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Radioactive decay simulations for testing of the timing detectors in the Nab experiment

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OAK RIDGE National Laboratory

Outline

- **Introduction**
- **Spallation Neutron Source (SNS)**
- **How the Nab Experiment Works**
- **Simulation of the Experiment**
- **Results**
- **Future Plans**

Introduction: Overall

The Nab experiment aims to yield a measurement of the electron-neutrino correlation parameter, a, and the Fierz interference term, b, in neutron beta decay.

These parameters are located in the energy and angular distribution of the particles produced through neutron beta decay.

Using silicon detectors, a direct measurement of the phase space distribution of the resultant electron energy and proton momentum can be obtained.

Introduction: The Detectors

The silicon detectors of the Nab experiment will be tested using well-known radioactive isotopes. Simulations of systematic testing use the associated energy levels, decay probabilities, and decay options of radioactive sources such as Ce-139, Ba-133, and Sn-113 to determine the expected results of experimental testing.

Monte Carlo simulations of the radioactive decay of Ce-139, Ba-133, and Sn-113 help determine the ability these isotopes have to be useful to the Nab experiment as a whole.

Spallation Neutron Source at ORNL

https://upload.wikimedia.org/wikipedia/commons/thumb/b/b7/Sns-facility-design.jpg/350px-Sns-facility-design.jpg

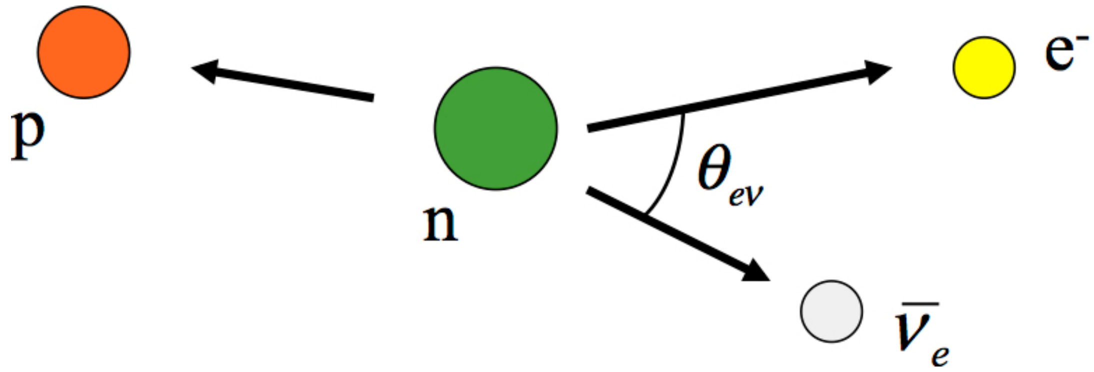
- World's most intense neutron source.
- An accelerator-based system produces neutrons through a process known as spallation, in which short proton pulses travel to a steel target filled with liquid mercury.
- The neutrons then scatter out to the various beamlines.

About the Experiment

- The Nab experiment takes precise measurements of the neutron beta decay reaction.
- Neutrons reach the Fundamental Neutron Physics beamline (BL-13) and decay inside the Nab experiment.
- A magnetic field attracts the electrons down and the protons up toward silicon detectors.
- The detectors are used to measure the time difference between the particles and will yield a measurement of the **a** and **b** parameters in the energy and the angular distribution of the produced particles.
- Overall, this will give a better understanding of the weak nuclear force.

