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Title: Simultaneous Radionuclide Production using (d,2n) and Secondary Neutron-induced (n,p) Reactions

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# Background/Introduction

Many of the radionuclides used for the diagnosis and treatment of illness are produced using one of two large-scale accelerator facilities in the United States – the Isotope Production facility (IPF) at Los Alamos National Laboratory (LANL) and the Brookhaven Linac Isotope Production facility (BLIP). These accelerators utilize energetic proton beams (100-800 MeV) to produce radionuclides via (p,xn) reactions with x ≤ 10, allowing a wide range of radionuclides to be produced simultaneously.

In addition to major national and international facilities, radionuclides are also produced using a “University network” of low-energy accelerators. This network provides enhanced local production capabilities throughout the country with significantly less proliferation risk than that associated with reactor-based production [1]. Reference [2] contains a list of reactions that are used to produce a broad range of radionuclides. Of particular interest to this proposal are the several of the so-called “theranostic pairs” of radionuclides that can be “co-loaded” in a patient to provide individualized treatment plans for patients, and the promising alpha-therapeutic radionuclide 225Ac.

Unfortunately, the production rates of these radionuclides are often limited due to either channel fragmentation in the case of spallation, or the lack of significant target areal density due to energy loss in the target in the case of low-energy (p,n) and (p,) reactions. Furthermore, these production pathways often require sole use of the university-based machine, limiting their production rate and increasing the cost/unit activity of the radionuclides.

One way to alleviate these issues is to use a wider variety of beam-target combinations. The (d,xn) reaction is particularly compelling in that it produces both the same radionuclide as the commonly-used (p,n) reaction while simultaneously making a significant energetic secondary neutron flux (ESNF) from the breakup of the unreacted primary deuteron beam. This ESNF can also be used to produce high specific-activity radionuclides via charge exchange reactions such as (n,p) and (n,).

Several recent references [3,4] suggest that (n,x) reactions may be used for the production of high-specific activity radionuclides. However, there is often either a paucity of data or conflicting measurements for these reaction cross sections. Recently *Qaim* pointed out the need for improved nuclear data for (n,p) cross sections producing non-standard beta-emitters [5,6]. In this proposal we will explore the production of multiple “high-priority” radionuclides simultaneously through the use of a primary heavy-ion (e.g., A>1) beam on a composite target that includes three layers:

* Layer #1: A (d,2n) reaction produces Activity #1.
* Layer #2: Unreacted deuterons produce an ESNF via break-up on a thick Be target.
* Layer #3: (n,p) and/or (n,2n) reactions on mm-thick targets produces Activities #2-4.

In this proposal we will quantitatively determine energy differential cross sections (e.g., excitation functions) for the production of the isomeric radionuclide 193mPt via the 193Ir(d,2n) reaction for deuterons with energies between 16 and 50 MeV using a stacked target approach. We will then perform a series of measurements quantifying the production rate of the 64,67Cu theranostic pair via the natZn(n,p) reaction with ESNF neutrons formed from the break-up of energetic deuterons on a thick Be target. Lastly, we will explore the use of the 226Ra(n,2n)225Ra reactions as a production mechanism for the promising targeted alpha-therapeutic radionuclide 225Ac. The measurements will be carried out at the LBNL 88-Inch cyclotron by a UC-Berkeley nuclear engineering graduate student and post-doctoral researcher under the supervision of local faculty and staff.

## Radionuclide production using thick target deuteron break-up neutrons (TTDBN)

Thick target deuteron breakup (TTDB) has long been known to produce an intense, forward-focused neutron beam [7,8]. Recently, researchers at UCB and LBNL have been working to characterize the energy-differential neutron flux arising from deuteron break-up for beams with energies from 20-29 MeV [9], and using these beams to provide light-yield measurements for new classes of organic scintillators [10]. Most recently, the neutron yield from the breakup of 16 MeV deuterons on a thick beryllium target was measured by the UC-LBNL-LLNL collaboration [11]. One noteworthy aspect of TTDB neutrons is there near complete lack of a thermal component due to the lack of moderating material near the breakup target.

The fraction of the deuteron beam broken up depends on the break-up cross section and the linear energy loss (*dE/dx*) of the deuteron beam in the target. The latter of these two factors leads to significantly enhanced breakup for low-Z target materials, ranging from 0.5% for 16 MeV deuterons to nearly 10% at 50 MeV on thick beryllium targets as reported by *Meulders* [8]. Furthermore, these neutrons are strongly forward-focused, with more than ½ of the beam coming out within a 10° cone.

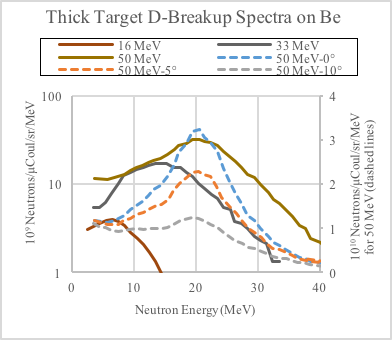


Figure 1: Thick Be target deuteron break-up neutron spectrum for *Ed=* 16, 33 and 50 MeV (solid lines) and for 50 MeV at 0°, 5° and 10° (dashed lines)

Figure 1 to the right shows the neutron energy spectrum resulting from thick target deuteron break-up on Be at 16, 33 and 50 MeV, over all angles (solid lines), and for forward angle from 0°-10° (dashed lines) from *Meulders*. The spectrum is broad and peaked at slightly less than half of the incident deuteron energy. It should be noted that higher energy deuterons result in a significantly greater overall neutron yield due to their greater range in the Be target.

The angle-differential data presented in this plot highlights the importance of keeping the neutron production target (layer #2) close to the second radionuclide generating target (layer #3).

Targets placed within this secondary neutron field will have a fraction *F* of their atoms converted via fast neutron reactions via the relation:

(1)

where ** is the decay constant of the radionuclide, is energy- and spatial-differential neutron flux, is the energy differential cross section and *t* is the irradiation interval.

For example, if a 10 µA 50 MeV deuteron beam is made incident on a Be target, roughly 10% of the beam is broken up. If a second target with an energy-averaged (n,p) cross section of 50 mb is located immediately behind the breakup target, and all of the resulting neutrons are made incident on it, approximately 1.6x10-13 of the atoms in the target will be converted per second, yielding a total of roughly 1.4x10-8 (14 parts per billion) of the sample converted per day. The 1:109 level of radionuclide conversion is a good fiducial since it has been shown to be sufficient for the carrier-free separation of Cu radionuclides from a Zn target [12], allowing the production of high-specific activity radionuclides.

# Proposed Research/Methods

In this proposal we will determine simultaneous radionuclide production rates for a composite target that utilizes the 193Ir(d,2n) and the 64,67Zn(n,p) reactions to simultaneously make 193mPt and 64,67Cu radioisotopes using a composite target comprised of natIr, Be and natZn layers. We will also explore the use of the ESNF to generate the promising alpha-therapeutic radionuclide 225Ac.

There are many potential composite targets that could be utilized for simultaneous radionuclide production. Table I on the right lists a total of 9 potential (d,2n), (n,p) and (n,2n) reactions that could be “mixed and matched” to allow for the co-production of multiple radionuclides. The first four entries in this table are the (d,2n) reactions used to produce both a radionuclide and a ESNF, and the second set of five are (n,p) and (n,2n) reactions driven by the ESNF from the unreacted deuteron beam. The last reaction also requires -decay of the 225Ra reaction product to make the radionuclide 225Ac. These reactions will use deuteron beams with energies below 50 MeV on targets thin enough to allow the unreacted deuteron beam to emerge after a loss of approximately 5-10 MeV. The energy-degraded deuterons would then hit a thick target (≥1 cm) beryllium layer, thereby maximizing the ESNF yield on a second group of potential targets that could be used to produce radionuclides via (n,x) reactions. The range of the ESNF neutrons in the target is much larger than 1 mm, meaning that yields could be trivially expanded by scaling up the thickness of the neutron target. However, doing so would lower the fraction of the target converted, potentially making high-efficiency chemical separation difficult to perform.

|  |  |  |
| --- | --- | --- |
| Reaction | Major decay Gamma-ray Energy and Intensity | |
| keV | % |
| **193Ir(d,2n)193mPt** | **133.50 (3)** | **0.115** |
| 86Sr(d,2n)86Y | 1153.1 (3) | 0.69 (8) |
| 44Ca(d,2n)44Sc | 1157.020 (15) | 99.9 (4) |
| 72Ge(d,2n)72As | 833.99 (3) | 81.0 |
| **64Zn(n,p)64Cu** | **511** | **35.2 (4)** |
| **67Zn(n,p)67Cu** | **184.577 (10)** | **48.7 (3)** |
| 47Ti(n,p)47Sc | 159.381 (15) | 68.3 (4) |
| 77Se(n,p)77As | 239.011 (6) | 1.59 (\*) |
| **226Ra(n,2n)225Ra** → 225Ac (-decay) | 218.0 (1)  440.45 (1) | 11.44  25.94 (15) |

Table I: Radionuclide production pathways under consideration in this proposal. This proposal will focus on the three reactions shown in **boldface.**

In this proposal we will focus on designing and testing the production rate of 3 radionuclide producing reactions listed in Table II using the three-part composite target design; 193Ir(d,2n)193mPt together with 64,67Zn(n,p)64,67Cu. We will use natural abundance targets accessible commercially through GoodfellowUSA. Finally, in the last part we willfocus on the production of 225Ac via the ESNF-induced (n,2n) reaction on 226Ra using a pair of 226Ra targets prepared for us by researchers at the National Isotope Development Center at ORNL.

