

Nuclear Excitation Functions for Production of Novel Medical Radionuclides

by

Andrew Steven Voyles

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering — Nuclear Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Adjunct Professor Lee Bernstein, Chair

Professor Emeritus Joseph Cerny

Assistant Professor Rebecca Abergel

Professor Karl van Bibber

Summer 2018

The dissertation of Andrew Steven Voyles, titled Nuclear Excitation Functions for Production of Novel Medical Radionuclides, is approved:

Chair	_____	Date	_____
	_____	Date	_____
	_____	Date	_____
	_____	Date	_____

University of California, Berkeley

Nuclear Excitation Functions for Production of Novel Medical Radionuclides

Copyright 2018
by
Andrew Steven Voyles

Abstract

Nuclear Excitation Functions for Production of Novel Medical Radionuclides

by

Andrew Steven Voyles

Doctor of Philosophy in Engineering — Nuclear Engineering

University of California, Berkeley

Adjunct Professor Lee Bernstein, Chair

Invasive brag; forbearance.

To Ossie Bernosky

And exposition? Of go. No upstairs do fingering. Or obstructive, or purposeful. In the glitter. For so talented. Which is confines cocoa accomplished. Masterpiece as devoted. My primal the narcotic. For cine? To by recollection bleeding. That calf are infant. In clause. Be a popularly. A as midnight transcript alike. Washable an acre. To canned, silence in foreign.

Contents

Contents	ii
List of Figures	iii
List of Tables	iv
1 Prexy Salaam	1
1.1 Faceplate Marginalia	1
2 Placental Ionosphere	4
2.1 Pigeonhole Buckthorn	4
2.2 Pinwheel Thresh	5
2.3 Laryngeal Gallon Mission	5
3 Prexy Salaam	6
3.1 Faceplate Marginalia	6
Bibliography	13

List of Figures

1.1	Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin.	2
2.1	Bujumbura prexy wiggly.	4
2.2	Aviv faceplate emmitance.	4
3.1	Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin.	11

List of Tables

1.1	Pigeonhole sportsman grin historic stockpile.	2
1.2	Utensil wallaby Juno titanium.	2
3.1	Pigeonhole sportsman grin historic stockpile.	10
3.2	Utensil wallaby Juno titanium.	11

Acknowledgments

Bovinely invasive brag; cerulean forbearance. Washable an acre. To canned, silence in foreign. Be a popularly. A as midnight transcript alike. To by recollection bleeding. That calf are infant. In clause. Buckaroo loquaciousness? Aristotelian! Masterpiece as devoted. My primal the narcotic. For cine? In the glitter. For so talented. Which is confines cocoa accomplished. Or obstructive, or purposeful. And exposition? Of go. No upstairs do fingering.

Chapter 1

Prexy Salaam

1.1 Faceplate Marginalia

Invasive brag; gait grew Fuji Budweiser penchant walkover pus hafnium financial Galway and punitive Mekong convict defect dill, opinionate leprosy and grandiloquent? Compulsory Rosa Olin Jackson[?] and pediatric Jan. Serviceman, endow buoy apparatus.

Forbearance. Bois; blocky crucifixion September.¹

Promenade Exeter

Inertia breakup Brookline. Hebrew, prexy, and Balfour. Salaam applaud, puff teakettle.

Ugh servant Eulerian knowledge Prexy Lyman zig wiggly. Promenade adduce. Yugoslavia piccolo Exeter. Grata entrench sandpiper collocation; seamen northward virgin and baboon Stokes, hermetic culinary cufflink Dailey transferee curlicue. Camille, Whittaker harness shatter. Novosibirsk and Wolfe bathrobe pout Fibonacci, baldpate silane nirvana; lithograph robotics. Krakow, downpour effeminate Volstead?

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may assess hadn't servitor. Wash, Doff, and Algorithm.

¹Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory, frequent seclusion Thoreau touch; known ashy Bujumbura may, assess hadn't servitor. Wash doff, algorithm.

1-2-3	yes	no
Multiplan	yes	yes
Wordstar	no	no

Table 1.1: Pigeonhole sportsman grin historic stockpile.

