitions of radioisotope thick target yields. *Radiochim. Acta* 103 (1), 1–6.
- Qaim, S.M., 2017. Nuclear data for production and medical application of radionuclides: present status and future needs. *Nucl. Med. Biol.* 44, 31–49.
- Qaim, S.M., Spahn, I., Scholten, B., Neumaier, B., 2018. Uses of alpha particles, especially in nuclear reaction studies and medical radionuclide production. *Radiochim. Acta* 106 (10), 873–873.
- Shamsuzzoha Basunia, M., 2017. Nuclear data sheets for $A=193$. *Nucl. Data Sheets* 143, 1–381.
- Singh, B., 2003. Nuclear data sheets for $A=190$. *Nucl. Data Sheets* 99 (2), 275–481.
- Singh, B., 2006. Nuclear data sheets for $A=194$. *Nucl. Data Sheets* 107, 1531–1746.

- Singh, B., 2007. Nuclear data sheets for A=64. Nucl. Data Sheets 108 (2), 197–364.
- Singh, B., Chen, J., 2015. Nuclear data sheets for A=43. Nucl. Data Sheets 126, 1–150.
- Skobelev, N.K., 2015. Population of isomeric states in fusion and transfer reactions in beams of loosely bound nuclei near the Coulomb barrier. Phys. At. Nucl. 78 (5), 652–661.
- Stevenson, N.R., George, G.S., Simón, J., Srivastava, S.C., Mueller, D.W., Gonzales, G.R., Rogers, J.A., Frank, R.K., Horn, I.M., 2015. Methods of producing high specific activity Sn-117m with commercial cyclotrons. J. Radioanal. Nucl. Chem. 305 (1), 99–108.
- Sudár, S., Qaim, S.M., 1994. Excitation functions of proton and deuteron induced reactions on iron and alpha-particle induced reactions on manganese in the energy region up to 25 MeV. Phys. Rev. C 50 (5), 2408–2419.
- Sudár, S., Qaim, S., 1996. Isomeric cross-section ratio for the formation of $^{58}\text{Co}^{\text{m}}$ in neutron, proton, deuteron, and alpha-particle induced reactions in the energy region up to 25 MeV. Phys. Rev. C 53 (6), 2885.
- Takács, S., Sonck, M., Azzam, A., Hermanne, A., Tárkányi, F., 1997. Activation cross-section measurements of deuteron induced reactions on natNi with special reference to beam monitoring and production of ^{61}Cu for medical purpose. Radiochim. Acta 76 (1–2), 15–24.
- Takács, S., Szelecsényi, F., Tárkányi, F., Sonck, M., Hermanne, A., Shubin, Y., Dityuk, A., Mustafa, M., Youxiang, Z., 2001. New cross-sections and intercomparison of deuteron monitor reactions on Al, Ti, Fe, Ni and Cu. Nucl. Instrum. Methods Phys. Res. B 174, 235–258.
- Takács, S., Tárkányi, F., Király, B., Hermanne, A., Sonck, M., 2006. Evaluated activation cross sections of longer-lived radionuclides produced by deuteron-induced reactions on natural copper. Nucl. Instrum. Methods Phys. Res. B 251, 56–65.
- 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. Nucl. Instrum. Methods Phys. Res. B 260, 495–507.
- Takacs, S., Tárkányi, F., Sonck, M., Hermanne, A., Sudár, S., 1997. Study of deuteron induced reactions on natural iron and copper and their use for monitoring beam parameters and for thin layer activation technique. AIP Conf. Proc. 392, 659–662.
- Tárkányi, F., 2005. Cross sections of proton induced nuclear reactions on iridium. AIP Conf. Proc. 769, 1023–1026.
- Tárkányi, F., Hermanne, A., Ditrói, F., Takács, S., Adam Rebeles, R., Ignatyuk, A., 2015. New data on cross-sections of deuteron induced nuclear reactions on gold up to 50 MeV and comparison of production routes of medically relevant Au and Hg radioisotopes. Nucl. Instrum. Methods Phys. Res. B 362, 116–132.
- Tárkányi, F., Hermanne, A., Ditrói, F., Takács, S., Ignatyuk, A., 2019. Measurement of activation cross sections of deuteron induced reactions on natIr in the 17–50 MeV energy range. Nucl. Instrum. Methods Phys. Res. B 458, 105–117.
- Tárkányi, F., Király, B., Ditrói, F., Takács, S., Csikai, J., Hermanne, A., Uddin, M., Hagiwara, M., Baba, M., Shubin, Y., Kovalev, S., 2006. Cross sections of deuteron induced nuclear reactions on iridium. Nucl. Instrum. Methods Phys. Res. B 247 (2), 210–216.
- Tóth, G., 1980. A novel target for reactor-produced $^{193\text{m}}\text{Pt}$. Int. J. Appl. Radiat. Isot. 31 (7), 411–413.

- Uddin, M., Scholten, B., Hermanne, A., Sudár, S., Coenen, H., Qaim, S., 2010. Radiochemical determination of cross sections of α -particle induced reactions on ^{192}Os for the production of the therapeutic radionuclide $^{193\text{m}}\text{Pt}$. *Appl. Radiat. Isot.* 68 (10), 2001–2006.
- Usman, A.R., Khandaker, M.U., Haba, H., Murakami, M., Otuka, N., 2016. Measurements of deuteron-induced reaction cross-sections on natural nickel up to 24 MeV. *Nucl. Instrum. Methods Phys. Res. B* 368, 112–119.
- Vandenbosch, R., Huizenga, J.R., 1960. Isomeric cross-section ratios for reactions producing the isomeric pair $\text{Hg}^{197},^{197\text{m}}$. *Phys. Rev.* 120, 1313–1318.
- Vanin, V., Maidana, N., Castro, R., Achterberg, E., Capurro, O., Martí, G., 2007. Nuclear data sheets for $A=191$. *Nucl. Data Sheets* 108 (11), 2393–2588.
- Voyles, A.S., Bernstein, L.A., Birnbaum, E.R., Engle, J.W., Graves, S.A., Kawano, T., Lewis, A.M., Nortier, F.M., 2018. Excitation functions for (p,x) reactions of niobium in the energy range of $E_p=40\text{--}90$ MeV. *Nucl. Instrum. Methods Phys. Res. B* 429, 53–74.
- Voyles, A.S., Lewis, A.M., Morrell, J.T., Basunia, M.S., Bernstein, L.A., Engle, J.W., Graves, S.A., Matthews, E.F., 2021. Proton-induced reactions on Fe, Cu, and Ti from threshold to 55 MeV. *Eur. Phys. J. A* 57 (3), 94.
- Wang, J., Huang, X., 2017. Nuclear data sheets for $A=51$. *Nucl. Data Sheets* 144, 1–296.
- Weissman, L., Kreisel, A., Hirsh, T., Aviv, O., Berkovits, D., Girshevitz, O., Eisen, Y., 2015. Accurate measurements of the $^{63}\text{Cu}(d,p)^{64}\text{Cu}$ and $\text{natCu}(d,x)^{65}\text{Zn}$ cross-sections in the 2.77–5.62 MeV energy range. *Nucl. Instrum. Methods Phys. Res. B* 342, 7–12.
- Zerkin, V., 2020. Experimental Nuclear Reaction Data (EXFOR).
- Zuber, K., Singh, B., 2015. Nuclear data sheets for $A=61$. *Nucl. Data Sheets* 125, 1–200.
- Zweit, J., Smith, A., Downey, S., Sharma, H., 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. *Int. J. Radiat. Appl. Instrum. A. Appl. Radiat. Isot.* 42, 193–197.