## (d,2n) Candidate Reactions

A host of nuclear reaction models are employed in the isotope production community, including most notably the ALICE package which uses a classical treatment of angular momentum conservation. For the purposes of this proposal we will compare more modern reaction model packages including the EMPIRE-3.2 (Malta) [13] used in the preparation of the Evaluated Nuclear Data File (ENDF) and the TALYS-1.8 model [14] used by the basic nuclear science research community.

We will start by considering one of the reactions listed in Table I above - 86Sr(d,2n)86Y.

Figure 2 to the right shows this energy differential cross sections from the TALYS and EMPIRE reaction models, together with the “energy-adjacent” reactions 86Sr(d,n) and 86Sr(d,3n). Both the energy dependence and the overall magnitude of the modeled (d,2n) cross sections from TALYS and EMPIRE are in good agreement with each other, reaching a peak near 17 MeV before tailing off with the opening of the (d,3n) channel.

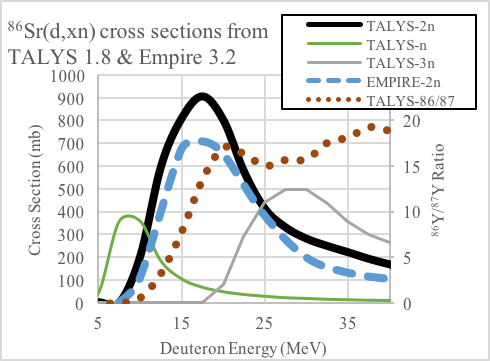


Figure 2: TALYS-1.8 reaction model calculations for the 86Sr(d,xn) reactions for 1≤x ≤3 (solid lines) and for 86Sr(d,2n) using EMPIRE-3.2 (dashed lines)

The ratio of the (d,2n) to (d,n) reaction is also shown in figure 2 because 87Y (*t½=*3.33 d), which is produced by the (d,n) reaction, is a relatively long-lived unwanted activity that is co-produced with the 86Y (t½=14.74 h). The 86Y/87Y ratio rises rapidly to approximately 17 at 20 MeV (corresponding to the opening of the (d,3n) channel) and remains close to 20 through 40 MeV. It should be noted that 87Y is also co-created, albeit at lower levels, when 86Y is produced by 86Sr(p,n) via the (p,) reaction, with a bit less than 1% contamination being present at typical medical cyclotron energies (≈11 MeV).

In contrast, the (d,3n) channel makes the much shorter-lived 85gY (t½=2.68 h) and 85mY (t½=4.86 h) radionuclides that can be removed by waiting for it to decay prior to separating it from the Sr production target. If a higher beam energy were employed, then either a thicker 86Srtarget could be used, leading to increased production of 86Y together with a significantly enhanced ESNF spectrum from deuteron break-up on the Be target layer.

The other (d,2n) reactions listed in Table I make 193mPt, 72As and 44Sc respectively. Figure 3 below shows these cross sections as a function of incident deuteron energy from TALYS. Similar results are seen using EMPIRE. All of these excitation functions are peaked near 17 MeV and drop off with increasing energy due to the opening of the (d,3n) reactions.

The co-production of unwanted activities via the energy-adjacent (d,n) and (d,3n) reactions for these other reactions are summarized in Table II below. The most problematic is 72As, which is “bracketed” by the production of long-lived unwanted activities.

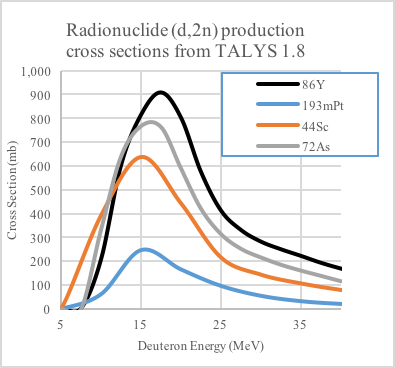


Figure 3: Excitation functions for the four (d,2n) reactions listed in Table II modeled using the TALYS reaction code.

|  |  |  |
| --- | --- | --- |
| (d,2n) Nuclide | (d,n) nuclide | (d,3n) nuclide |
| **193mPt (4.33 d)**  ***193gPt (50 y)*** | **194Pt (stable)** | **192Pt (stable)** |
| 86Y (14.74 h) | *87Y (3.33 d)* | 85Y (2.68 h) |
| 72As (1.08 d) | *73As (80.3 d)* | *71As (2.72 d)* |
| 44Sc (3.97 h) | 45Sc (stable) | *46Sc (83 d)* |

Table II: Radionuclides produced by the (d,xn) reactions considered in this proposal. Nuclides in *red italics* are unwanted co-produced activities.

In direct contrast, the production of 193mPt is ideal in that the adjacent nuclei are both stable. This means that the energetic “tail” of the (d,n) channel produces no unwanted activities, and higher energy deuterons could be safely used to produce 193mPt together with a more robust ESNF yield for the co-production of radionuclides via (n,p) reactions. This makes the 193Ir(d,2n) the best initial candidate for this initial foray into simultaneous radionuclide production using (d,2n) reactions

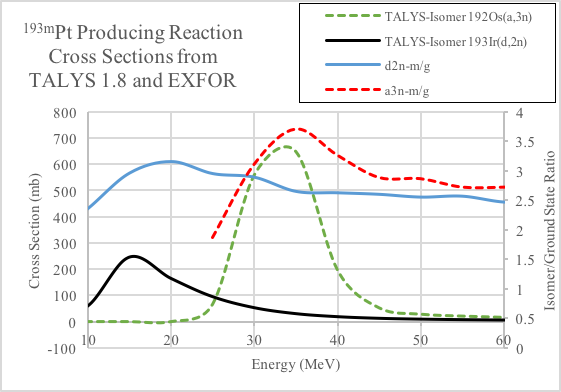


Figure 4: Cross section calculations using TALYS-1.8 for 193Ir(d,2n)193mPt and the ratio of 193mPt/193gPt(sold lines), and for the 192Os(,3n)193mPt reaction and the ratio of 193mPt/193gPt (dashed lines). The vertical axis on the right applies to the isomer-to-ground state ratios.

According to reference [1], the current production pathway for 193mPt is the 192Os(,3n) reaction. This reaction requires the use of isotopically-enriched osmium targets, which is less than ideal. Furthermore, even though it utilizes a more massive projectile than the (d,2n) reaction, reaction modeling from both TALYS and EMPIRE indicate that it doesn't lead to significantly enhanced production of the high-spin isomeric activity of interest for medical applications. This is shown in figure 4 to the right, which includes the results of TALYS calculations for both the (d,2n) and the (,3n) reaction channels, as well as isomer-to-ground state ratios for both of these cases.

The peak cross sections for the (d,2n) and (,3n) reactions are 249 and 647 mb respectively, seeming to favor the (,3n) reaction by a factor of 2.6. However, this doesn't take into account the more limited range of -particle compared to deuterons. The thickness over which an particle goes from 40 MeV down to 25 MeV in an 192Os target, which corresponds to the peak of the (,3n) cross section, is only 180 mg/cm2. In contrast, the range of a deuteron covering the peak (d,2n) energy region (25-17.5 MeV) is 400 mg/cm2. When these range differences are taken into account the advantage of the (,3n) reaction compared to the (d,2n) reaction is only 17% more effective at producing the radionuclide. This modest production rate difference, together with the difficulties arising from the use of an osmium target, indicate that the 193Ir(d,2n)193mPt reaction is likely the preferred production reaction. Optimizing the production of 193mPt using deuteron-induced reactions may be the topic of a future proposal by this group.

## (n,p) Candidate Reactions

Figure 5 below shows the excitation functions for a number of (n,p) reactions that can be used for radionuclide production in the back layer of the target calculated using TALYS overlaid with the ESNF neutron spectra from *Meulders* [8]. Two of the radionuclides (64Cu and 47Ti) have significantly higher production cross sections than the other two (67Cu and 77As) for neutron energies below 20 MeV, leading to significantly higher production rates for ESNF neutrons from lower energy deuteron breakup.