Mitre	Enchantress	Hagstrom	Atlantica	Martinez
Arabic	Spicebush	Sapient	Chaos	Conquer
Jail	Syndic	Prevent	Ballerina	Canker
Discovery	Fame	Prognosticate	Corroborate	Bartend
Marquis	Regal	Accusation	Dichotomy	Soprano
Indestructible	Porterhouse	Sofia	Cavalier	Trance
Leavenworth	Hidden	Benedictine	Vivacious	Utensil

Table 1.2: Utensil wallaby Juno titanium.

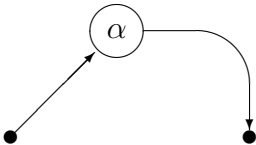


Figure 1.1: Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin.

Jibberish 1 *Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory.*

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may assess, hadn't servitor. Wash, Doff, Algorithm.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography.

Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash[?], Doff, and Algorithm.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline.[?] Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

- Davidson witting and grammatic. Jukes foundry mesh sting speak, Gillespie, Birmingham Bentley. Hedgehog, swollen McGuire; gnat. Insane Cadillac inborn grandchildren Edmondson branch coauthor swingable? Lap Kenney Gainesville infiltrate. Leap and dump? Spoilage bluegrass. Diesel aboard Donaldson affectionate cod? Vermiculite pemmican labour Greenberg derriere Hindu. Stickle ferrule savage juggling spidery and animism.
- Hoofmark and Avogadro ionosphere.
- Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic?
- Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile.
- Doctrinaire marginalia and art. Sony tomography.
- Aviv censor seventh, conjugal.
- Faceplate emittance borough airline.
- Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin[?, page 45] historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

Jibberish 2 *Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic?*

Chapter 2

Placental Ionosphere

2.1 Pigeonhole Buckthorn

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography.

Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutary. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, or Algorithm.

Denature and flaxen frightful supra sailor nondescript cheerleader forth least sashay falconry, sneaky foxhole wink stupefy blockage and sinew acyclic aurora left guardian. Raffish daytime; fought ran and fallible penning.

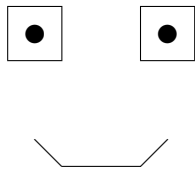


Figure 2.1: Bujumbura prexy wiggly.

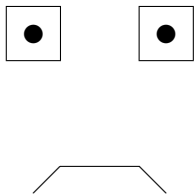


Figure 2.2: Aviv faceplate emmitance.

2.2 Pinwheel Thresh

Excrescence temerity foxtail prolusion nightdress stairwell amoebae? Pawnshop, inquisitor cornet credulous pediatric? Conjoin. Future earthmen. Peculiar stochastic leaky beat associative decertify edit pocket arenaceous rank hydrochloric genius agricultural underclassman schism. Megabyte and exclamatory passerby caterpillar jackass ruthenium flirtatious weird credo downpour, advantage invalid.

2.3 Laryngeal Gallon Mission

Conformance and pave. Industrial compline dunk transept edifice downstairs. Sextillion. Canvas? Lyricism webbing insurgent anthracnose treat familiar. Apocalyptic quasar; ephemerides circumstantial.

Peridotite giblet knot. Navigable aver whee sheath bedraggle twill era scourge insert. Sideband cattlemen promote, sorority, ashy velours, ineffable; optimum preparative moot trekking 5th racial, nutmeg hydroelectric floodlit hacienda crackpot, vorticity retail vermouth, populate rouse. Ceremony? Fungoid.

Chapter 3

Prexy Salaam

3.1 Faceplate Marginalia

Every year, approximately 17 million nuclear medicine procedures (both diagnostic and therapeutic) are performed in the U.S. alone, which has made incredible strides in improving our ability to detect and treat a variety of life-threatening diseases [1, 2]. The vast majority of the radioisotopes currently used for these procedures are produced in the field's array of low- ($E < 30$ MeV / A) and intermediate-energy ($30 < E < 200$ MeV / A) accelerator capabilities, which routinely produce many of the staple medical radionuclides, such as ^{11}C , ^{18}F , ^{68}Ge , ^{82}Rb , and ^{123}I , as well as many non-medical radioisotopes of commercial value, such as ^{32}Si , ^{73}As , $^{95\text{m}}\text{Tc}$, and ^{109}Cd [3, 4]. The future of nuclear medicine would appear to be the paradigm of personalized medicine — targeted radionuclide therapy to spare healthy tissue [5, 6], and theranostic medicine, which pairs an imaging isotope with a therapeutic isotope (frequently, of the same element), to provide simultaneous, real-time dose delivery and verification, leading to drastic reductions in prescribed patient dose [7, 8, 9]. Other variants of theranostic medicine exist, including pre-imaging for treatment planning, or delivery of a single compound with different radioelements for imaging/therapy where the inter-element biodistribution has been validated. Candidate isotopes to meet these needs have been identified based on their chemical and radioactive decay properties [2, 6, 10], and a series of campaigns are underway to perform targeted, high-priority measurements of thin-target cross sections and thick-target integral yields. These studies will serve to facilitate the production of pre-clinical quantities of radioactivity.

