Evaluation of Gamma Beam Energies to Create ^{111m}Cd, ^{115m}In, and ^{113m}In Metastable Isotopes

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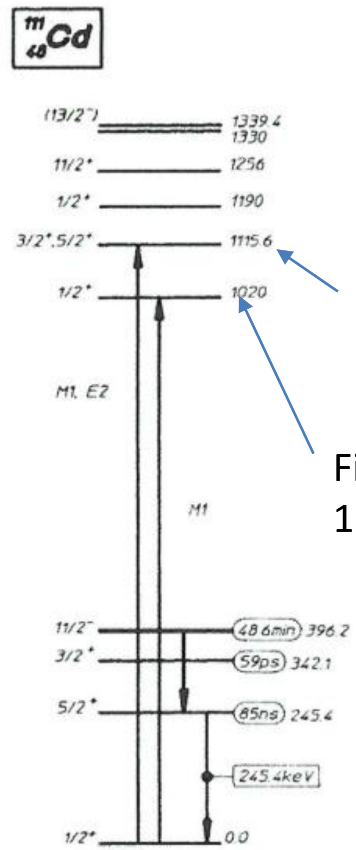
Theresa L Benyo, NASA GRC
Bruce Steinetz, NASA GRC
Lawrence Forsley, Vantage Partners LLC

Introduction

- Investigate Electron Screened Enhanced Nuclear Reactions with Dynamitron Electron Accelerator
  - Deuterated materials with stationary deuteron center-of-mass system
  - Exposed to photons with kinetic energies above and below the deuteron photo-dissociation energy
- Expose cadmium and indium with known gamma spin-up
  - Experimentally determined beam loss from the Dynamitron
  - Discovered lower spin-up threshold from previous experiments

Energy Level Diagrams of Cadmium

J. A. Anderson, et. al. 1988



Reported threshold 1.19MeV

First threshold 1.02MeV

FIG. 1. Energy level diagram of the excited states of ^{111}Cd between 1000 and 1500 keV which may be important in the production of the 48.6 m isomer as reported in Ref. 5. Also shown are all excited states below 400 keV. Half-lives of the states are shown to the right of each state and known (Ref. 6) gamma transitions are shown by the arrows. Populations of the 48.6 m isomer are most conveniently detected by the 245.4 keV fluorescent transition as indicated.

Energy Level Diagrams of Indium

W. K. Tuttle, et. al. 1979

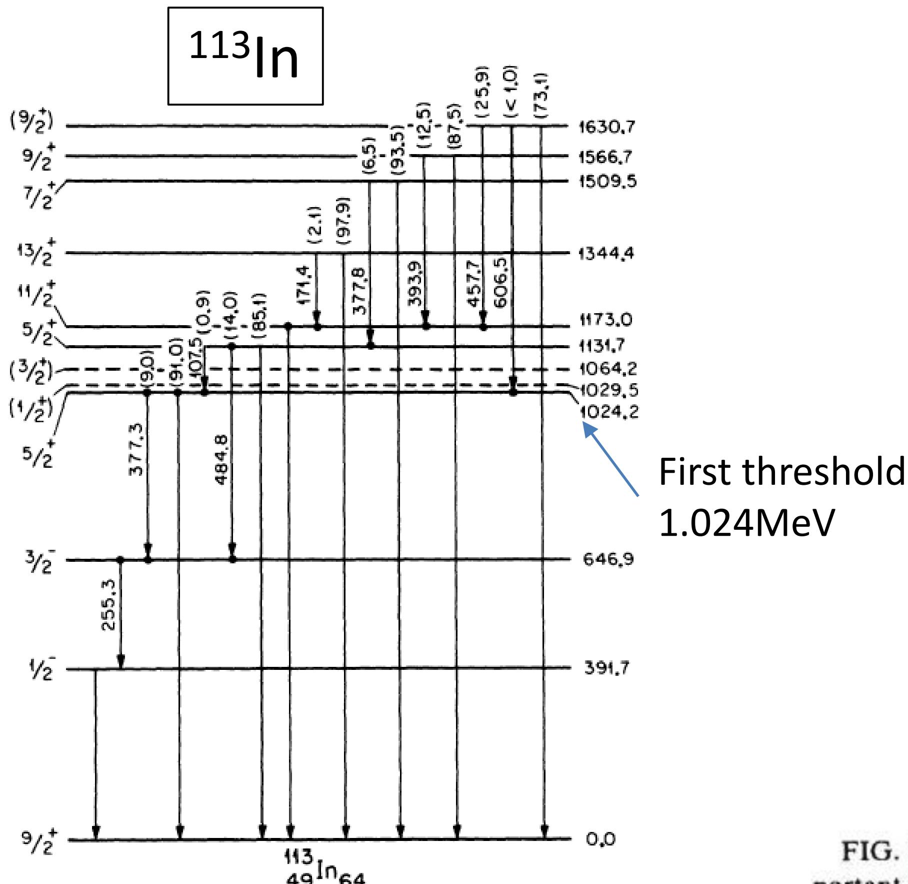


FIG. 2. Level diagram of states observed in the Coulomb excitation of ^{113}In. Branching ratios and coincidences are displayed according to the convention of the Nuclear Data Sheets. Dashed lines indicate low spin positive parity states analogous to those in ^{115}In.

C. B. Collins, et. al. 1988

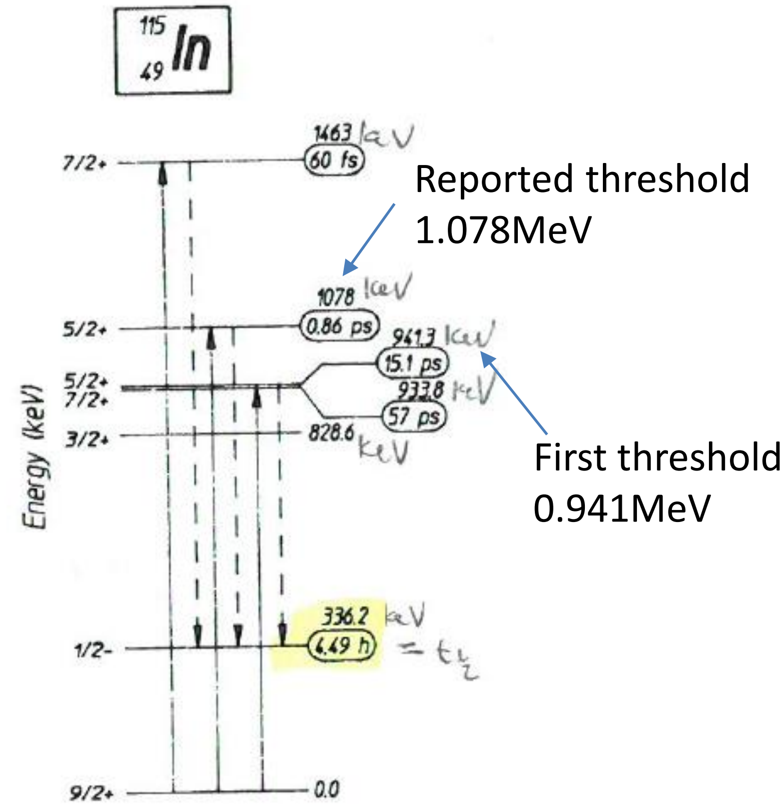


FIG. 1. Energy level diagram of the excited states of ^{115}In important in the production of populations of the isomer (Ref. 14). Half-lives of the states are shown to the right of each and sequences of (γ,γ') reactions leading to the isomer are shown by the arrows. Dashed γ' transitions occur by cascading through levels not shown.