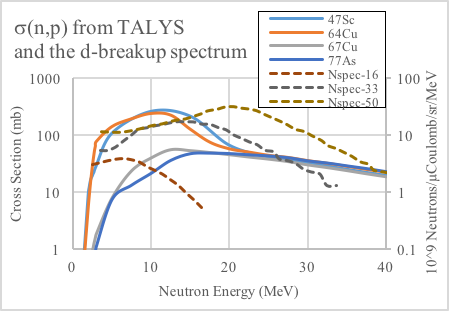


Figure 5: Cross section calculations using TALYS-1.8 for the production of 47Sc, 64Cu, 67Cu and 77As(sold lines, left hand vertical axis), and the thick target deuteron breakup neutron spectrum for 16, 33 and 50 MeV deuterons (dashed lines, right hand vertical axis).

The larger ESNF production at higher incident deuteron energy suggests the use of a more energetic deuteron beam together with the addition of a thin deuteron break-up target in front of the three-part target stack could be gainfully employed to enhance the ESNF while maintaining an optimal energy for production of the first nuclide via (d,2n). Alternatively, a deuteron energy well above the peak of the (d,2n) channel could be used to enhance the yield of the (n,p) reaction product in the back layer at the expense of production rate for the (d,2n) product. The former approach would not only result in a decrease in the (d,2n) yield, but would also subject the (d,2n) layer to an intense ESNF that could stimulate (n,p) reactions on it.

It is worth noting that while the use of separated isotope targets enhances the production of the desired radionuclides while avoiding the production of unwanted activities, they are not essential for the production of 64,67Cu via (n,p) since all of the other activities induced by ESNF neutrons on the stable Zn isotopes are relatively short-lived. This advantage makes the 64,67Zn(n,p) reactions are lead candidates for this initial co-production proposal.

## Early results for the production of 64,67Cu via d-breakup on natZn

In early June 2016 a penny was irradiated in a ESNF formed via the break-up of a 16 MeV deuteron beam on a thick Be target as a part of a separate experimental activity at the LBNL 88-Inch cyclotron. Figure 7 below shows the resulting spectrum. The spectrum clearly shows significant production of both the 64Cu from 64Zn (49% abundance) and 67Cu from 67Zn (4.04% abundance). 65Zn (*t½*=244 d) and 69Zn (t½=56.4 m) are also present, but they would be removed by the chemical separation of the Cu from the Zn target. While the analysis of this scoping study has not yet started, it is clear that natZn(n,p) offers a clean and reasonable path for the production of 64,67Cu.

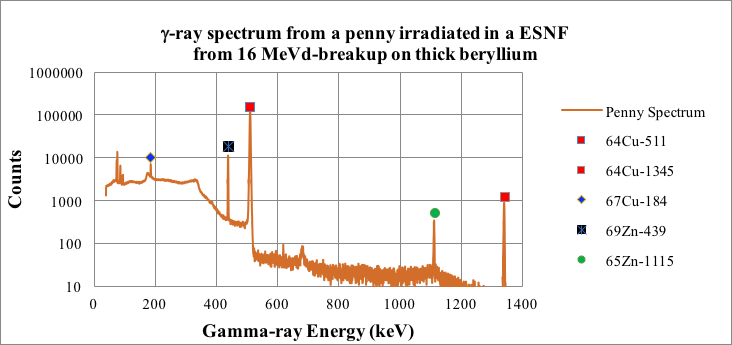


Figure 7: Gamma-ray spectrum of a modern penny (97.5% Zn) taken following irradiation in the neutron field resulting from the break-up of 16 MeV deuterons in a thick Be target at the LBNL 88-Inch cyclotron. All of the major transitions are from either (n,p) or (n,2n) reaction channels.

## Production of 225Ac via the 226Ra(n,2n) reaction

Following the initial submission of this proposal it became clear that the ESNF from thick target deuteron breakup offered an excellent production pathway for the promising targeted alpha-therapeutic radionuclide 225Ac. This nucleus is nearly unique in that it has a relatively long half-life (10 days) followed by a quick succession of 4 -decays capable of producing the sort of double-strand DNA damage needed to deter tumor growth.

Unfortunately, there are few optimal paths for the production of 225Ac. One approach is to use high-energy proton-induced spallation of 232Th. However, this channel invariably leads to the co-production of 227Ac, which has a lifetime of 21.772 (3) years, making it an unwanted contaminant.

A second approach is to use the 226Ra(p,2n)225Ac reaction. However, this reaction is also challenging since the reactivity of radium necessitates the use of an irregular salt target with a limited thickness and target heating from the proton beam could present a potential contamination hazard.



Figure 6: Cross section for the 226Ra(n,2n) reaction from the ENDF-B8.b5, TENDL-2015 databases and the sole measurement at 14.5 MeV from *O’Connor*.

Our plan is to explore an alternative approach using the 226Ra(n,2n)225Ra reaction followed by -decay of the 225Ra into 225Ac (t½=14.9±0.2 days). This approach takes advantage of the lower value of (*Z2/A*) for radium compared to higher-Z actinides, which leads to a limited fission cross section, and a correspondingly higher (n,2n) cross section for neutron energies up to 20 MeV. Figure 6 to the right shows the predicted value for the 226Ra(n,2n) cross section from the ENDF-B7.1 and TENDL databases together with the sole measurement from O’Conner [15]. The details of this experiment will be presented below.

# Project Tasks

Four tasks will be carried out as a part of this proposal:

1. Measurements of (d,xn) cross sections as a function on incident deuteron energy from 25-55 MeV using a “stacked target” methodology on natIr.
2. Measurements of ESNF energy-integral (n,p) production rates on natural abundance Zn targets using the thick target deuteron breakup on a thick Be target.
3. Scoping studies for the production of 47Sc from the ESNF-induced 47Ti(n,p) reaction.
4. Measurements of the ESNF energy-integral (n,2n) 225Ac production rates on two 1-mg 226Ra samples.

The activities supported under this proposal will be carried out at the 88-Inch cyclotron at Lawrence Berkeley National Laboratory. The 88-Inch Cyclotron (the “88”) at Lawrence Berkeley National Laboratory (LBNL)[[1]](#footnote-1) is a variable energy, high-current, multi-particle cyclotron capable of accelerating ions ranging from protons to uranium at energies approaching and exceeding the Coulomb barrier. Maximum currents on the order of 10 particle•µamperes, with a beam power limitation of 1.5 kW, can be extracted from the machine for use in experiments in 7 experimental “caves”. Intense light-ion beams, including deuterons, can be used in both the cyclotron vault and Cave 0. The beam-time will be made available as an in-house research program.

Figure 8 below shows the layout of the 88”. The (d,2n) measurements will take place in Cave 0 using an electrostatically- and magnetically-suppressed beam-dump to hold foil stacks designed to measure the (d,xn) reactions for x=1-3 over 5 energy points. This set-up has already been successfully used to measure Zr(d,xn), Fe(p,xn) and La(p,xn) cross sections in collaboration with researchers from the University of Wisconsin and Jülich.

The (n,p) and (n,2n) cross section measurements will also be carried out in Cave 0 where high-current deuteron beams will be made incident on a water-cooled beryllium break-up target located less than 5 cm away from the neutron targets. This configuration is capable of generating an ESNF of up to ≤1013 n/s/cm2 via thick target deuteron breakup.