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \xi$$

$$\times\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$



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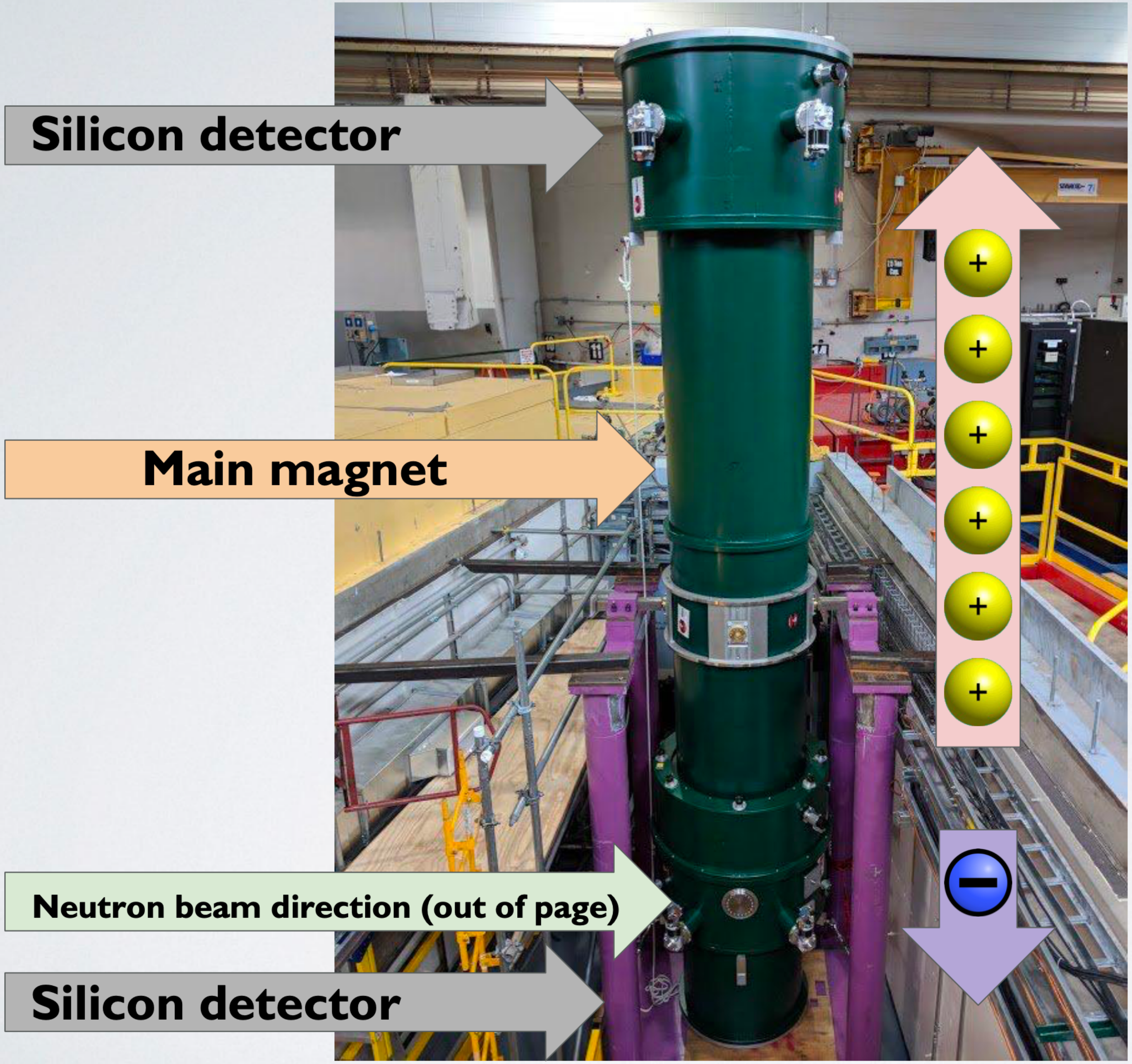
Silicon detector
Main magnet
Neutron beam direction (out of page)
Silicon detector
+
+
+
+
+
+

The Nab collaboration

Active and recent collaborators:

R. Alarcon[a], S.Baeßler[b,c] (Project Manager), S. Balascuta[a], L. Barrón Palos[n], T.L. Bailey[m], K. Bass[i], N. Birge[i], A. Blose[f], D. Borissenko[b], J.D. Bowman[c] (Co-Spokesperson), L. Broussard[c], A.T. Bryant[b], J. Byrne[d], J.R. Calarco[c,i], J. Caylor[i], K. Chang[b], T. Chupp[o], T.V. Cianciolo[c], C. Crawford[f], X. Ding[b], M. Doyle[b], W. Fan[b], W. Farrar[b], N. Fomin[i], E. Frlež[b], J. Fry[b], M.T. Gericke[g], M. Gervais[f], F. Glück[h], G.L. Greene[c,i], R.K. Grzywacz[i], V. Gudkov[j], J. Hamblen[e], C. Hayes[m], C. Hendrus[o], T. Ito[k], A. Jezghani[f], H. Li[b], M. Makela[k], N. Macsai[g], J. Mammei[g], R. Mammei[l], M. Martinez[a], D.G. Matthews[f], M. McCrea[f], P. McGaughey[k], C.D. McLaughlin[b], P. Mueller[c], D. van Petten[b], S.I. Penttilä[c] (On-site Manager), D.E. Perryman[i], R. Picker[p], J. Pierce[c], D. Počanić[b] (Co-Spokesperson), Yu Qian[b], G. Randall[a], G. Riley[i], K.P. Rykaczewski[c], A. Salas-Bacci[b], S. Samiei[b], E.M. Scott[i], T. Shelton[f], S.K. Sjue[k], A. Smith[b], E. Smith[k], E. Stevens[b], J.W. Wexler[m], R. Whitehead[i], W.S. Wilburn[k], A.R. Young[m], B.Zeck[m]