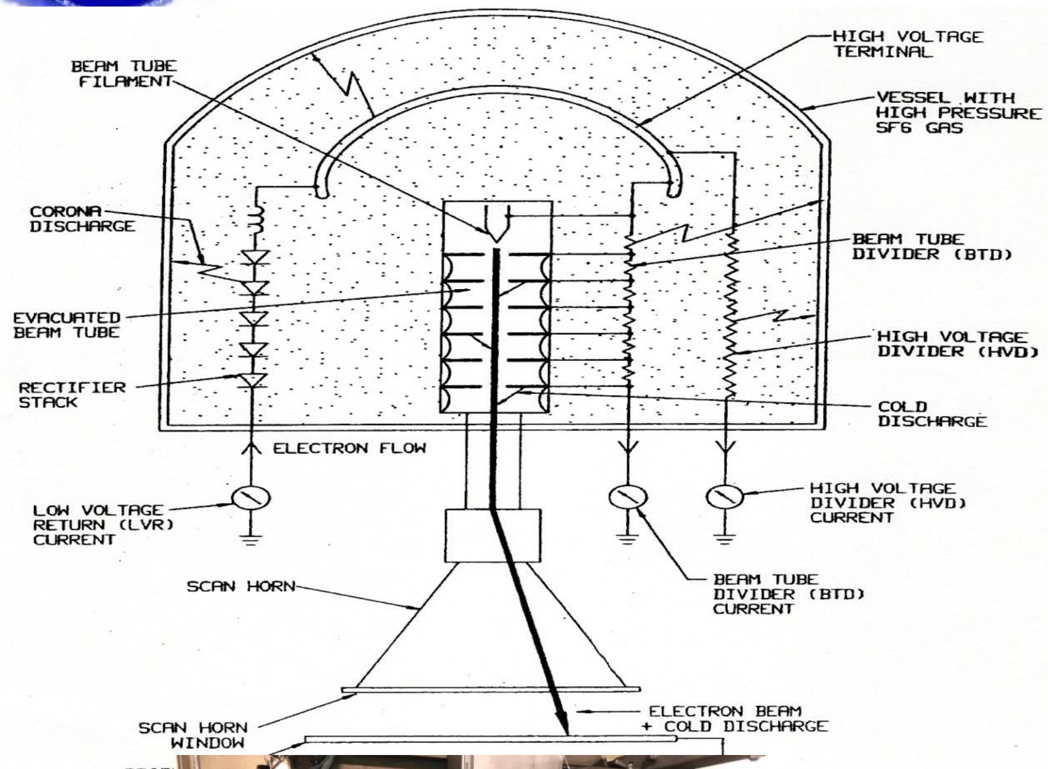
Cd/In Irradiation: Gamma Spin-up Threshold

- Cadmium and indium materials (small sheets and ingots) exposed at IBA Industrial from Sept 2017 to July 2018.
- Gamma Spin-ups of ^{111}Cd, ^{115}In & ^{113}In were observed
- Minimum beam energy thresholds for ^{111m}Cd & ^{115m}In creation were guided by previous research of Collins & Anderson
- After the 2nd wave of tests, it was determined that the minimum thresholds reported by Collins & Anderson (C&A) were underestimated and data from IBA exposures were closer to Brookhaven reported data.
  - ^{111}Cd(γ,γ')^{111m}Cd
    - C&A -> 1.19MeV; IBA -> 1.02MeV; Brookhaven -> 1.02MeV
  - ^{115}In(γ,γ')^{115m}In
    - C&A -> 1.078MeV; IBA -> 0.94MeV; Brookhaven -> 0.941MeV
  - ^{113}In(γ,γ')^{113m}In
    - Tuttle -> 1.024MeV; IBA -> 1.024MeV; Brookhaven -> 1.024MeV

Cd/In Irradiation: Dynamitron Beam Loss

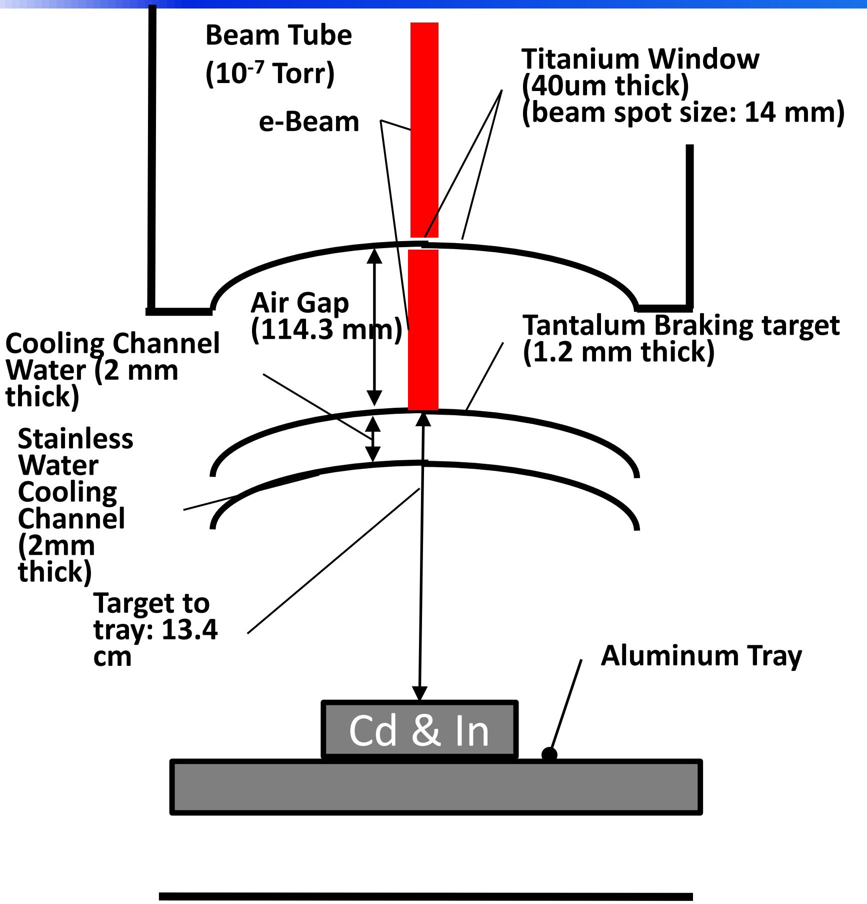
- Beam loss of the IBA tantalum braking target as reported with the SANDIA Monte Carlo TIGER Code.
  - As beam energy decreases, the beam loss increases
    - At 1.16MeV setting, the beam loss is 74.12keV
    - At 1.00MeV setting, the beam loss is 77.77keV
  - Linear fit of experimental data show beam losses of
    - 59.15keV with ^{113m}In (1024keV min threshold)
    - 59.12keV with ^{111m}Cd (1020keV min threshold)
    - 69.58keV with ^{115m}In (941keV min threshold)