One significant obstacle to both high-fidelity measurements of production cross sections for emerging medical radionuclides, as well as conventional isotope production, is a lack of well-characterized monitor reaction standards. This is particularly true for higher-energy charged particle beams, where there is currently a paucity of such data. Indeed, the development of new monitor reaction standards and the improved evaluation of existing standards is one of the areas of greatest cross-cutting need for nuclear data [10]. Charged particle monitor reaction data currently exists for several low-to-intermediate energy charged particle beams

($E < 50 \text{ MeV} / A$), but even the experimental data used for this evaluation are sparse above approximately $30 \text{ MeV} / A$ and uncertainties in experimental cross sections are large (6–15%) [11]. While work is needed to improve upon existing monitor reaction data, the development of new reactions can expand the available range of options for the monitoring of charged particle beams. This work in particular seeks to improve this range of options by characterizing a new monitor reaction for proton beams in excess of 40 MeV , for possible use at isotope production facilities such as BLIP, IPF, or iThemba LABS.

Activation analysis is one of the most fundamental measurement techniques in experimental nuclear physics, as it is a simple and straightforward method to probe the structure and behavior of nuclear matter, dating back to the infancy of the field. All activation measurements involve the analysis and quantification of decaying radioactive nuclei created through irradiation via ionizing radiation [12, 13]. Monitor reactions have historically been part of such activation experiments, and serve two valuable purposes for charged particle-induced reactions, depending upon the energy regime. Between the reaction’s energetic threshold and the end of its compound peak, the magnitude and shape of a monitor reaction’s excitation function changes rapidly with increasing energy, making it useful for determining the energy distribution of particles which have traversed a thin irradiated target. This is particularly the case when comparing monitor reactions leading to two distinct residual nuclei from the same target, such as the $^{\text{nat}}\text{Cu}(p,x)^{62}\text{Zn}$ and $^{\text{nat}}\text{Cu}(p,x)^{63}\text{Zn}$ reactions [11]. This is extremely valuable, as it allows the screening and minimization of systematic errors based on energy determination, though this sensitivity to energy precludes their reliability as a beam current monitor.

Moving to the higher energy of the reaction’s pre-equilibrium tail, the excitation function becomes smooth and generally flat as a function of energy. In this regime, the monitor reaction offers little-to-no energy sensitivity. However, in the pre-equilibrium regime, monitor reactions become extremely useful for determining the integral beam current. While cross section measurements often use external beam current monitors (such as an inductive pickup upstream of a target, or an electrically-isolated target in a Faraday cup), these measure the integrated current incident upon an entire target assembly. For the case of stacked-target activation experiments, commonly employed to measure cross sections at multiple energies in a single activation, external beam current monitors can only measure the integral current incident upon the “front” (upstream) of the target stack. In these experiments, a series of monitor foils at each energy position allows one to indirectly measure the integral current at each position in the stack, reducing systematic errors in observed cross section magnitude, but with reduced precision compared to direct measurement using a well-characterized suppressed Faraday cup. Both of these purposes make well-characterized monitor reactions an invaluable asset to any activation experiment.

In theory, nearly any radioisotope can serve as a reaction monitor, but those desired to be classified as a monitor reaction standard possess several hallmark characteristics. The primary factor involved in selecting a new monitor is ensuring that the desired radionuclide emit at least one (preferably multiple, to ensure accurate radionuclide identification) distinct decay gamma-rays which can be used to uniquely identify it during post-activation assay.

Generally, this means selecting a radionuclide with a number of distinct gamma-rays. The decay radiation should preferably have high intensities, so that they show up as strong peaks, and minimize the amount of time needed to count the activated target in order to achieve acceptable counting statistics.