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U.S. DEPARTMENT OF ENERGY

Office of Science

OAK RIDGE National Laboratory

UNIVERSITY of VIRGINIA

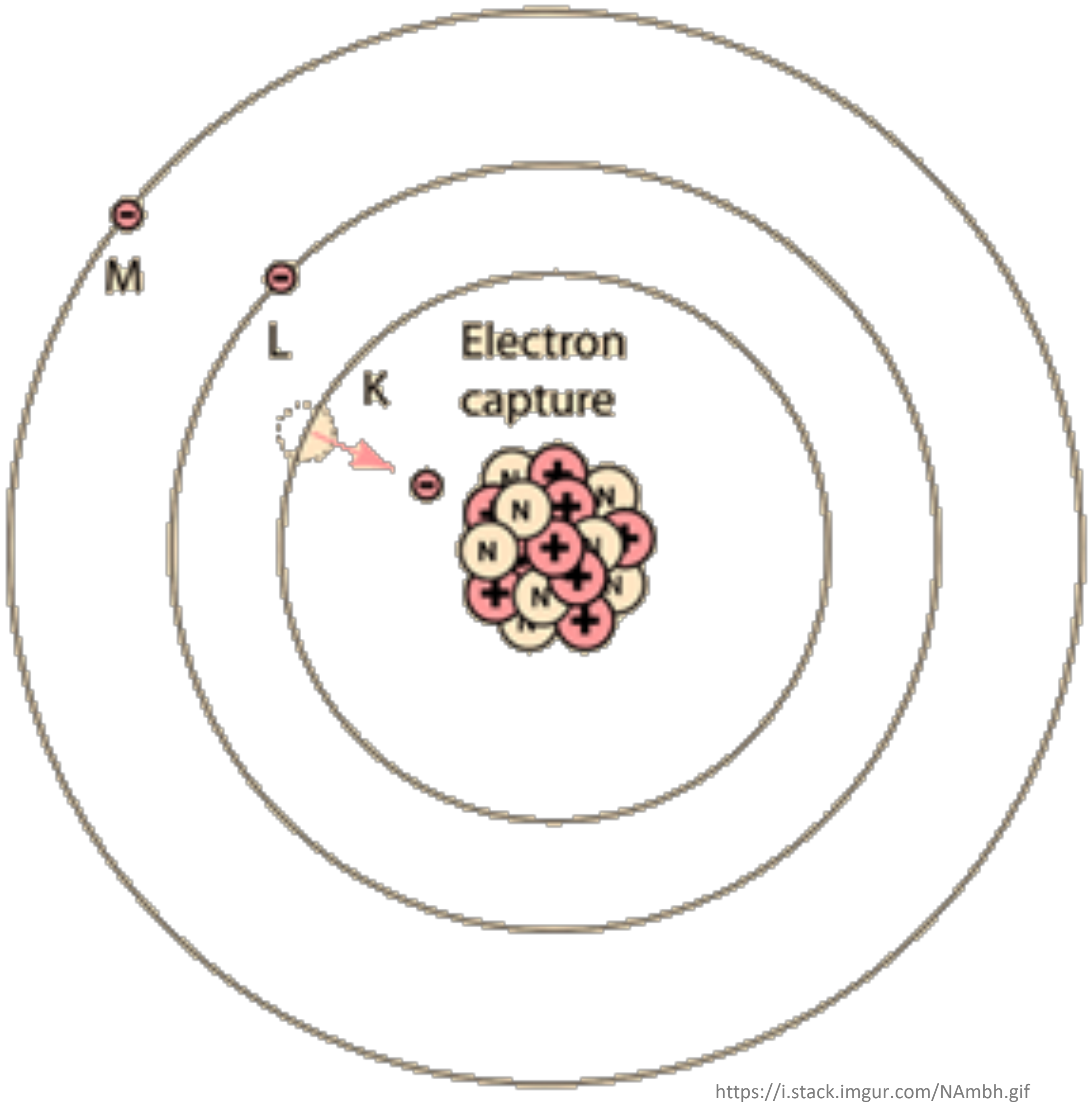
Simulation of Neutron Decay

- I have helped develop a simulation to test the performance of the silicon detectors that will be used to measure the proton and the electron produced in beta decay.
- C++ code is used to simulate the radioactive isotope decay and the time difference between the resulting particles.
- The radioactive sources studied were all chosen based on the 100% electron capture decay mode.

https://about.gitlab.com/images/press/logo/png/gitlab-logo-gray-stacked-rgb.png

Electron Capture

- During electron capture, an electron in an atom's inner shell is drawn into the nucleus. It combines with a proton and forms a neutron and a neutrino.
- Since an atom loses a proton during electron capture, it changes from one element to another.
- This mode produces abundant electrons and photons in each decay, and the timing between the produced particles can then be studied in detail in our simulation.
- Our code uses well-known isotopes and their associated energy levels, decay probabilities, and decay options. This information is from the National Nuclear Data Center.



https://i.stack.imgur.com/NAmbh.gif

Running the Experiment

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- A small job is submitted to UTC's SimCenter that specifies the radioactive source to study and the total number of decays.
- The SimCenter facility used high-performance computers to run simulations.
  - It consists of 921 CPU cores.
- One large-scale simulation can be broken into several jobs.
- The jobs go to different computers, reducing the total amount of time it takes to run an entire simulation.
- For example, a simulation of 100,000,000 total decays can be broken into 10,000 jobs that each simulate 10,000 decays. The total simulation takes about twenty hours to complete.
- To put this into perspective, a job of one million decays takes about twenty-seven hours to complete on a laptop. At the SimCenter, it takes about twenty minutes.