Dynamitron Tests: Experimental Setup



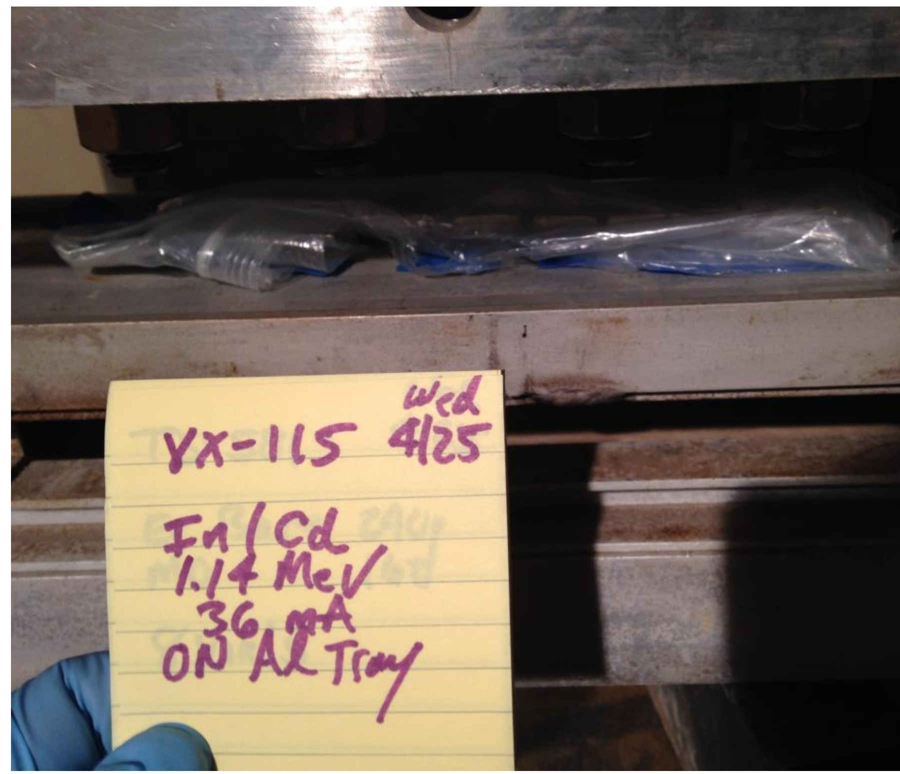
- Dynamitron
  - Electron source current intensity: 0 to 36 mA
  - Beam energy voltage: 0.4 to 3MV
  - Continuous electron beam sweeps the length of the cooling tray
  - Tantalum braking target installed for photon production
- Sample Preparation
  - Indium and cadmium rectangular pieces were lined up and held together in a plastic bag (holder)
  - Holder with samples positioned on the cooling tray to run along the length of the beam sweep
- Sample Exposure
  - Samples exposed to electron beam with braking target for either 15 minutes or 60 minutes

Side view of Dynamitron Electron Beam Path and Braking Target



Cross sectional view of electron beam, titanium window, braking target, cooling channel, and Cd & In sample location.

Cadmium & Indium On Tray



Anderson & Collins: Cd Gamma Spin-Up

- Reports $^{111}Cd(\gamma,\gamma')^{111m}Cd$ reaction at 1.3MeV & 1.4 MeV
  - Data from Figure 2
    - Strong 245keV peak with gamma end-point energy of 1.4MeV
    - Weak 245keV peak with gamma end-point energy of 1.3MeV
    - No data shown for gamma end-point energy of 1.2MeV
  - Coincides with Sept 2017 data from initial NASA/IBA Tests
    - Good activation at 1.4MeV end-point energy but not lower
  - Does not coincide with Apr 2018 data where 245keV gamma peak was present with a 1.12MeV beam setting

J. A. Anderson, et. al. 1988

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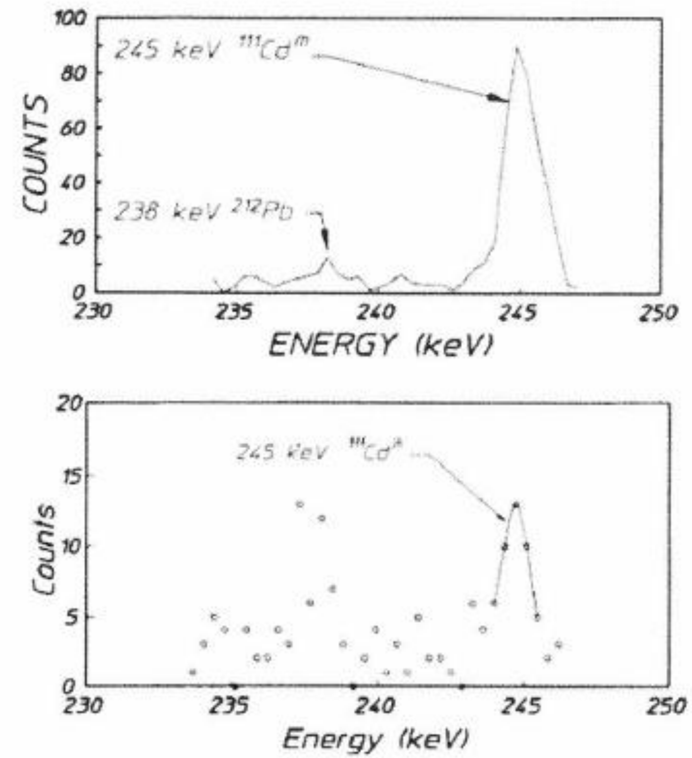
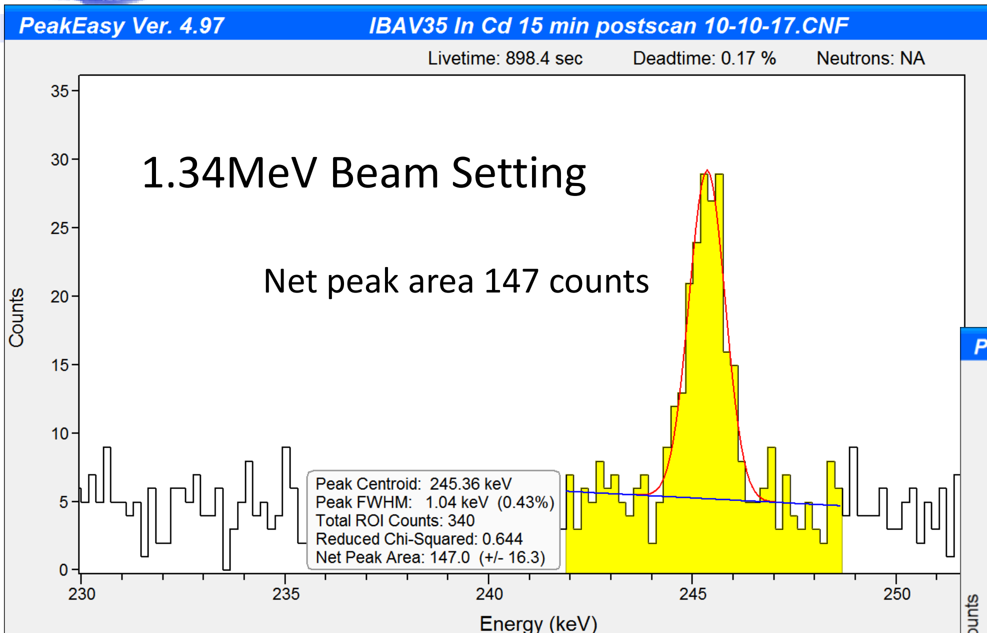
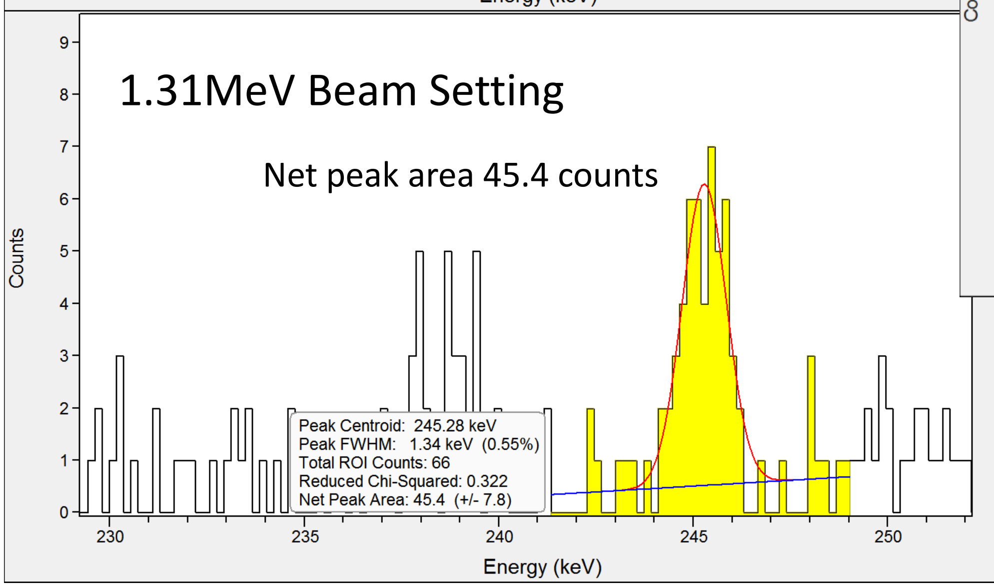
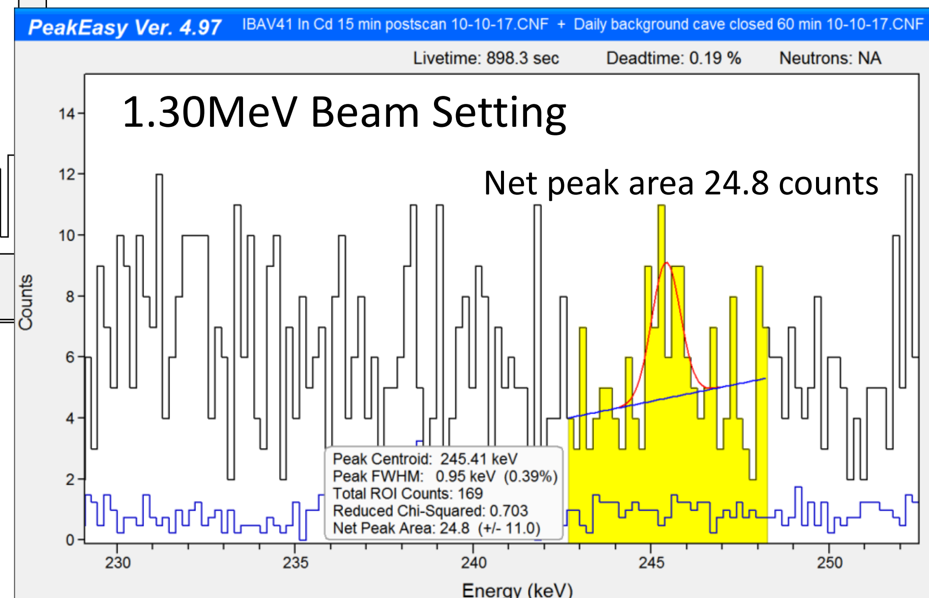