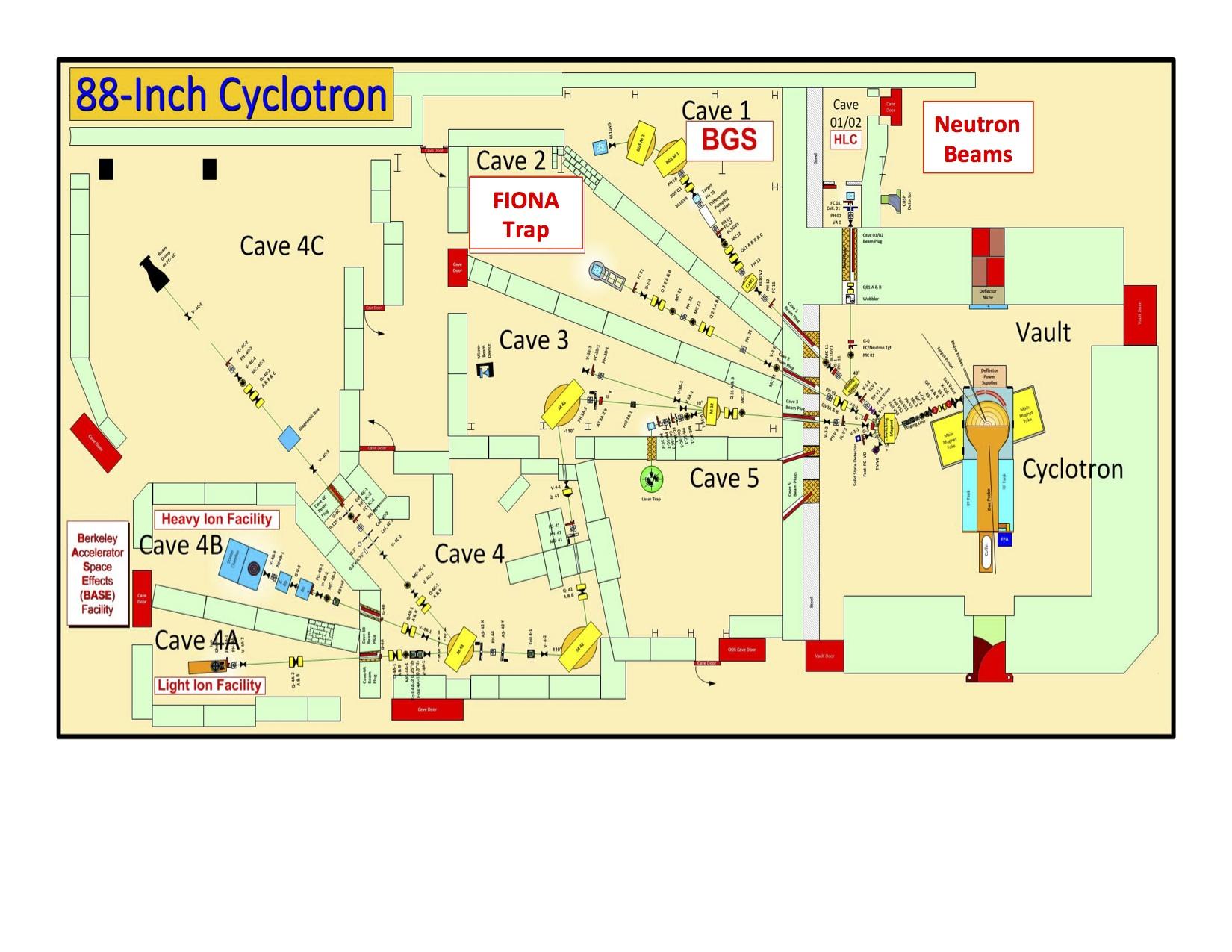


Figure 8: Layout of the LBNL 88-Inch cyclotron. The red arrows show where the deuteron beams will be transported for the proposed activities. The blue triangle schematically represents the neutron fields.

## Charged-particle measurements using the LBNL 88-Inch cyclotron (Task #1)

We will measure deuteron-induced cross sections over a wide projectile energy range utilizing the “stacked target” (ST) approach. The ST method involves irradiating “foil packs” consisting of a sample for which the reaction cross section needs to be measured, together with natCu and natTi standard monitor foils. Activation of these monitor foils helps determine the incident beam energy and provides a secondary determination of the integrated beam current. These packs are interspersed with Al degraders which lower the incident charged particle beam energy, thereby allowing for the simultaneous measurement of reaction cross sections over a wide energy range. Table III below shows the projected number of decay -rays observed using a 1% photopeak HPGe detector following a 1 µamp•hour run on a 10 mg/cm2 target using the TALYS-1.8 production cross section shown in figures 3 & 4 above. The decay data was taken from Evaluated Nuclear Structure Decay File (ENSDF). This table shows that reasonable counting statistics can be obtained in a short run using thin targets.

The (d,xn) reaction that we will explore in this proposal will be 193Ir(d,2n)193mPt reaction. As mentioned above in, this reaction has the advantage that both the (d,n) and (d,3n) reactions form stable nuclides that will not need to be chemically separated from the desired 193mPt activity. The cross section for the population of the isomer 193mPt isomerwill be determined through gamma-ray counting using the on-site Gamma Spec Lab at the 88-Inch cyclotron (see Appendix 5 below). The gamma-branch from the isomer is quite weak (0.115%) since it is a M4 transition and decays primarily through internal conversion (≈890). However, we anticipate being able to utilize some of the X-rays decays as well, albeit with more significant corrections for attenuation from the X-rays in the iridium targets.

Currently, the Gamma Spec Lab only has the capacity to record “singles” gamma-ray spectra with pre-determined counting intervals. In order to enhance our ability to determine the yields from these experiments we will procure an Ortec DSPEC50 digitizer to allow for recording of event-by-event data in list mode.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Reaction | Major decay -ray Energy and Intensity | | Projected Counts (in units of 106 counts) | | | |
| keV | % | 20 MeV | 30 MeV | 40 MeV | 50 MeV |
| **193Ir(d,2n)193mPt** | **133.50 (3)**  ***66.831***  ***65.122*** | **0.115**  ***7.21 (16)***  ***4.25 (9)*** | **0.062**  ***4.0***  ***2.4*** | **0.12**  ***7.7***  ***4.6*** | **0.32**  ***21***  ***12*** | **0.98**  ***63***  ***37*** |
| 86Sr(d,2n)86Y | 1153.1 (3) | 0.69 (8) | 7.0 | 1.4 | 2.3 | 65 |
| 44Ca(d,2n)44Sc | 1157.02 (2) | 99.9 (4) | 590 | 427 | 354 | 236 |
| 72Ge(d,2n)72As | 833.99 (3) | 81.0 | 716 | 1430 | 2640 | 7240 |

Table III: Projected counting statistics following a counting period equal to twice the lifetime of the radionuclide on a 1% photopeak efficiency HPGe detector for a 1 hour run using a 1 µampere deuteron beam on a 10 mg/cm2 target for 4 potential (d,2n) reactions. We will measure the first of these only, 193Ir(d,2n)193mPt (t ½=4.33 d), as a part of this proposal. The entries in *italics* correspond to X-rays from conversion of the 193mPt decay that can be used to identify the radionuclide as well.

This (d,2n) measurement will take place in a single run at the 88-Inch cyclotron in year 1. The data will be analyzed by Mr. Jonathan Morrell as a part of his Ph.D. studies. In addition to being part of his thesis research, this measurement will be submitted for publication in an appropriate peer-reviewed journal. This activity will constitute the first task carried out under this proposal.

## (n,p) measurements using thick target d-breakup (Tasks #2 and #3)

The (n,p) cross section measurements will also take place at the LBNL 88-Inch cyclotron using a high-intensity, energetic, deuteron beam on a thick beryllium target over the course of two experiments at different deuteron beam energies (33 and 44 MeV). The neutron production for these experiments will utilize a thick Be neutron production target and a set of 1 mm thick natural abundance zinc and titanium target for the production of 64,67Cu via the 64,67Zn(n,p) reactions. This activity constitutes the second task carried out under this proposal.

The modest thickness of the Zn and Ti targets will not significantly degrade the ESNF, allowing multiple targets to be irradiated simultaneously for production. However, since the purpose of this proposal is research rather than production, we will not use multiple Zn foils. Instead, we will perform a “scoping” irradiation of natTi to study the viability of producing of 47Sc via (n,p) reactions. This activity will constitute the third task carried out under this proposal.

Table IV below lists the (n,p) reaction that will be studied together with the most intense gamma-rays following the decay of the activities formed assuming a 1 µamp•hour run on a 1 cm thick Be break-up target followed by a counting interval equal to twice the lifetime of the activities formed. The values in the table also assume that the ESNF given by *Meulders* and the production cross section calculated using TALYS are correct, and that the gamma-ray spectrometer at the 88-Inch cyclotron counting facility is employed. Excellent counting statistics are predicted for all cases.

While the purpose of this proposal is to determine the production rates for the radionuclides formed via the (d,2n) and the (n,p) reactions, it is illustrative to list the production rate for these radionuclide assuming that the production cross sections from the TALYS calculations are correct and that the d-breakup neutron yields and spectra are as predicted by *Meulders*. The 4th column in table V below lists the fraction of the target converted to the desired radionuclide via the (n,p) reaction. We will not perform chemical separations as a part of this proposal, but our goal will be to obtain a minimum of 1:109conversion of the target to allow for the production of high-specific activity radionuclide samples via carrier-free chemical separation. Efficient carrier-free separation of radioactive Cu from Zn has already been shown to be possible at this level [12]. While this is easily the case at the 1 µamp level for 47Sc and 64Cu, 67Cu and 77As would require slightly higher beam current in order to obtain the desired activity ratio.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Reaction | Major decay -ray Energy and Intensity | | Projected Counts (in unit of 106) | | |
| keV | % | 16 MeV | 33 MeV | 50 MeV |
| 64Zn(n,p)64Cu | 511 | 35.2 (4) | 437 | 3920 | 8260 |
| 67Zn(n,p)67Cu | 184.577 (10) | 48.7 (3) | 70 | 631 | 1330 |
| 47Ti(n,p)47Sc | 159.381 (15) | 68.3 (4) | 733 | 6570 | 13900 |

Table IV: Projected counting statistics following a counting period equal to twice the lifetime of the radionuclide on a 1% photopeak efficiency HPGe detector for a 1 hour run using a 1 µampere deuteron beam on a thick Be neutron production target for 4 (n,p) reactions under consideration in this proposal, including the two that we will measure in the proposal (64Cu and 67Cu). A 1 mm target thickness is assumed.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Reaction | 25 to 20 MeV  d-beam range | | mCi per  µamp•day | Activity ppb in the neutron target | Major decay -ray Energy and Intensity | |
| mg/cm2 | µm | keV | % |
| **193Ir(d,2n)193mPt** | **275** | **122** | **1.74** | **-** | **133.50 (3)** | **0.115** |
| 86Sr(d,2n)86Y | 210 | 562 | 167 | - | 1153.1 (3) | 0.69 (8) |
| 44Ca(d,2n)44Sc | 180 | 1161 | 51 | - | 1157.02 (2) | 99.9 (4) |
| 72Ge(d,2n)72As | 205 | 385 | 97 | - | 833.99 (3) | 81.0 |
| **64Zn(n,p)64Cu** | **-** | **-** | **7.03** | **1.45** | **511** | **35.2 (4)** |
| **67Zn(n,p)67Cu** | **-** | **-** | **0.17** | **0.18** | **184.577 (10)** | **48.7 (3)** |
| 47Ti(n,p)47Sc | - | - | 0.95 | 1.46 | 159.381 (15) | 68.3 (4) |
| 77Se(n,p)77As | - | - | 2.24 | 0.36 | 239.011 (6) | 1.59 |

Table V: Projected production rates in mCi/µamp•day assuming a given thickness target for the (d,2n) reaction, a thick Be neutron production target and a 1 mm thick (n,p) target, and using the TALYS production cross section and neutron spectra and yields from *Meulders*.