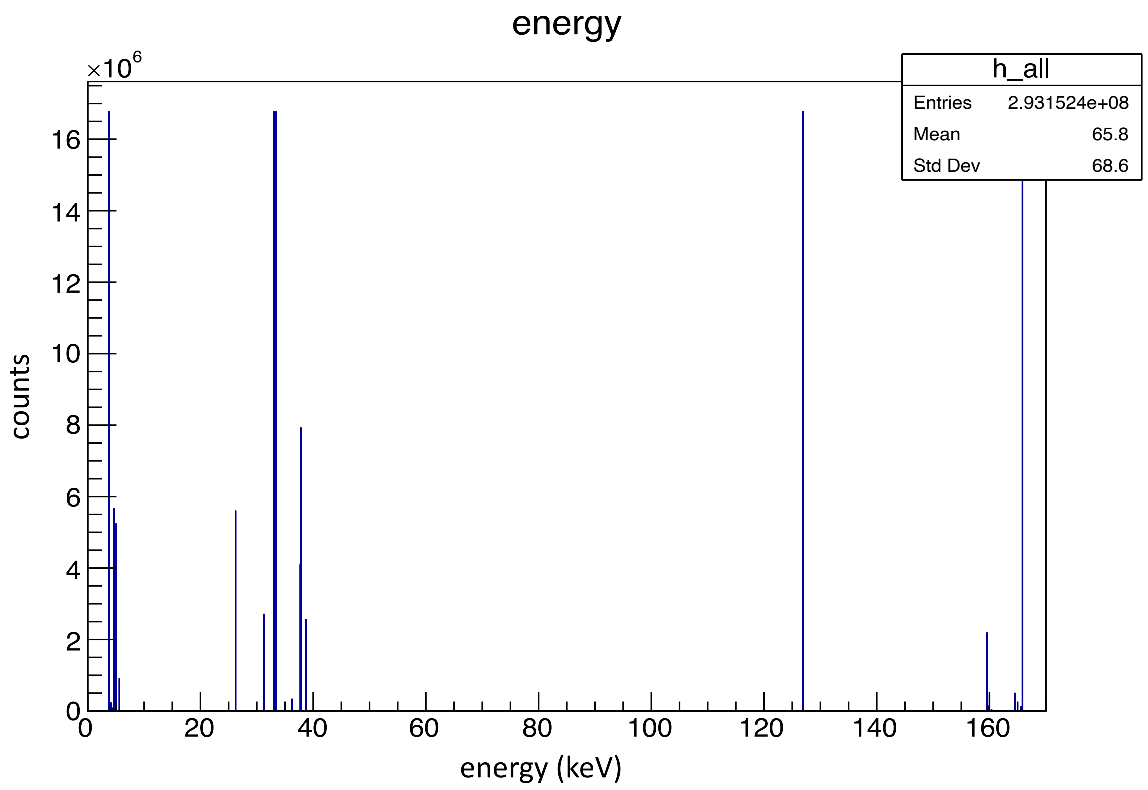
https://d35c7d8c.web.cern.ch/sites/d35c7d8c.web.cern.ch/files/website-banner-allnew-croped_3.png