FIG. 2. Spectra showing the 245 keV line from the decay of $^{111}Cd^{m}$. The spectra were obtained from an 8.02 gm, natural Cd foil sample. The small peak near 238 keV is due to the decay of naturally occurring ^{212}Pb in the counting environment. (a) Fluorescence from $^{111}Cd^{m}$ following irradiation with a single bremsstrahlung pulse having an end point energy of 1.4 MeV. Counting time was 3600 sec. (b) Fluorescence following excitation with an end point of 1.3 MeV; counting time was 2700 sec.

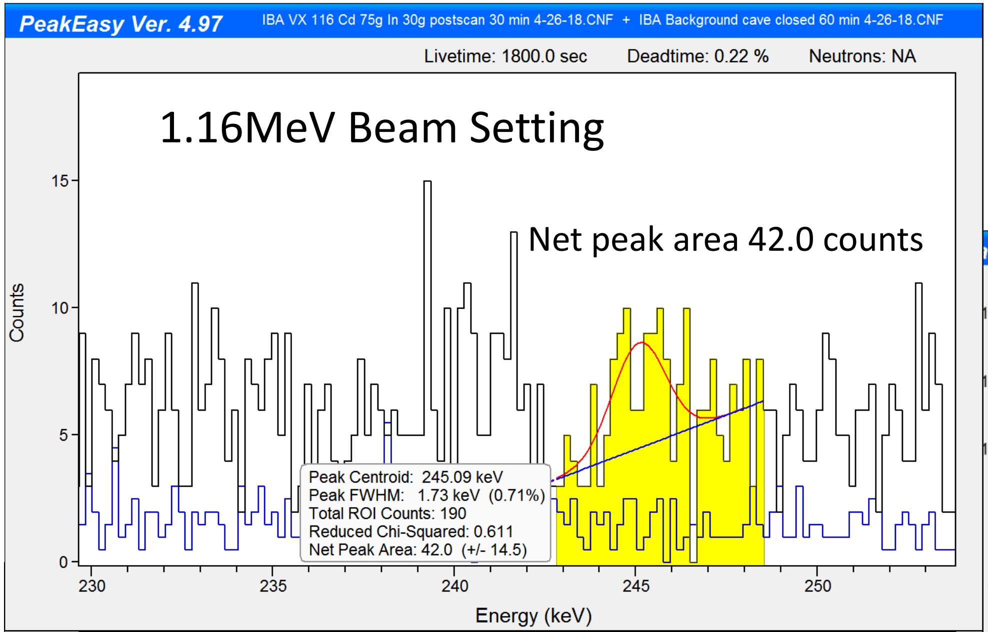
Cd Gamma Spin-up: Gamma Scans Oct 2017

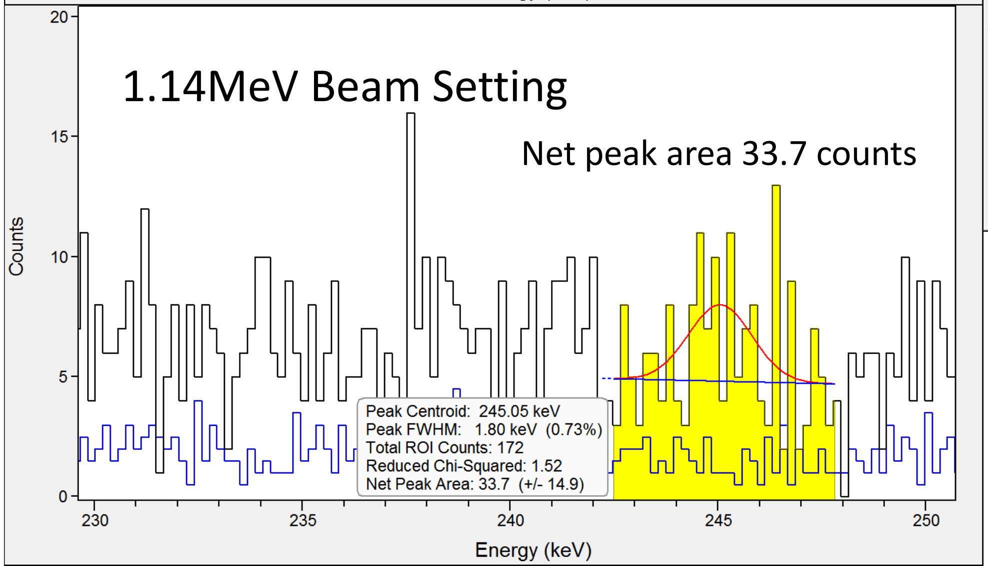


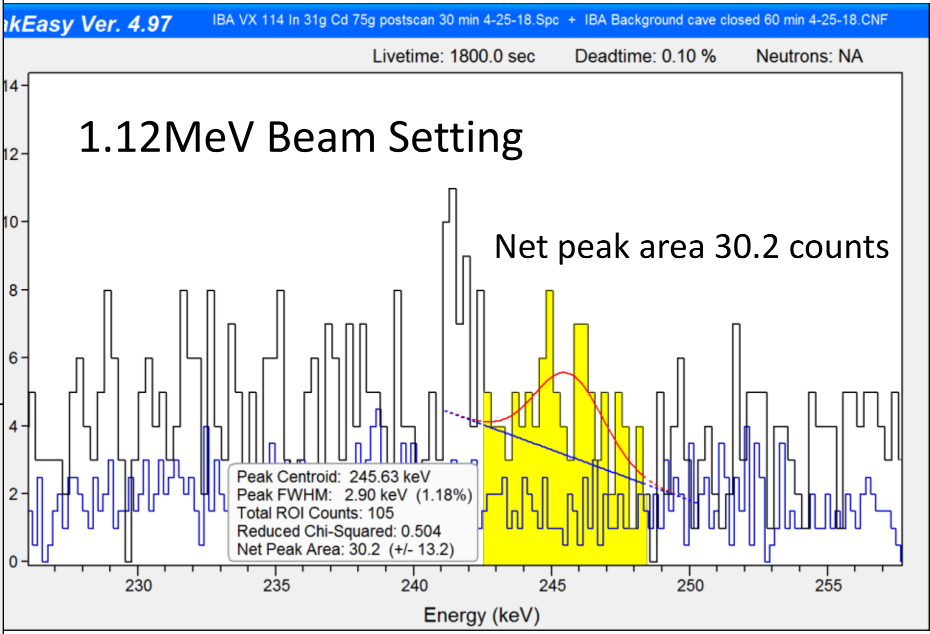