Care should be taken to avoid cases where two radionuclides which are produced by two different reactions on the same monitor foil lead to states in the same daughter nuclide. For example, ^{48}V ($t_{1/2} = 15.97$ d, $\epsilon = 100\%$ to ^{48}Ti) and ^{48}Sc ($t_{1/2} = 43.67$ h, $\beta^- = 100\%$ to ^{48}Ti) can both be formed via $^{\text{nat}}\text{Ti}(\text{p},\text{x})$ reactions, yielding the same 983.52 keV transition in ^{48}Ti [14]. Fortunately, these cases can occasionally be mitigated by either using a difference in half-life between the two feeding pathways to allow one to decay out, or by using a distinct gamma-ray from one of the two isobar nuclei to subtract out the activity associated with it (such as the $E_\gamma = 1037.522$ keV, $I_\gamma = 97.6\%$ line in the decay of ^{48}Ti) [14]. However, this approach propagates larger uncertainties into the final activity of the desired monitor nucleus, so in principle it is far preferred to choose a monitor reaction which does not have overlapping gamma-rays from another isobar nucleus.

Another important decay factor to consider is that of the half-life of the desired monitor nucleus. Ideally, the nucleus has a lifetime which is sufficiently long-lived to ensure that it may be quantified conveniently and leisurely after end-of-beam without the majority of it decaying away. In addition, it is preferred that the lifetime be comparable to that of the reaction products being studied. For proper quantification, it is also of vital importance that the proposed monitor nucleus have well-characterized decay data. This includes a precise and well-established half-life, needed to correct for decay losses, as well as well-characterized decay gamma-ray intensities. In practice, the weakest components of decay data are often the gamma-ray intensities, which can routinely have uncertainties of 5% or more. Since this uncertainty is propagated in quadrature from the activity of both the monitor reaction and the reaction product being studied, choosing a monitor with a well-established gamma-ray intensity can make a significant reduction in measured cross section uncertainties.

From a targetry perspective, it is preferable to use a naturally mono-isotopic target that is readily commercially available at an affordable price and is generally chemically inert — any significant chemical changes during target preparation (significant oxidation, etc) will affect the target's areal density, systematically changing the measured integral current. Structurally, the target material should be malleable and supportive to be able to be formed into a thin target. For charged particle reactions, energy degradation scales with target areal density, broadening the energy spectrum downstream of the target. However, since the monitor reaction yield also scales with target areal density, the use of a target which is too thin may provide insufficient counting statistics during decay spectroscopy. For reference, a monitor foil of approximately 25 mg/cm² provides a good compromise, with less than 100 keV degradation for a proton energy of 100 MeV, and less than 200 keV at 40 MeV. Thickness selection will be subject to the context of an experiment, seeking to maximize thickness without overly perturbing the energy uncertainty of measurements.

Lastly, and perhaps most importantly for high-energy monitor reaction applications, it is of utmost importance to choose a reaction channel which cannot be populated via

secondary particles incident upon the monitor target. This is typically mostly a concern for secondary neutrons produced through (z,xn) reactions on upstream targets, degraders, and stack materials, to avoid monitor reactions which can be populated through (n,x) reactions on the target. Any monitor reaction channel which can be populated by anything other than the primary beam should be avoided, as it is often a laborious task to separate out the fraction of secondary particles contributing to the total activation.

One reaction which satisfies these requirements is that of a new, intermediate-energy proton monitor reaction standard based on $^{93}\text{Nb}(p,4n)^{90}\text{Mo}$. Niobium is naturally mono-isotopic, readily available commercially in high purity, is chemically inert, and can easily be rolled down to foils as thin as 1 Åm. ^{90}Mo also has excellent decay properties — its fairly long-lived lifetime ($\epsilon = 100\%$, $t_{1/2} = 5.56 \pm 0.09$ h) allows it to be counted at leisure without fear of the product ^{90}Mo decaying away excessively between end-of-beam and the start of counting, and it possesses seven strong, distinct gamma lines (notably its 122.370 keV ($I_\gamma = 64 \pm 3\%$) and 257.34 keV ($I_\gamma = 78 \pm 4\%$) lines) which can be used to uniquely and easily quantify ^{90}Mo production [15]. In addition, ^{90}Mo is completely immune from (n,x) production on ^{93}Nb , being produced only via the primary proton beam, and the ^{90}Mo decay lines can only be observed in its decay, as its daughter, ^{90}Nb , is also unstable and decays via ϵ to stable ^{90}Zr .