## 226Ra(n,2n) measurements using thick target d-breakup (Tasks #4)

The fourth activity we will perform will be a measurement of the ESNF-integrated 226Ra(n,2n) cross section for two different incident neutron energy ranges. This will be accomplished by irradiating two 1 mg samples of 226Ra prepared for this purpose by staff from the National Isotope Distribution Center at Oak Ridge National Lab. The irradiations will utilize the TTDB beam at the 88-Inch cyclotron at deuteron energies of 33 and 50 MeV. The samples will be placed <5 cm from the deuteron break-up target in Cave 0 and will be “sandwiched” between In, Zr, Ni and Al foils, which will be used to measure the integrated neutron fluence and flux via activation.

Following irradiation, the radium samples will be stored for approximately 17.5 days to allow most of the 225Ra to beta-decay into 225Ac. The 225Ac will then be chemically separated from the radium targets to allow for observation of the 218 transition following the decay of 221Fr. The chemical separation will be performed by UC Berkeley graduate student Andrew Voyles under the tutelage of Dr. Jon Batchelder and Prof. Rebecca Abergel from the UC Berkeley Department of Nuclear Engineering using the radiation lab at LBNL.

Figure 10: The number of 225Ra and225Ac nuclides present in the radium samples as a function of time after the end of beam (dashed blue and dotted black lines) and the number of 218 keV -rays emitted from the decay of 221Fr (solid red line).

We will irradiate the 226Ra samples in the ESNF from thick Be target breakup at deuteron energies of 33 and 44 MeV for 1 day at 5 µA beam currents and a distance of 10 cm from the break-up target. Figure 10 on the right shows the number of 225Ra (t½=14.9±0.2 d) and 225Ac (t½=9.9203±0.003 d) present as a function of time from the end of beam together with the 218 keV transitions from the decay of 221Fr (t½=4.9±0.2 m) arising from the decay of 225Ac for a deuteron beam energy of 33 MeV using the TENDL-2015 cross section values. The rates for a deuteron beam energy of 44 MeV are predicted to be 30% higher. While we will only obtain energy-integrated cross section from these measurements, the different between the two energies should be sufficient to indicate whether the TENDL-2015 or ENDF values better reflect the actual cross sections.

The radium samples will be obtained from the National Isotope Development Center and will be prepared by the group led by Dr. S. Mirzadeh. A quote for the acquisition of the targets ($20k) is submitted under separate cover.

# Timetable of Activities

The following is a timetable for the activities that will be carried out under this proposal.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Task # | Sub-Task # | **Description** | **FY18** | | **FY19** | | | | **FY20** | |
| Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| 1 | 1.1 | Perform 193Ir(d,2n) irradiations |  |  |  |  |  |  |  |  |
|  | 1.2 | Ir data analysis |  |  |  |  |  |  |  |  |
|  | 1.3 | Prepare manuscript/submit for publication |  |  |  |  |  |  |  |  |
| 2 | 2.1 | Perform TTDBN irradiation on Zn |  |  |  |  |  |  |  |  |
|  | 2.2 | Zn data analysis |  |  |  |  |  |  |  |  |
|  | 2.3 | Prepare manuscript/submit for publication |  |  |  |  |  |  |  |  |
| 3 | 3.1 | Ti scoping irradiations |  |  |  |  |  |  |  |  |
|  | 3.2 | Preliminary analysis of Ti and Se foil data |  |  |  |  |  |  |  |  |
| 4 | 4.1 | 33 MeV TTDBN irradiation of 226Ra sample #1 |  |  |  |  |  |  |  |  |
|  | 4.2 | Separation, counting & analysis of Ra sample #1 |  |  |  |  |  |  |  |  |
|  | 4.3 | 44 MeV TTDBN irradiation of Ra sample #2 |  |  |  |  |  |  |  |  |
|  | 4.4 | Separation, counting & analysis of Ra sample #2 |  |  |  |  |  |  |  |  |
|  | 4.5 | Prepare manuscript/submit for publication |  |  |  |  |  |  |  |  |

## 

## Roles and Responsibilities/Training plan

The activities carried out under this proposal will be carried out by a team consisting of the senior personnel mentoring graduate students from the UC-Berkeley department of nuclear engineering. While the entire team will aid in the preparation for and fielding of the experiments, we will have student-mentor pairs work on the analysis and interpretation of the data. We have found this type of “one-on-one” mentoring to be the most effective educational environment for students. The following is a list of the personnel involved, their background, and the activities they will perform.:

1. Dr. Lee Bernstein (2 month’s salary – Tasks 1-4): Dr. Bernstein is the head of the joint LBNL/UC-Berkeley nuclear data group, and he has over 24 years of experience in low-energy nuclear structure and reactions research. He is a Co-PI for the Nuclear Science and Security Consortium, and leads its nuclear data crosscutting area. He teaches the core nuclear physics laboratory and lecture courses in the UC-Berkeley department of nuclear engineering, and is the principal advisor for 5 graduate students. Dr. Bernstein will provide project oversight for all four tasks and act as the thesis advisors for the students working on this proposal.
2. Dr. M.S. Basunia (2 month’s salary – Tasks 1-4): Dr. Basunia is a nuclear structure evaluator at LBNL with extensive experience performing neutron-induced reaction measurements. He will guide Jon Morrell in the interpretation of the decay data used to assess the radionuclide yields.
3. Dr. J.C. Batchelder (4 month’s salary support, Tasks 1-4): Dr. Batchelder is an Assistant Research Engineer at UC Berkeley, and a nuclear structure evaluator with more than two decades of experience measuring the properties of unstable nuclei using radioactive beams and decay spectroscopy. Dr. Batchelder is also a Ph.D. Nuclear Chemist. He will supervise Andrew Voyles in the Ac/Ra separation at LBNL and will aid in the interpretation and analysis of the data.
4. Mr. Jonathan Morrell (18 month’s salary+tuition support, Tasks 1-4): Mr. Morrell is entering his second year of graduate students at UC-Berkeley. Mr. Morrell has already performed a measurement of the natLa(p,xn) for x≤6 reaction cross sections using the 88-Inch cyclotron. Mr. Morrell will analyze the data from the cross section measurements proposed in this work with assistance from Drs. Bernstein and Batchelder.
5. Mr. Andrew Voyles (10 month’s salary, Task 4): Mr. Voyles is slated to graduate in August 2018. He will work with Dr. Batchelder to perform the Ac separation from the Ra targets during a short post-doctoral appointment following completion of his Ph.D.

# Coordinated research activities

These activities will be coordinated with two other ongoing efforts supported separately by the US Nuclear Data Program:

1. A program to measure energy differential 235U(d,n), 238U(p,3n) and 232Th(7Li,3n)excitation functions. This work is the subject of a Nuclear Data Interagency Working Group collaboration with Dr. Michael Fassbender from Los Alamos National Laboratory (LANL).
2. Measurements of this (n,p) cross sections on several of the same materials at ≈2.7 MeV via activation in ratio to the 115In(n,n’)115mIn and 58Ni(n,p)58Co dosimetry standards. This work is being carried out at the UC-Berkeley High Flux Neutron Generator, which is an intense ion-source based DD neutron generator designed to maximize neutron flux on samples by placing them within 6 mm of the neutron production target. The 64Zn(n,p)64Cu and 47Ti(n,p)47Sc cross sections have already been measured at the HFNG [16] and are in substantial agreement with earlier work by *Shimizu et al.,* [17].

# Follow-on work and plans for future Isotope Production

The results of this proposal will be the nuclear data needed to design a customizable platform for the simultaneous production of 193mIr and either 64,67Cu or 225Acusing deuteron beams and intermediate energy accelerators. This proposal does not directly address the separation of the activities produced by the (d,2n), (n,p) and (n,2n) activities from the targets, but given the large body of data on this matter we anticipate limited difficulty carrying these separations out. These separations will be the subject of a follow-on proposal that will be submitted, pending success of this work.