Cd Gamma Spin-up: Gamma Scans Apr 2018







Collins & Anderson: In Gamma Spin-Up

- Report $^{115}In(\gamma,\gamma')^{115m}In$ reaction at 1.078MeV
  - Data from Figure 2
    - Strong 336keV peak with gamma end-point energy of 1.3MeV
  - Almost coincides with Sept 2017 data from initial NASA/IBA Tests
    - Good activation at 1.2MeV end-point energy but not lower
  - Does not coincide with Oct 2017 data where 336keV peak was present with 0.99MeV beam energy

C. B. Collins, et. al. 1988

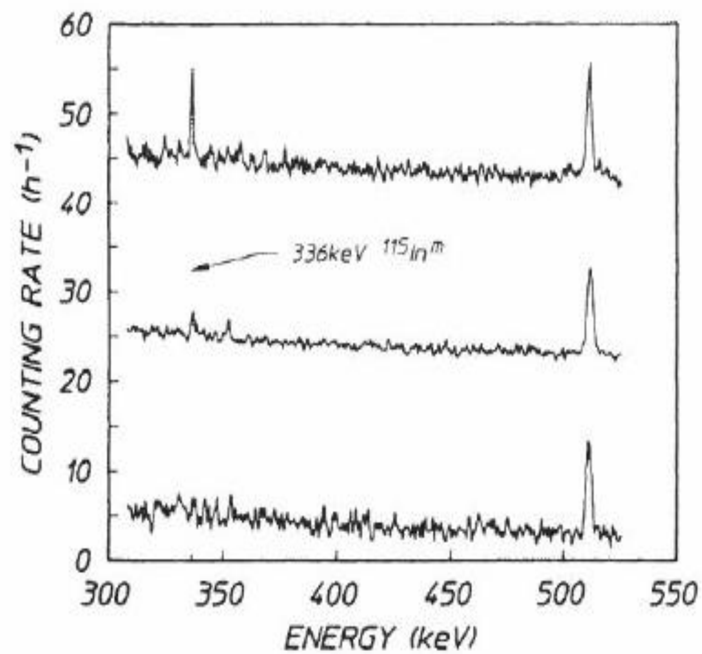
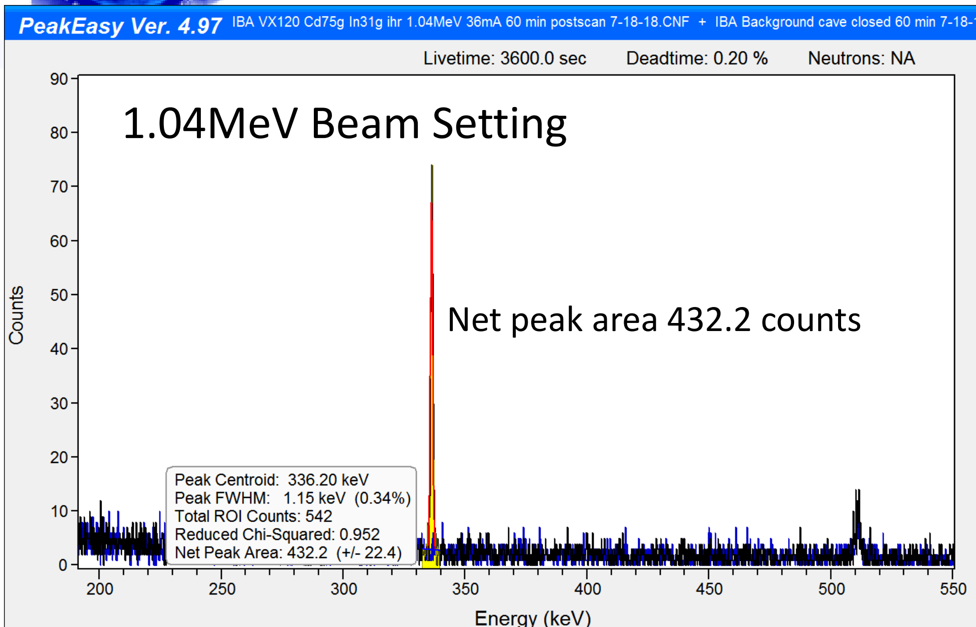
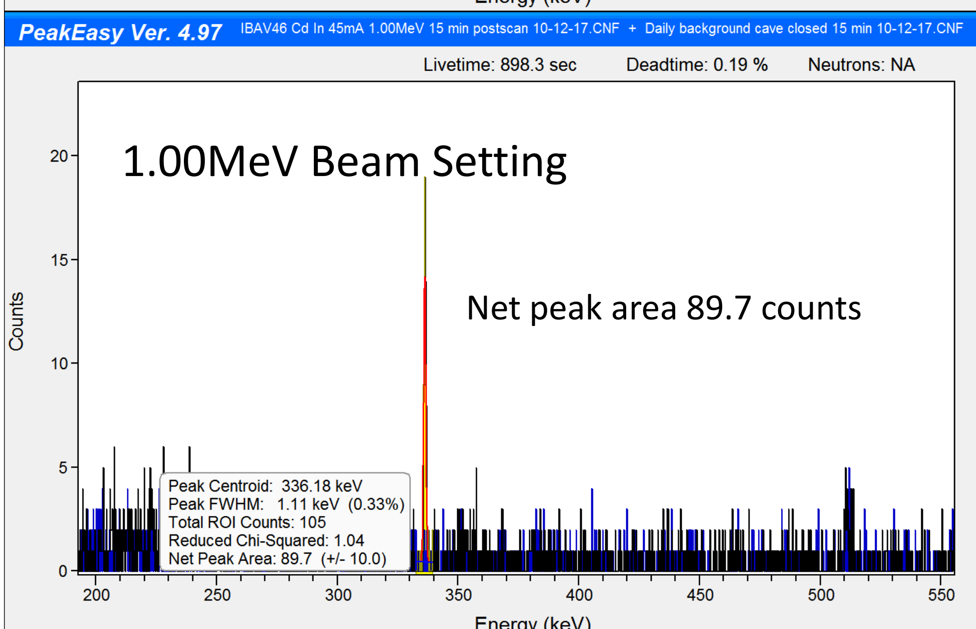
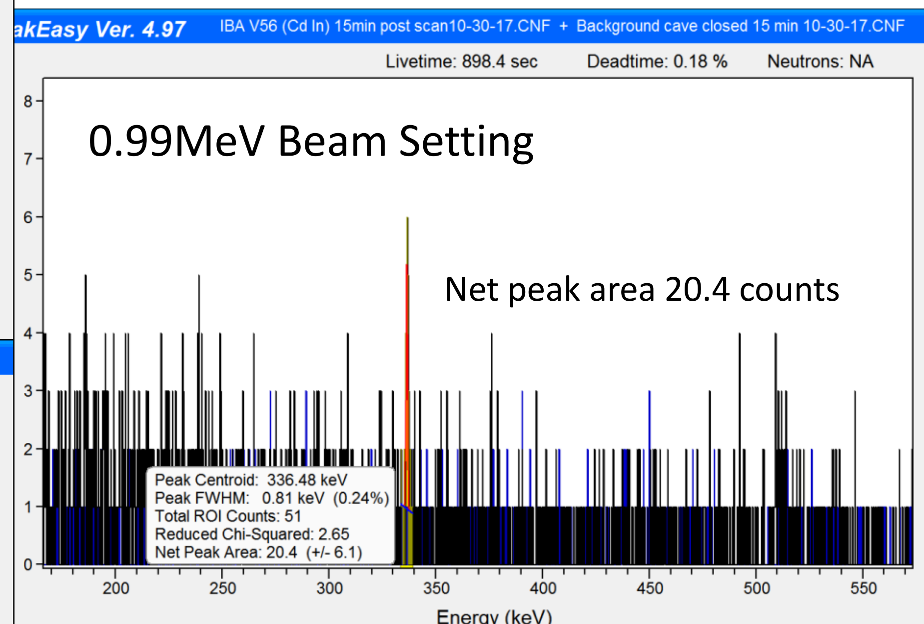