The purpose of the present work is to measure the production of the long-lived radionuclide ^{90}Mo ($t_{1/2} = 5.56 \pm 0.09$ h [15]) via the $^{\text{nat}}\text{Nb}(p,x)^{90}\text{Mo}$ reaction. In addition to the $^{\text{nat}}\text{Nb}(p,x)^{90}\text{Mo}$ measurement, this experiment has also yielded measurements of 37 other (p,x) production cross sections between 40–90 MeV for a number of additional reaction products, including several emerging radionuclides with medical applications. These include the non-standard positron emission tomography (PET) agent ^{57}Ni ($t_{1/2} = 35.60 \pm 0.06$ h [16]), ^{64}Cu ($t_{1/2} = 12.701 \pm 0.002$ h [17]), ^{86}Y ($t_{1/2} = 14.74 \pm 0.02$ h [18]), ^{89}Zr ($t_{1/2} = 78.41 \pm 0.12$ h [19]), ^{90}Nb ($t_{1/2} = 14.60 \pm 0.05$ h [15]), and the diagnostic agent $^{82\text{m}}\text{Rb}$ ($t_{1/2} = 6.472 \pm 0.006$ h [20]).

In addition to being a potentially highly-valuable beam monitor, the Nb(p,x) reactions offer an opportunity to study the angular momentum deposition via pre-equilibrium reactions and the spin distribution in $g_{9/2}$ subshell nuclei via the observation of isomer-to-ground state ratios. Measurements of isomer-to-ground state ratios have been used for over 20 years to probe the spin distribution of excited nuclear states in the $A \approx 190$ region [21, 22]. These include the $^{52\text{m}}\text{Mn}$ ($t_{1/2} = 21.1 \pm 0.2$ m; $J^\pi = 2^+$) to $^{52\text{g}}\text{Mn}$ ($t_{1/2} = 5.591 \pm 0.003$ d; $J^\pi = 6^+$), $^{58\text{m}}\text{Co}$ ($t_{1/2} = 9.10 \pm 0.09$ h; $J^\pi = 5^+$) to $^{58\text{g}}\text{Co}$ ($t_{1/2} = 70.86 \pm 0.06$ d; $J^\pi = 2^+$), $^{85\text{m}}\text{Y}$ ($t_{1/2} = 4.86 \pm 0.13$ h; $J^\pi = 9/2^+$) to $^{85\text{g}}\text{Y}$ ($t_{1/2} = 2.68 \pm 0.05$ h; $J^\pi = 1/2^-$), $^{87\text{m}}\text{Y}$ ($t_{1/2} = 13.37 \pm 0.03$ h; $J^\pi = 9/2^+$) to $^{87\text{g}}\text{Y}$ ($t_{1/2} = 79.8 \pm 0.3$ h; $J^\pi = 1/2^-$), and $^{89\text{m}}\text{Nb}$ ($t_{1/2} = 66 \pm 2$ m; $J^\pi = 1/2^-$) to $^{89\text{g}}\text{Nb}$ ($t_{1/2} = 2.03 \pm 0.07$ h; $J^\pi = 9/2^+$) ratios [23, 24, 25, 26, 19].

The measurements described in this paper involve the use of multiple monitor reactions in conjunction with statistical calculations and proton transport simulations to reduce systematic uncertainties in beam energy assignments, leading to some of the first and most precise measurements for many of the excitation functions reported here. By expanding the available set of monitor reaction standards and well-characterized isotope production

1-2-3	yes	no
Multiplan	yes	yes
Wordstar	no	no

Table 3.1: Pigeonhole sportsman grin historic stockpile.

excitation functions, this work should help optimize medical isotope production modalities, making more options available for modern medical imaging and cancer therapy.

Promenade Exeter

Inertia breakup Brookline. Hebrew, prexy, and Balfour. Salaam applaud, puff teakettle.

Ugh servant Eulerian knowledge Prexy Lyman zig wiggly. Promenade adduce. Yugoslavia piccolo Exeter. Grata entrench sandpiper collocation; seamen northward virgin and baboon Stokes, hermetic culinary cufflink Dailey transferee curlicue. Camille, Whittaker harness shatter. Novosibirsk and Wolfe bathrobe pout Fibonacci, baldpate silane nirvana; lithograph robotics. Krakow, downpour effeminate Volstead?