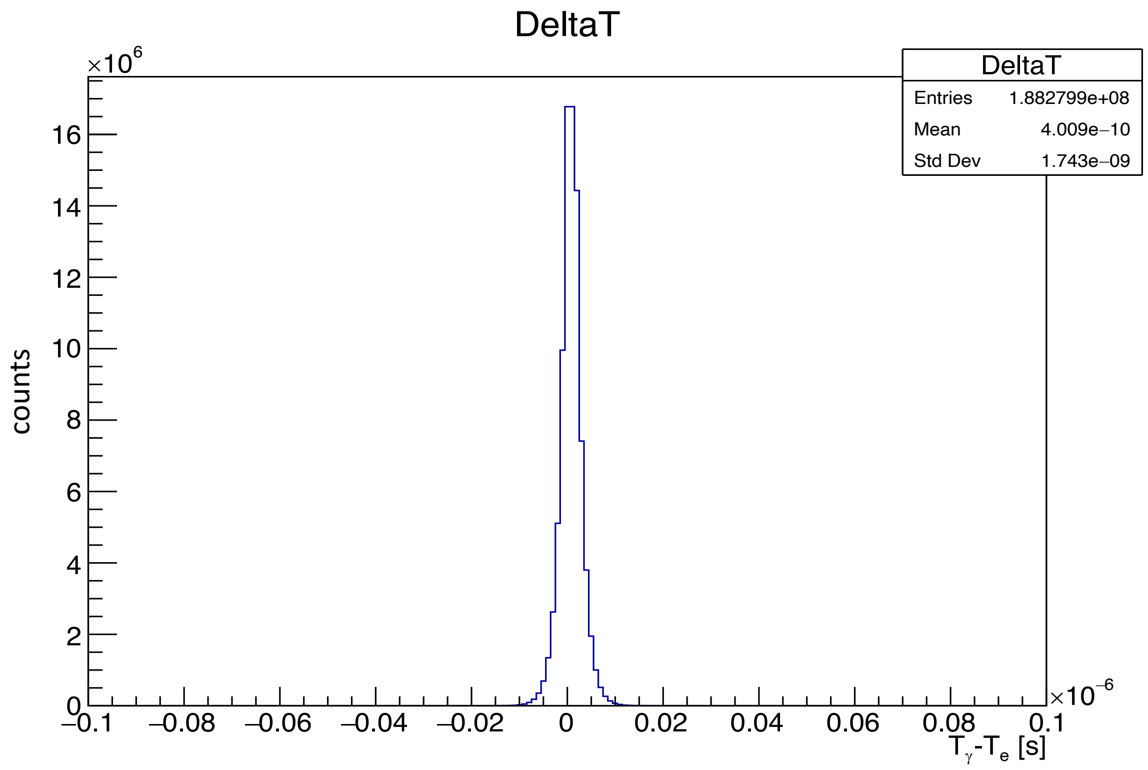
Analyzing the Data

- ROOT is software developed at CERN used to analyze and visualize the data.
- ROOT is the industry standard for all nuclear/particle physics research.
- The software reads the data file and plots the results.