# Appendix 1: BIOGRAPHICAL SKETCH – Lee A. Bernstein

## Dr. Lee A. Bernstein

Title: Nuclear Data Group Leader, LBNL.

Adjunct Professor, U.C. Berkeley Dept. of Nuclear Engineering.

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1. **Professional Preparation**

Rutgers University   Physics   B.A. – 1988

University of Maryland   Physics   M.S. –1990

Rutgers University Physics Ph.D. – 1994

Post-Doc: LLNL   N-division   1994-1996

**(b) Appointments**

* Nuclear Data Group Leader, Lawrence Berkeley National Laboratory – June 2016-present
* Adjunct Professor, U.C. Berkeley Dept. of Nuclear Engineering – January 2015-present
* NIF Nuclear Diagnostics Deputy Group Leader, Lawrence Livermore Nat’l Lab – 2009-2013
* Staff Scientist - LLNL – 1996-June 2016
* Postdoctoral Researcher – LLNL – 1994-1996

**(c) Recent Awards**

* Fellow of the American Physical Society (Nuclear Physics) – September 2015
* Three LLNL Physics and Life Sciences Directorate Awards for the Outstanding Mentoring, Postdoctoral supervision and External Leadership – 2015
* LLNL Directors Science and Technology Award for the Development of the Radiochemical Acquisition of Gaseous Samples (RAGS) diagnostic system at the National Ignition Facility– 2014

**(d) Publications** (Selected 10)

1. Neutron Spectroscopy for pulsed beams with frame overlap using a double time-of-flight technique. K.P. Harrig, B.L. Goldblum, J.A. Brown, D.L. Bleuel, L.A. Bernstein, J. Bevins, M. Harasty, T.A. Laplace, E.F. Matthews. Nucl. Inst. Methods in Physics, A 877 (2018) 359–366.
2. Beam-induced back-streaming electron suppression analysis for an accelerator type neutron generator designed for 40Ar/39Ar geochronology. Cory Waltz, Mauricio Ayllon, Tim Becker, Lee Bernstein, Ka-Ngo Leung, Leo Kirsch, Paul Renne, Karl Van Bibber. Appl. Rad. Isotopes, Vol. 125, Pages 124–128 (July 2017).
3. RAINIER: A Simulation Tool for Distributions of Excited Nuclear States and Cascade Fluctuations”. L.E. Kirsch, L.A. Bernstein. Accepted for publication – Nucl. Instrum Methods A (February 2018).
4. Statistical properties of 243Pu, and 242Pu(n,γ) cross section calculation. T.A. Laplace, F. Zeiser, M. Guttormsen, A.C. Larsen, D.L. Bleuel, L.A. Bernstein, B.L. Goldblum, S. Siem, F.L. Bello Garotte, J.A. Brown, L. Crespo Campo, T. K. Eriksen, F. Giacoppo, A. Gorgen, K. Hadynska-Klek, R. A. Henderson, M. Klintefjord, M. Lebois, T. Renstrøm, S. J. Rose, E. Sahin, T. G. Tornyi, G. M. Tveten, A. Voinov. Phys.Rev. C 93, 014323 (2016).
5. -ray decay from neutron-bound and unbound states in 95Mo and a novel technique for spin determination. M. Wiedeking, M. Krticka, L.A. Bernstein, J.M. Allmond, M.S. Basunia, D.L. Bleuel, J.T. Burke, B.H. Daub, P. Fallon, R.B. Firestone, B. L. Goldblum, R. Hatarik, P. T. Lake, A. C. Larsen, I.-Y. Lee, S. R. Lesher, S. Paschalis, M. Petri, L. Phair, N. D. Scielzo, and A. Volya. Phys.Rev. C 93, 024303 (2016).
6. “Measurement of the 64Zn,47Ti(n,p) Cross Sections using a DD Neutron Generator for Medical Isotope Studies”. A.S. Voyles, M.S. Basunia, J.C. Batchelder, J.D. Bauer, T.A. Becker, L.A. Bernstein. E.F. Matthews, P.R. Renne,, D. Rutte,, M.A. Unzueta, K.A. van Bibber. Nucl. Instrum. Meth. B 410 (2017) 230–239. <http://dx.doi.org/10.1016/j.nimb.2017.08.021>
7. 239Pu(n,2n)238Pu cross section deduced using a combination of experiment and theory. L. A. Bernstein, J. A. Becker, P. E. Garrett, W. Younes, D. P. McNabb, D. E. Archer, C. A. McGrath, H. Chen, R. O. Nelson, M. B. Chadwick, G. D. Johns, W. S. Wilburn, M. Devlin, D. M. Drake, and P. G. Young. Phys. Rev. C65, 021601(R).
8. Photon Strength Function at Low Energies in 95Mo. M. Wiedeking, L.A. Bernstein, J.M. Allmond, M.S. Basunia, D.L. Bleuel, J.T. Burke, P. Fallon, R.B. Firestone, B.L. Goldblum, R. Hatarik, M. Krtička, P.T. Lake, A.C. Larsen, I-Y. Lee, S.R. Lesher, S. Paschalis, M. Petri, L. Phair, N.D. Scielzo, Nucl. Data Sheets 119, p. 258 (2014).
9. Relative light yield and temporal response of a stilbene-doped bibenzyl organic scintillator for neutron detection. J.A. Brown, B.L. Goldblum, L.A. Bernstein, D.L. Bleuel, N.M. Brickner, J.A. Caggiano, B.H. Daub, G.S. Kaufman, R. Hatarik, T.W. Phillips, S.A. Wender, K. van Bibber, J. Vujic, N.P. Zaitseva. Journal of Applied Physics 115 #19, 193504 (2014).
10. Probing reaction dynamics with the 196Pt (n, xn) reactions for x≤ 15. L.A. Bernstein, J.A. Becker, W. Younes, D.E. Archer, K. Hauschild, G.D. Johns, R.O. Nelson, W.S. Wilburn, D.M. Drake. Physical Review C57, #6, 2799-2803, (1998).

**(e) Synergistic Activities**

* Dr. Bernstein is the Laboratory Point-of-Contact for the Nuclear Science and Security Consortium (NSSC) led by UC Berkeley. He is responsible for encouraging connections between NSSC students and laboratory researchers at LBNL, LLNL, LANL, SNL and ORNL. He also leads the nuclear data crosscutting area and is the principle advisor for 5 graduate students.
* Dr. Bernstein is also a member of the Nuclear Structure and Decay Section of the IAEA, performing nuclear structure compilation and evaluation.