FIG. 2. Three sequential spectra from an intrinsic Ge detector begun at times 6.5, 9.2, and 19.0 h after the irradiation with a flash of bremsstrahlung with an 1.3 MeV end point. Data have been offset by 40, 20, and 0 counts/h, respectively. The 336.2 keV peak is seen to decay with the appropriate half-life of 4.49 h for $^{115}In^{m}$. The other structure is the annihilation peak at 511 keV, present in the background at a constant rate.

In Gamma Spin-up: Gamma Scans



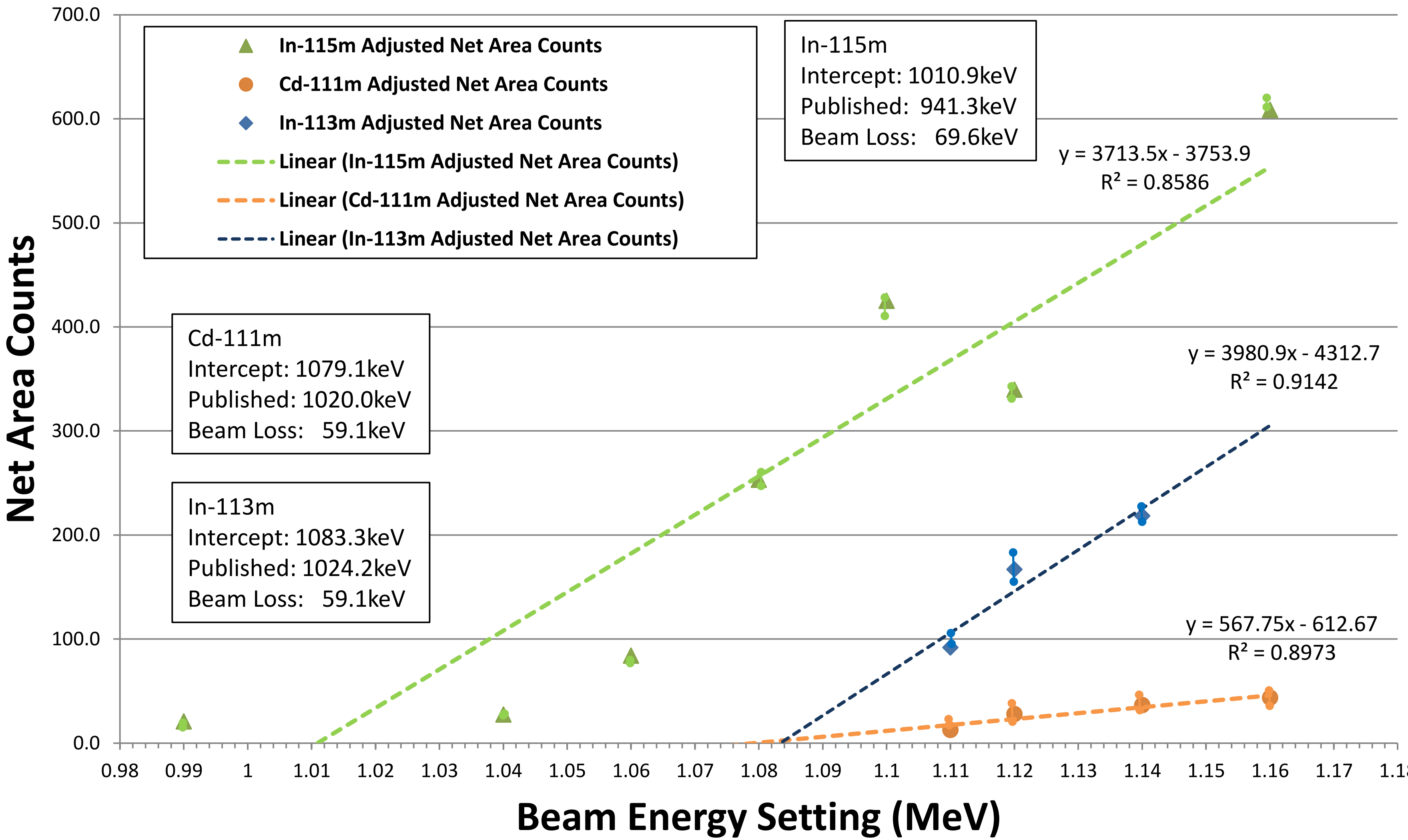




Determining Beam Loss from Data

- Net Area Counts
  - Adjusted to account for different beam currents, exposure times and gamma scan times
  - Adjusted for difference in time between beam off and start of gamma scan time
  - Use known ½ life of isotopes to make adjustment
- Perform Linear Regression of Adjusted Net Area Counts Data
- Determine Beam Loss
  - Subtract known minimum threshold from intercept

Net Area Counts vs. Beam Energy



Note: Uncertainty of Beam Setting = ±42keV

Cd & In Gamma Spin Up Conclusion

- Published threshold data from Anderson & Collins
  - $^{111}Cd(\gamma,\gamma')^{111m}Cd$: with 1.19MeV gammas
  - $^{115}In(\gamma,\gamma')^{115m}In$: with 1.078MeV gammas

- Data verified the beam loss of the IBA tantalum braking target to be between 60-80keV as reported by IBA assuming thresholds of 1.02MeV (^{111m}Cd), 941keV (^{115m}In), and 1.024MeV (^{113m}In).
  - Linear fit shows beam loss of 59keV with ^{111m}Cd & ^{113m}In data and 69keV with ^{115m}In data.
  - Follows trend that as beam energy decreases, the beam loss increases.