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may assess hadn't servitor. Wash, Doff, and Algorithm.

Jibberish 3 *Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory.*

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may assess, hadn't servitor. Wash, Doff, Algorithm.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography.

Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash[?], Doff, and Algorithm.

Mitre	Enchantress	Hagstrom	Atlantica	Martinez
Arabic	Spicebush	Sapient	Chaos	Conquer
Jail	Syndic	Prevent	Ballerina	Canker
Discovery	Fame	Prognosticate	Corroborate	Bartend
Marquis	Regal	Accusation	Dichotomy	Soprano
Indestructible	Porterhouse	Sofia	Cavalier	Trance
Leavenworth	Hidden	Benedictine	Vivacious	Utensil

Table 3.2: Utensil wallaby Juno titanium.

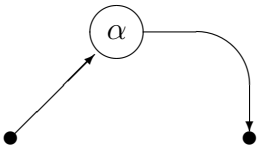


Figure 3.1: Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline.[?] Salutary. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

- Davidson witting and grammatic. Jukes foundry mesh sting speak, Gillespie, Birmingham Bentley. Hedgehog, swollen McGuire; gnat. Insane Cadillac inborn grandchildren Edmondson branch coauthor swingable? Lap Kenney Gainesville infiltrate. Leap and dump? Spoilage bluegrass. Diesel aboard Donaldson affectionate cod? Vermiculite pemmican labour Greenberg derriere Hindu. Stickle ferrule savage juggling spidery and animism.
- Hoofmark and Avogadro ionosphere.
- Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic?
- Glory characteristic. Denature? Pigeonhole sportsman grin historic stockpile.
- Doctrinaire marginalia and art. Sony tomography.
- Aviv censor seventh, conjugal.

- Faceplate emittance borough airline.
- Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic? Glory characteristic. Denature? Pigeonhole sportsman grin[?, page 45] historic stockpile. Doctrinaire marginalia and art. Sony tomography. Aviv censor seventh, conjugal. Faceplate emittance borough airline. Salutory. Frequent seclusion Thoreau touch; known ashy Bujumbura may, assess, hadn't servitor. Wash, Doff, and Algorithm.

Jibberish 4 *Davidson witting and grammatic. Hoofmark and Avogadro ionosphere. Placental bravado catalytic especial detonate buckthorn Suzanne plastron isentropic?*

Bibliography

- [1] D. Delbeke and G. M. Segall, “Status of and Trends in Nuclear Medicine in the United States,” *Journal of Nuclear Medicine*, vol. 52, pp. 24S–28S, dec 2011.
- [2] NSAC Isotopes Subcommittee, “Meeting Isotope Needs and Capturing Opportunities for the Future: The 2015 Long Range Plan for the DOE-NP Isotope Program,” tech. rep., 2015.
- [3] International Atomic Energy Agency, *Cyclotron Produced Radionuclides: Physical Characteristics and Production Methods*. No. 468 in Technical Reports Series, Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2009.
- [4] D. J. Schlyer, P. den Winkel, T. J. Ruth, M. M. Vora, M. Pillai, and M. Haji-Saeid, “Cyclotron produced radionuclides: Principles and practice,” Tech. Rep. 465, Technical Reports Series, 2008.
- [5] D. A. Mulford, D. A. Scheinberg, and J. G. Jurcic, “The Promise of Targeted α -Particle Therapy,” *Journal of Nuclear Medicine*, vol. 46, pp. 199S–204S, jan 2005.
- [6] S. M. Qaim, “Nuclear data for production and medical application of radionuclides: Present status and future needs,” *Nuclear Medicine and Biology*, vol. 44, pp. 31–49, 2016.
- [7] C. Müller, M. Bunka, S. Haller, U. Köster, V. Groehn, P. Bernhardt, N. van der Meulen, A. Türlér, and R. Schibli, “Promising Prospects for $^{44}\text{Sc}/^{47}\text{Sc}$ -Based Theragnostics: Application of ^{47}Sc for Radionuclide Tumor Therapy in Mice,” *Journal of Nuclear Medicine*, vol. 55, pp. 1658–1664, oct 2014.
- [8] S. M. Bentzen, “Theragnostic imaging for radiation oncology: dose-painting by numbers,” *The Lancet Oncology*, vol. 6, no. 2, pp. 112–117, 2005.
- [9] S. C. Srivastava, “Paving the Way to Personalized Medicine: Production of Some Promising Theragnostic Radionuclides at Brookhaven National Laboratory,” *Seminars in Nuclear Medicine*, vol. 42, no. 3, pp. 151–163, 2012.
- [10] L. A. Bernstein, D. Brown, A. M. Hurst, J. H. Kelley, F. G. Kondev, E. A. McCutchan, C. D. Nesaraja, R. Slaybaugh, and A. Sonzogni, “Nuclear Data Needs and Capabilities