## ­­­Dr. M. Shamsuzzoha Basunia

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**Education:**

Rajshahi University, Bangladesh Physics B.S. – 1986

University of Texas at Austin Nuclear Engineering M.S. – 2000

University of Texas at Austin Nuclear Engineering Ph.D. – 2002

**Appointments:**

LBNL – Physicist Research Scientist 2013 – Present

LBNL – Physicist Project Scientist 2007 - 2012

LBNL – Postdoctoral Researcher 2003 - 2006

Bangladesh Atomic Energy Commission (BAEC) - Scientific Staff 1991 – 1997

**Publications** (Selected 10)**:**

1. **M. S. Basunia**; Nuclear Data Sheets for A=193, ***Nuclear Data Sheets, 143, 1, 2017.***
2. A.S. Voyles,, **M.S. Basunia**, J.C. Batchelder, J.D. Bauer, T.A. Becker, L.A. Bernstein, E.F. Matthews, P.R. Renne, D. Rutte, M.A. Unzueta, K.A. van Bibber; “Measurement of the 64Zn,47Ti(n,p) Cross Sections using a DD Neutron Generator for Medical Isotope Studies”, Nuclear Instrumentation and Methods – B
3. **M. S. Basunia,** R. B. Firestone, Zs. Revay, H. D. Choi, T. Belgya, J. E. Escher, A. Hurst, . Krticka,L. Szentmiklosi, B. Sleaford, and N. Summers; Determination of the 151Eu(n,*γ*)152*m*1*,g*Eu and 153Eu(n,*γ*)154Eu Reaction Cross Sections at Thermal Neutron Energy; ***Nuclear Data Sheets, 119, 88, 2014*.**
4. H. D. Choi, R. B. Firestone, **M. S. Basunia**, A. Hurst, B. Sleaford, N. Summers, J. E. Escher, Zs. Revay, L. Szentmiklosi, T. Belgya, and M. Krticka; Radiative Capture Cross Sections of 155,157Gd for Thermal Neutrons, Nucl. Science and Engineering,; ***Nuclear Science and Engineering 177, 219,* 2014**.
5. **M. S. Basunia**, R. M. Clark, B. L. Goldblum, L. A. Bernstein, L. Phair, J. T. Burke, C. W. Beausang, D. L. Bleuel, B. Darakchieva, F. S. Dietrich, M. Evtimova, P. Fallon, J. Gibelin, R. Hatarik, C.C. Jewett, S. R. Lesher, M. A. McMahan, E. Rodriguez-Vieitez, M. Wiedeking; The (3He,t*f*) as a surrogate reaction to determine (*n,f*) cross sections in the 10 to 20 MeV energy range, ***Nuclear Instruments and Methods in Physics Research B*, 267, 1899-1903, 2009**.
6. **M. S. Basunia**, H. A. Shugart, A. R. Smith, E. B. Norman; Measurement of cross sections for α- induced reactions on 197Au and thick-target yields for the (α,γ) process on 64Zn and 63Cu , ***Physical Review C*,** 75, 015802**, 2007.**
7. **M. S. Basunia**, E.B. Norman, H. A. Shugart, A. R. Smith, M. Dolinski, B. J. Quiter; Measurement of Cross Sections for the 63Cu(α,γ)67Ga Reaction from 6-8.8 MeV, ***Physical Review C*, 71, 035801, 2005.**
8. N.I. Molla, **S. Basunia**, M.R. Miah, S.M. Hossain, M.M. Rahman, S. Spellerberg, S.M. Qaim; Radiochemical study of Sc-45(n,p)Ca-45 and Y-89(n,p)Sr-89 reactions in the neutron energy range of 13.9 to 14.7 MeV; ***Radiochemica Acta***, 80 (4): 189-191 **1998.**
9. **M. S. Basunia**, S. M. Hossain, M. A. Hafiz, R. U. Miah, M. Rahman, N. I. Molla, M. R. Haque, and A. Yunus; Cross-section Measurement for (n,2n) Process of Chromium Isotope in the Energy Range 13.90-14.71 MeV, Vol. 7, 2-6, **1998**.
10. S. M. Hossain, **M.S. Basunia**, R.U. Miah, M. M. Rahman, N.I. Molla, K. Nehar, and A. Yunus; Measurements of Excitation Function for 89Y(n,2n)88Y Reaction in the Energy Range 13.90-14.71 MeV; Nuclear Science and Application, Vol.5, 2-5, **1996**.

## Dr. Jon C. Batchelder

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1. **Professional Preparation**

Michigan State University   Chemistry  B.A. – 1987

University of California, Berkeley  Chemistry Ph.D. - 1993

Post-Doc: Louisiana State Physics 1994 - 1996

Post-Doc: Oak Ridge Associated U. 1996 - 2000

**(b) Appointments**

* Staff Physicist: Oak Ridge Associated U. 2000 - 2015

Assistant Research Engineer, U.C. Berkeley 2015-present

**(c) Publications** (Selected 10)

1. "Beta-decay of 124Cd"

J. C. Batchelder, N. T. Brewer, C. J. Gross, R. Grzywacz, J. H. Hamilton, M. Karny, A. Fijalkowska, S. H. Liu, K. Miernik, S. W. Padgett, S. V. Paulaskas, K. P. Rykaczewski, A. V. Ramayya, D. W. Stracener, M. Wolinska-Cichocka, Phys. Rev. C. **94**, 024317 (2016).

2. "Ion Source Development for Ultratrace Detection of Uranium and Thorium"

Y. Liu, J. C. Batchelder, A. Galindo-Uribarri, R. Chua, S. Fan, E. Romero-Romeroa, D. W. Stracener, Nucl. Instr. Meth. Phys. Res. B. **361**, 267 (2015).

3. "Structure of Low-lying States in 124,126Cd populated by -decay of 124,126Ag"

J. C. Batchelder, N. T. Brewer, C. J. Gross, R. Grzywacz, J. H. Hamilton, M. Karny, A. Fijalkowska, S. H. Liu, K. Miernik, S. W. Padgett, S. V. Paulaskas, K. P. Rykacewski, A. V. Ramayya, D. W. Stracener, and M. Wolinska-Cichocka, Phys. Rev. C. **89**, 054321 (2014).

4. "Nuclear Isomerism"

J. C. Batchelder, *McGraw-Hill Encyclopedia of Science & Technology, 11th Edition,* McGraw-Hill, Vol 12, p 153, (2012).

5. "Low-lying Collective States in 120Cd populated by -decay of 120Ag: Breakdown of the Anharmonic Vibrator Model at the Three-Phonon Level"

J. C. Batchelder, N. T. Brewer, R. E. Goans, R. Grzywacz, B. O. Griffith, C. Jost, A. Korgul, S. H. Liu, S. V. Paulauskas, E. H. Spejewski, D. W. Stracener, Phys. Rev. C. **86**, 064311 (2012).

6. "Collective and Non-Collective States in 116Cd Studied via the -Decays of 116Agm1,m2,gs"

J. C. Batchelder, J. L. Wood, P. E. Garrett, K. L. Green, K. P. Rykaczewski, J. -C. Bilheux, C. R. Bingham, H. K. Carter, D. Fong, R. Grzywacz, J. H. Hamilton, D. J. Hartley, J. K. Hwang, W. Krolas, D. Kulp, Y. Larochelle, A. Piechaczek, A. V. Ramayya, E. H. Spejewski, D. W. Stracener, M. N. Tantawy, J. A. Winger, and E. F. Zganjar, Phys Rev C **80**, 054318 (2009).

7. "Study of Fine Structure in the Proton Radioactivity of 146Tm"

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**(d) Synergistic Activities**

• Scientific facility manager for the High Flux Neutron Generator (HFNG) at UC-Berkeley

• Extensive past experience in ion source development and testing of Uranium targets at the ORNL HRIBF facility.

**(e) Current Collaborators/Persons with Conflicts of Interest:**

* *LBNL: M.S. Basunia.*
* *University of California, Berkeley: K.A. Van Bibber, B.L. Goldblum. A.M. Hurst, L. Bernstein, R. B. Firestone, E. Browne, M. Fratoni*
* *Oak Ridge National Lab: C. D. Nesaraja, M. Smith, J. M. Allmond, K. Rykaczewski, D. W. Stracener, A. Uribarri-Galindo*
* *University of Tennessee: R. Grzywacz, B. C. Rasco*
* *Vanderbilt University: A. V. Ramayya, J. H. Hamilton*
* *Louisiana State University: E. F. Zganjar*
* *Mississippi State University: J. A. Winger*
* *Brookhaven National Lab: E. McCutchan, A. Sonzogni*
* *Michigan State University: M. Thoennessen, S. Liddick*
* *Argonne National Laboratory" G. Savard, F. G. Kondev*
* *Los Alamos National Lab: T. Kawano*
* *North Carolina State University: J. Kelley*

**(f) Graduate and Postdoctoral Advisors and Advisees:**

* Thesis Advisor: Prof. Joseph Cerny, University of California, Berkeley
* Post-doctoral Advisor: E. F. Zganjar, Louisiana State University
* Post-doctoral Advisor: H. K. Carter, Oak Ridge Associated Universities

Appendix 2: Current and Pending Support for Lee A. Bernstein

Current Support

Principal Investigator

Project/Proposal Title: Data Evaluation for Applied Nuclear Science (DEANS)

Source of Support: LBNL Lawrence Berkeley National Laboratory (DOE Prime)

Award: 7343496

Total Award Amount: $351k

Total Period Covered: 4/1/17 – 3/31/18

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 0.00 Acad: 0.00 Summer: 0.00

Principal Investigator

Project/Proposal Title: FREYA Fission Generator Development

Source of Support: DOE/NNSA

Total Award Amount: $300k

Total Period Covered: 10/1/16 – 09/30/19

Location of project: Lawrence Berkeley National Laboratory

Person months per year committed to the project: Cal: 0.00 Acad: 0.00 Summer: 0.00

Co-Principal Investigator

Project/Proposal Title: Nuclear Science and Engineering Nonproliferation Research Consortium

Source of Support: DOE

FOA: DE-FOA-0001300

Total Award Amount: $ 25M (Bernstein provision: $372k)

Total Period Covered: 7/1/2016 - 6/30/2021

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 0.80 Acad: 0.00 Summer 0.80

Co-Principal Investigator

Project/Proposal Title: Positron-Emitting Analogues of Alpha-Emitting Therapy Radionuclides

Source of Support: Department of Energy

FOA: DE-FOA-0001300

Total Award Amount: $110k

Total Period Covered: 10/01/16 – 9/30/2018

Location of project: Lawrence Berkeley National Laboratory

Person months per year committed to the project: Cal: 0.8 Acad: 0.00 Summer

Pending Support

Principal Investigator

Project/Proposal Title**:** Simultaneous Radionuclide Production using (d,2n) and Secondary Neutron-induced Reaction

Source of Support:Department of Energy

FOA: DE-FOA-0001588

Total Award Amount: $382k

Total Period Covered: 10/01/16 – 9/30/2018

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 1.0 Acad: 0.00 Summer

Principal Investigator

Project/Proposal Title: Improving the 238U(n,n’) cross section using gamma-neutron coincidences