- **NASA/IBA Data shows activation with Ta braking target and determined thresholds after taking into consideration the ~60-70keV beam loss:**
  - **$^{113}In(\gamma,\gamma')^{113m}In$: with ~1.024MeV gammas**
  - **$^{111}Cd(\gamma,\gamma')^{111m}Cd$: with ~1.020MeV gammas**
  - **$^{115}In(\gamma,\gamma')^{115m}In$: with ~0.941MeV gammas**

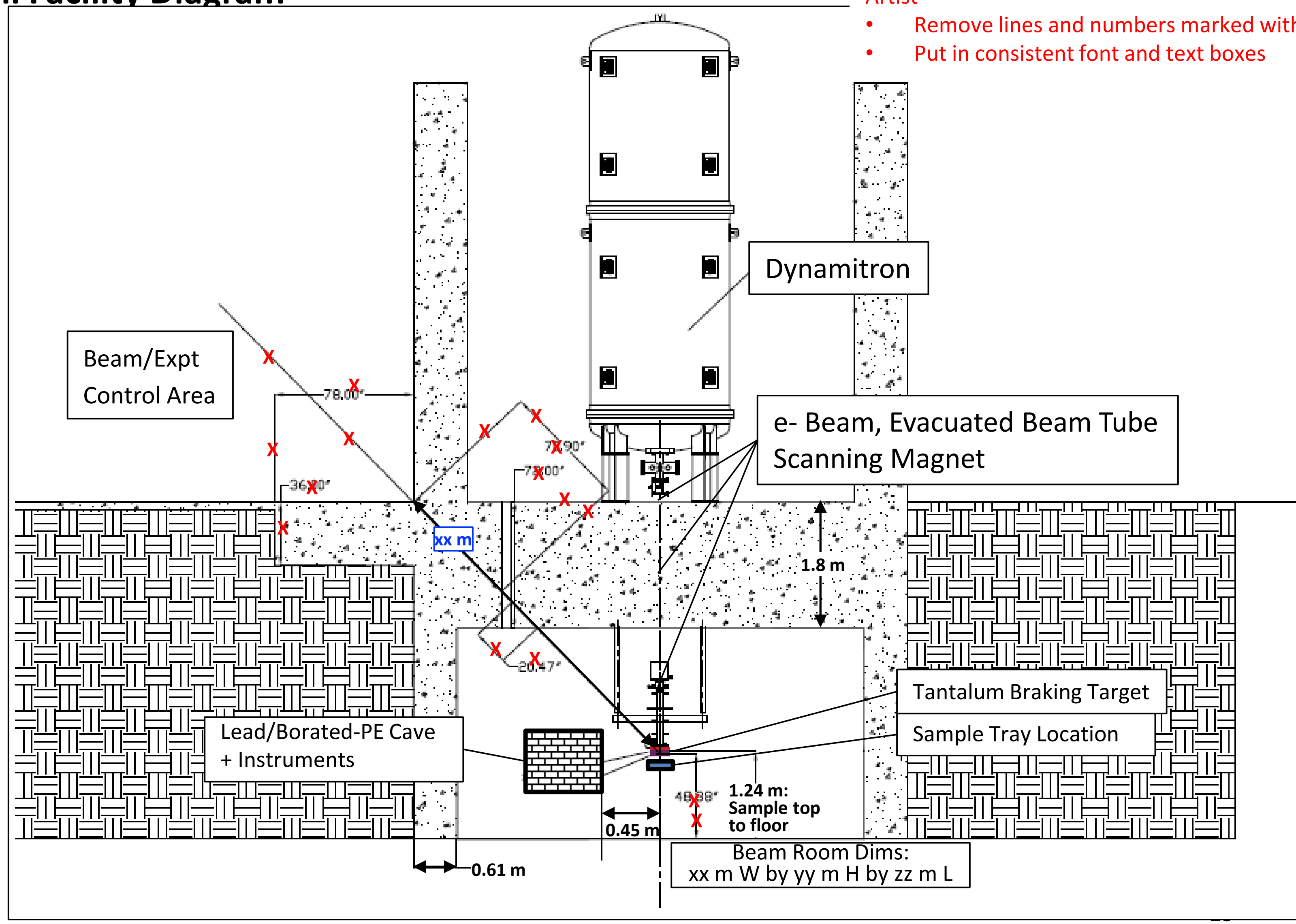
THANK YOU!
GRAZIE!

APPENDIX

Overall schematic of beam, samples, cave and instruments

a: Overall Facility Diagram

Artist
- Remove lines and numbers marked with X
- Put in consistent font and text boxes



Linear Fit of ^{111m}Cd: Counts vs. Beam Energy

J. A. Anderson, et. al. 1988

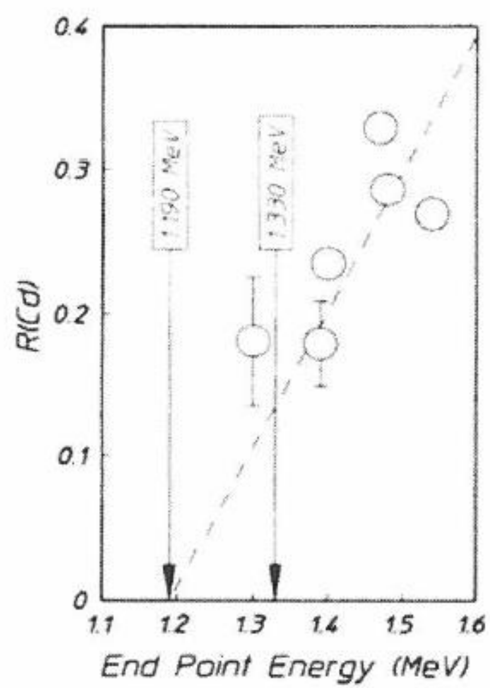
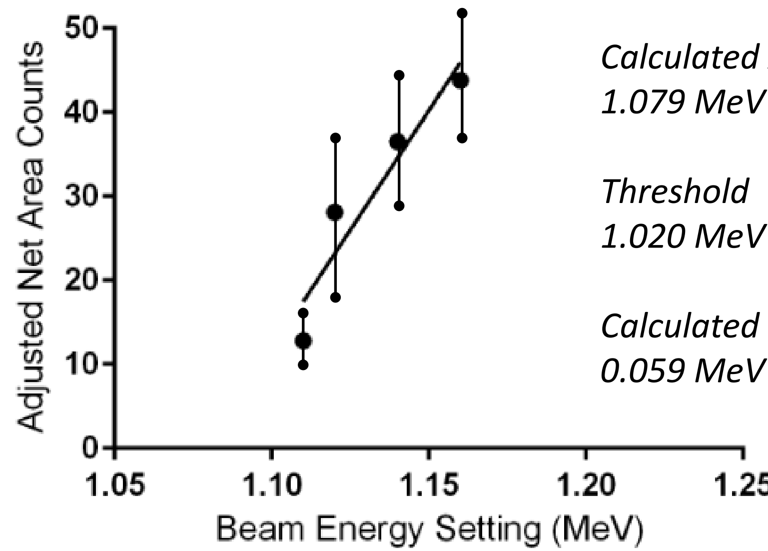


FIG. 4. Ratios of isomeric fractions produced in $^{111}Cd^m$ to those in $^{79}Br^m$, as corrected for the finite duration of the counting interval and plotted as a function of the end-point energy of the bremsstrahlung. Error bars show the counting statistical uncertainty. The dashed line shows a linear fit to the data intercepting the x axis at a gateway energy of 1.19 MeV. Excitation energy of the next higher gateway is shown at 1.33 MeV. In this figure and in Fig. 5, the error bars for the two least precise points have been shown. The statistical errors for the other points are commensurate with the plotting symbols in the figures.