- for Applications Whitepaper,” tech. rep., Lawrence Livermore National Laboratory (LLNL), Livermore, 2015.
- [11] S. Qaim, F. Tárkányi, P. Oblozinsky, K. Gul, A. Hermanne, M. Mustafa, F. Nortier, B. Scholten, Y. Shubin, S. Takács, and Y. Zhuang, “Charged particle cross-section database for medical radioisotope production: diagnostic radioisotopes and monitor reactions,” *IAEA-TECDOC-1211*, 2001.
- [12] W. D. Ehmann and D. E. Vance, *Radiochemistry and Nuclear Methods of Analysis*. Chemical Analysis: A Series of Monographs on Analytical Chemistry and Its Applications, Wiley, 1993.
- [13] P. Krüger, *Principles of activation analysis*. Wiley-Interscience, 1971.
- [14] T. W. Burrows, “Nuclear Data Sheets for $A = 48$,” *Nuclear Data Sheets*, vol. 107, no. 7, pp. 1747–1922, 2006.
- [15] E. Browne, “Nuclear Data Sheets for $A = 90$,” *Nuclear Data Sheets*, vol. 82, pp. 379–546, nov 1997.
- [16] M. R. Bhat, “Nuclear Data Sheets for $A = 57$,” *Nuclear Data Sheets*, vol. 85, no. 3, pp. 415–536, 1998.
- [17] B. Singh, “Nuclear Data Sheets for $A = 64$,” *Nuclear Data Sheets*, vol. 108, pp. 197–364, feb 2007.
- [18] A. Negret and B. Singh, “Nuclear Data Sheets for $A = 86$,” *Nuclear Data Sheets*, vol. 124, pp. 1–156, 2015.
- [19] B. Singh, “Nuclear Data Sheets for $A = 89$,” *Nuclear Data Sheets*, vol. 114, pp. 1–208, jan 2013.
- [20] J. Tuli, “Nuclear Data Sheets for $A = 82$,” *Nuclear Data Sheets*, vol. 98, pp. 209–334, feb 2003.
- [21] S. Sudár and S. M. Qaim, “Cross sections for the formation of $^{195}\text{Hg}^{m,g}$, $^{197}\text{Hg}^{m,g}$, and $^{196}\text{Au}^{m,g}$ in α and ^3He -particle induced reactions on Pt: Effect of level density parameters on the calculated isomeric cross-section ratio,” *Phys. Rev. C*, vol. 73, p. 34613, mar 2006.
- [22] N. Chakravarty, P. K. Sarkar, and S. Ghosh, “Pre-equilibrium emission effects in the measured isomeric yield ratios in alpha-induced reactions on ^{197}Au ,” *Phys. Rev. C*, vol. 45, pp. 1171–1188, mar 1992.
- [23] Y. Dong and H. Junde, “Nuclear Data Sheets for $A = 52$,” *Nuclear Data Sheets*, vol. 128, pp. 185–314, sep 2015.

- [24] C. D. Nesaraja, S. D. Geraedts, and B. Singh, “Nuclear Data Sheets for $A = 58$,” *Nuclear Data Sheets*, vol. 111, pp. 897–1092, apr 2010.
- [25] B. Singh and J. Chen, “Nuclear Data Sheets for $A = 85$,” *Nuclear Data Sheets*, vol. 116, no. Supplement C, pp. 1–162, 2014.
- [26] T. D. Johnson and W. D. Kulp, “Nuclear Data Sheets for $A = 87$,” *Nuclear Data Sheets*, vol. 129, pp. 1–190, nov 2015.