Source of Support: DOE

FOA: Last NEUP Call

Total Award Amount: $842k

Total Period Covered: 10/1/2017 - 9/30/2020

Location of project: LBNL/Ohio University

Person months per year committed to the project: Cal: 0.5 Acad: 0.00 Summer 0.00

Co-Principal Investigator

Project/Proposal Title:238U(p,xn) 237,236Np Nuclear Reaction Cross Section Acquisition and Target Design for the Production of 236gNp and 236Pu from Uranium Targets

FOA: LAB-17-1783

Source of Support: Department of Energy

Total Award Amount: $225k

Total Period Covered: 10/01/17 – 9/30/2020

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 0.5 Acad: 0.00 Summer

Principal Investigator

Project/Proposal Title: Correlated Neutron-gamma Data for Stewardship Science [THIS PROPOSAL]

Source of Support: DOE

FOA: DE-FOA-0001831

Total Award Amount: $878,044

Total Period Covered: 10/1/2018 - 9/30/2021

Location of project: LBNL/UC-Berkeley

Person months per year committed to the project: Cal: 1.0 Acad: 0.00 Summer 0.00

**Co-Principal Investigator**

**Project/Proposal Title: Nuclear Science and Engineering Nonproliferation Research Consortium**

Source of Support: **DOE**

FOA: DE-FOA-0001300

Total Award Amount: $ 25,000,000 (Bernstein provision: $372,058)

Total Period Covered: 7/1/2016 - 6/30/2021

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 0.00 Acad: 0.00 Summer 0.80

**Co-Principal Investigator**

**Project/Proposal Title:** 238U(p,xn) 237,236Np Nuclear Reaction Cross Section Acquisition and Target Design for the Production of 236gNp and 236Pu from Uranium Targets

Source of Support: **Department of Energy**

FOA: DE-FOA-0001588

Total Award Amount: $230,545

Total Period Covered: 10/01/16 – 9/30/2018

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 1.00 Acad: 0.00 Summer 0.0

**Co-Principal Investigator**

**Project/Proposal Title:** Positron-Emitting Analogues of Alpha-Emitting Therapy Radionuclides

Source of Support: **Department of Energy**

FOA: DE-FOA-0001588

Total Award Amount: $107,700

Total Period Covered: 10/01/16 – 9/30/2018

Location of project: Lawrence Berkeley National Laboratory

Person months per year committed to the project: Cal: 0.6 Acad: 0.00 Summer 0.0

**Principal Investigator**

**Project/Proposal Title:** Simultaneous Radionuclide Production using (d,2n) and Secondary Neutron-induced Reaction [THIS PROPOSAL]

Source of Support: **Department of Energy**

FOA: DE-FOA-0001588

Total Award Amount: $378,663

Total Period Covered: 10/01/16 – 9/30/2018

Location of project: University of California, Berkeley

Person months per year committed to the project: Cal: 1.0 Acad: 0.00 Summer 0.0

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# APPENDIX 4: FACILITIES & OTHER RESOURCES

## 88” Cyclotron Executive Summary

The 88-Inch Cyclotron (the “88”) at Lawrence Berkeley National Laboratory (LBNL) [1] is a variable energy, high-current, multi-particle cyclotron capable of accelerating ions ranging from protons to uranium at energies approaching and exceeding the Coulomb barrier. Maximum currents on the order of 10 particle•µamperes, with a maximum beam power of 2 kW, can be extracted from the machine for use in experiments in 7 experimental “caves”. Beam currents up to the mA level could also be developed through the use of internal ion sources and targets. In addition to single-isotope beams the cyclotron can produce mixed-ion “cocktail” beams for use in electronic upset and damage studies. The cyclotron can also produce high-intensity pulsed, neutron beams whose energy can be determined via time-of-flight with flux ≤107 n/s/cm2 (DE/E≈5% at En=10 MeV), or broad spectrum (E/E≈50%) with flux up to ≤1013 n/s/cm2 via thick target deuteron breakup. Neutrons can also be provided in Berkeley using the DD-based High Flux Neutron Generator (HFNG) located at the adjacent UC-Berkeley department of nuclear engineering.

The cyclotron also has an array of research equipment developed for heavy-element research including the Berkeley Gas-filled Separator (BGS) and the FIONA ion trap. Lastly, a wide variety of mobile neutron, particle and gamma-ray detectors together with a mobile data acquisition system are present at the cyclotron for use in user experiments.

The 88 was originally envisioned as a high-current, variable energy, light-ion accelerator for nuclear physics and nuclear chemistry studies, as well as for the production of isotopes used in scientific research. It started operation in 1961 and has maintained its position as a premier stable-beam facility through periodic upgrades, especially to its ion sources [2]. These ion sources have enabled acceleration of an ever-increasing variety of heavy-ion beams up to, and beyond, the Coulomb barrier. Protons, deuterons, and alpha particle beams are available up to maximum energies of 55, 65, and 130 MeV, respectively. For extracted beams the operational upper limits of current intensities are not known since we restrict running to a maximum power of 1.5 kW. These administrative limitations are self-imposed. There is no reason that we cannot exceed these restrictions with proper planning and preparation. One can readily envision extracted beams of several tens of particle-microamperes.

## Instrumentation and facility layout

The 88-Inch Cyclotron is host a number of unique instruments and capabilities. These include three electron cyclotron resonance (ECR) ion sources, featuring VENUS, the most powerful superconducting ECR ion source in the world. These ECRs provide a range of highly-charged ions up to and including fully-stripped U92+. The cyclotron also plays host to the Berkeley Gas-filled Separator (BGS). The BGS provides rejection of beam-like and fission fragment nuclides formed in heavy-ion reactions in excess 1:1012 for use in heavy-element research. The back end of the BGS can accommodate an array of pixelated Micron “W2” Si detectors three “Clover” HPGe detectors for use in alpha- and gamma-decay spectroscopy of evaporation product nuclides. Alternatively, the back end of the BGS can be coupled to the FIONA ion trap that can isolate a single charge-to-mass ratio fragment.

The 88-Inch also has a mobile data acquisition system that can be used to with the three in-house “clover” HPGe detectors and an array of 6-10 modular neutron detectors. LBNL is also a member of the clovershare program, providing access to an additional 6-10 detectors on a by-arrangement basis. Lastly, LBNL has a pair of well-calibrated shielded HPGe detectors located outside of the experimental caves that can be used to measure activities off-line for cross section or decay spectroscopy measurements.

# Appendix 5: Equipment

The 88-Inch cyclotron includes all instrumentation along the beam-lines required for the (d,2n) and (n,p) cross section measurements, including:

* Faraday cups for current measurements
* Vacuum pumps, pressure gauges etc.
* Fixed and movable radiation monitors

In addition, the 88-Inch include a Gamma Spec Lab with two calibrated single-crystal HPGe detectors that will be utilized to determine activity levels by post-run counting. More information about the gamma-lab can be found online at <http://cyclotron.lbl.gov/gamma-spectroscopy-lab>

# APPENDIX 6: DATA MANAGEMENT PLAN

**Data types and sources**

The data resulting from this experiment will include:

* Written notes in two log books:
  + A gamma counting logbook
  + Operators notes on the tuning/running of the cyclotron
* List mode data from the DSPEC50 Ortec digital HPGe data acquisition system.
* “Singles” -ray spectra taken with the detector during the course of the experiment.
* Photographs of the experimental set-up.

All of the data will be copied and stored at LBNL and UC-Berkeley and made available to all members of the collaboration.

Nuclear data generated by the proposed work will be shared with the public through the submission of peer-reviewed manuscripts, conference presentations (NuDat, CSEWG), and by interaction with the DOE's Nuclear Data program.  This will include compilation into both the Unevaluated Nuclear Data File (XUNDL) for any nuclear structure and decay data, and EXFOR for experimental cross section measurements.

**Content and format**

The repository chosen by the isotope production arm of the nuclear data community is EXFOR, jointly maintained by the National Nuclear Data Center (NNDC) in Brookhaven and the IAEA. Interaction with these bodies will be accomplished through the CSEWG meeting, previously mentioned and by publication in appropriate forums where data are conscientiously selected for inclusion in the repository.

**Sharing and preservation**

The proposed work includes milestones for the communication of measured data to the public via the publications, conferences, and internationally maintained repositories outlined previously. No access restrictions are anticipated, and the data must be communicated in the specified formats to be acceptable for publication or sharing in these accepted scientific forums. The data are expected to be available indefinitely as the repositories depend on international funding for their continued operation, and any delay in their availability will only result from the time devoted to careful analysis of experimental results.

**Protection**

No human subject research will be conducted by the proposed work and no communication of personal identifying information is anticipated for any reason.

**Rationale**

The plan of the proposed work is to make all measured data available to the scientific community as expeditiously as possible.

**Software & Codes**

No software will be created as a result of the proposed work.

1. http://cyclotron.lbl.gov [↑](#footnote-ref-1)