Calculated X-intercept
1.079 MeV

Threshold
1.020 MeV

Calculated Beam Loss
0.059 MeV

Best-fit values	
Slope	568.8 ± 136.0
Y-intercept	-613.9 ± 154.0
X-intercept	1.079
1/Slope	0.001758
95% Confidence Intervals	
Slope	-16.30 to 1154
Y-intercept	-1277 to 48.85
X-intercept	-infinity to 1.110
Goodness of Fit	
R square	0.8974
Sy.x	5.222
Is slope significantly non-zero?	
F	17.50
DFn,DFd	1,2
P Value	0.0527
Deviation from horizontal?	Not Significant
Data	
Number of XY pairs	4
Equation	Y = 568.8*X - 613.9

https://www.graphpad.com/quickcalcs/linear1/

Linear Fit of ^{115m}In: Counts vs. Beam Energy

C. B. Collins, et. al. 1988

38 ACTIVATION OF ^{115}In^{m} BY SING

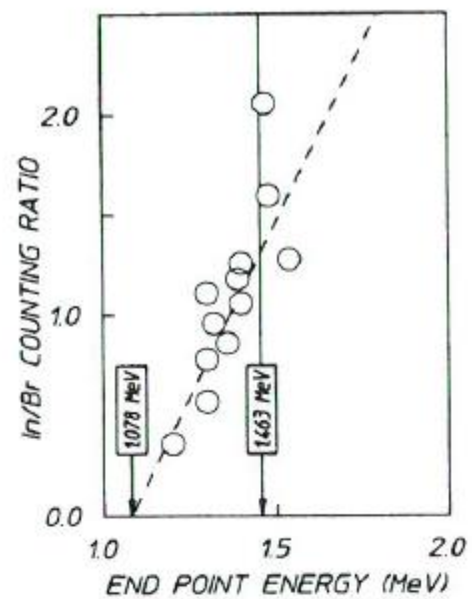
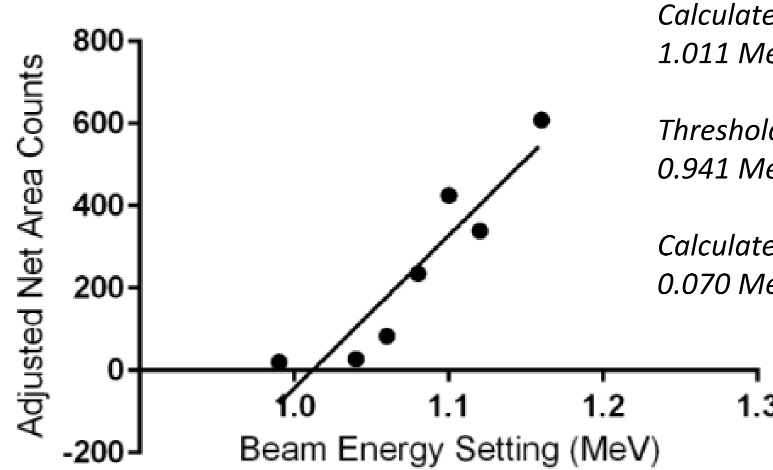


FIG. 4. Ratios of fluorescent photons from ^{115}In^{m} to those from ^{79}Br^{m}, produced by single discharges from PITHON, as corrected for the finite duration of the counting interval and plotted as a function of the end-point energies of the electrons producing the bremsstrahlung. The dashed line shows a linear fit to the data intercepting the x axis at a single gateway energy of 1.078 MeV. The excitation energy of the next higher gateway is also shown at 1.463 MeV. Statistical uncertainities are smaller than the data points.



Calculated X-intercept
1.011 MeV

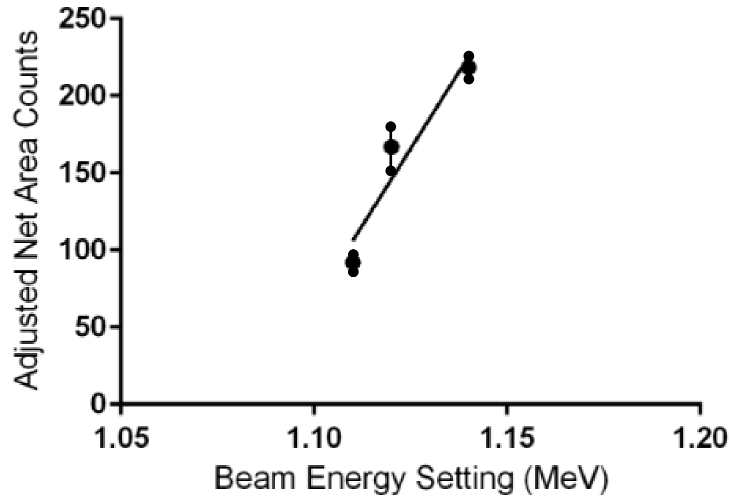
Threshold
0.941 MeV

Calculated Beam Loss
0.070 MeV

Best-fit values	
Slope	3712 ± 677.3
Y-intercept	-3755 ± 731.3
X-intercept	1.012
1/Slope	0.0002694
95% Confidence Intervals	
Slope	1971 to 5453
Y-intercept	-5635 to -1875
X-intercept	0.9440 to 1.041
Goodness of Fit	
R square	0.8573
Sy.x	92.08
Is slope significantly non-zero?	
F	30.04
DFn,DFd	1,5
P Value	0.0028
Deviation from horizontal?	Significant
Data	
Number of XY pairs	7
Equation	Y = 3712*X - 3755

https://www.graphpad.com/quickcalcs/linear1/

Linear Fit of ^{113m}In: Counts vs. Beam Energy



Best-fit values	
Slope	3979 ± 1220
Y-intercept	-4310 ± 1370
X-intercept	1.083
1/Slope	0.0002513
95% Confidence Intervals	
Slope	-11521 to 19478
Y-intercept	-21722 to 13102
X-intercept	-infinity to +infinity
Goodness of Fit	
R square	0.9141
Sy.x	26.35
Is slope significantly non-zero?	
F	10.64
DFn,DFd	1,1
P Value	0.1894
Deviation from horizontal?	Not Significant
Data	
Number of XY pairs	3
Equation	Y = 3979*X - 4310

Calculated X-intercept
1.083 MeV

Threshold
1.024 MeV

Calculated Beam Loss
0.059 MeV

https://www.graphpad.com/quickcalcs/linear1/