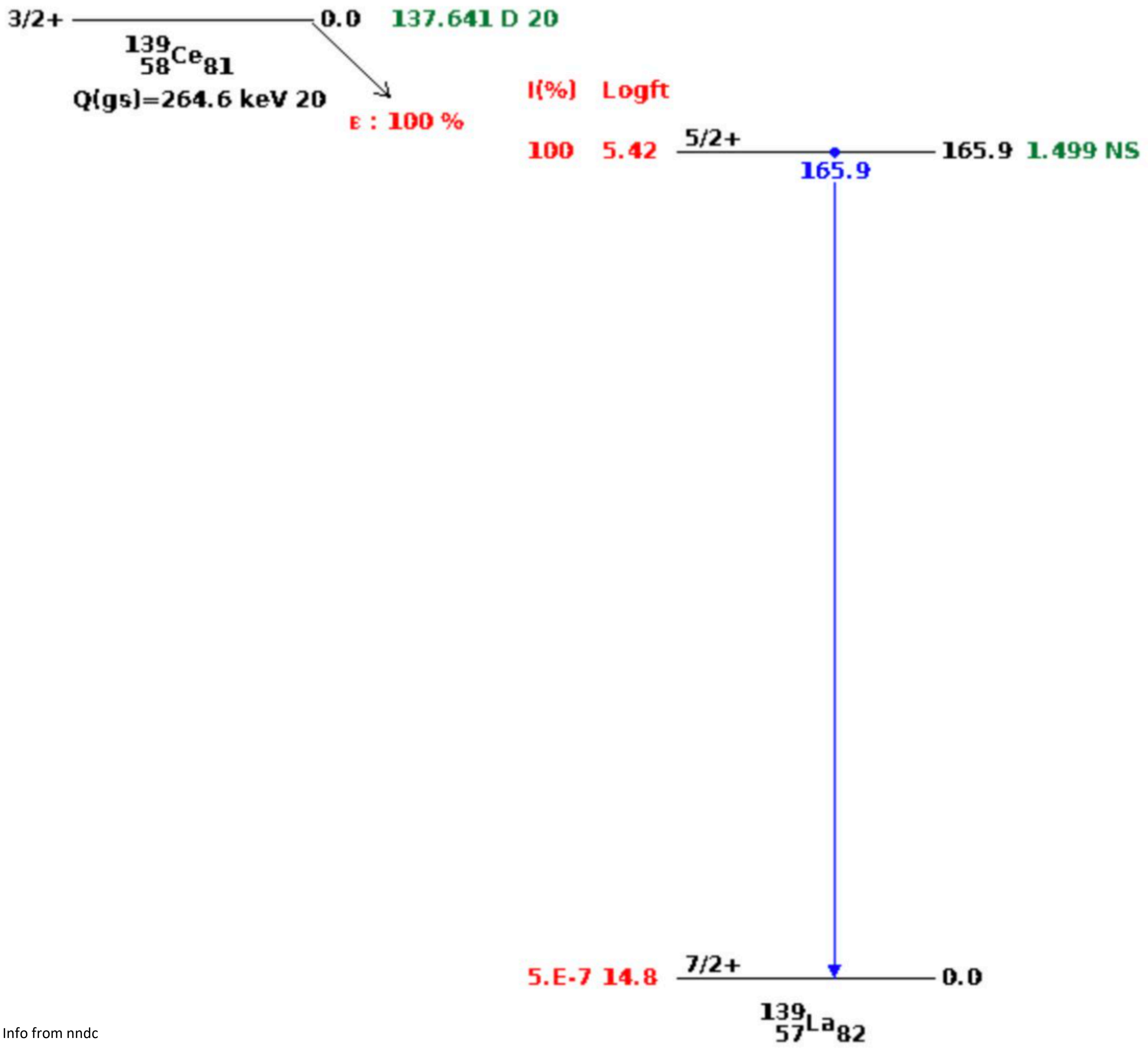
Simulation of Ce-139 Decay

- A test of 10,000 jobs of 10,000 decays was submitted to the SimCenter.
- This simulation took about twenty hours to complete.



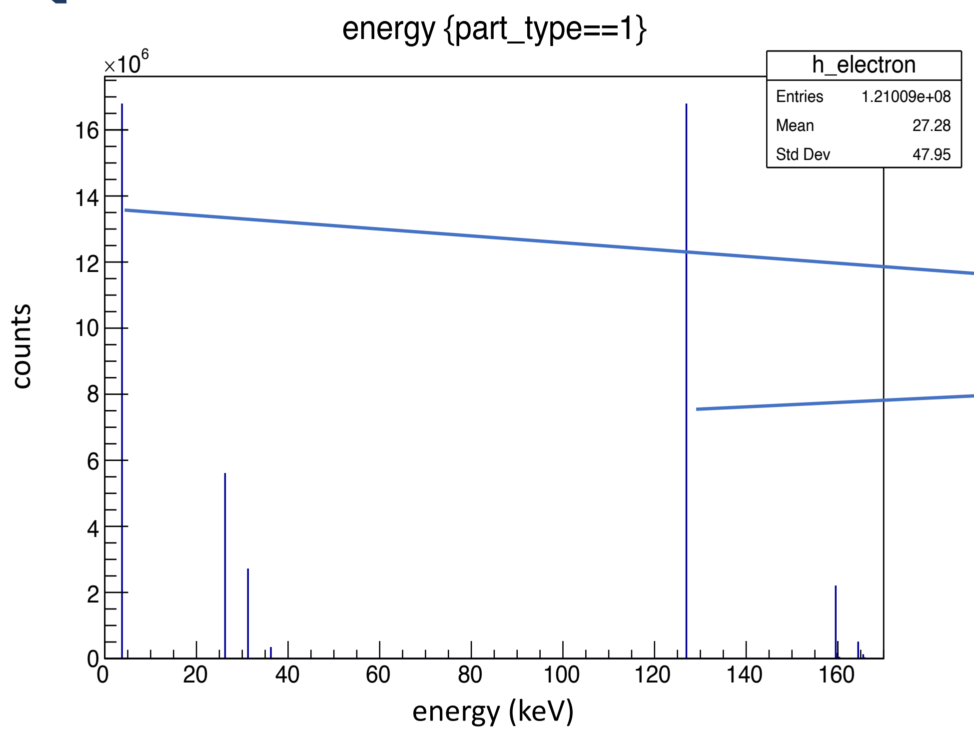


Ce-139 Decay Scheme



Info from nndc

Ce-139: Produced Electrons

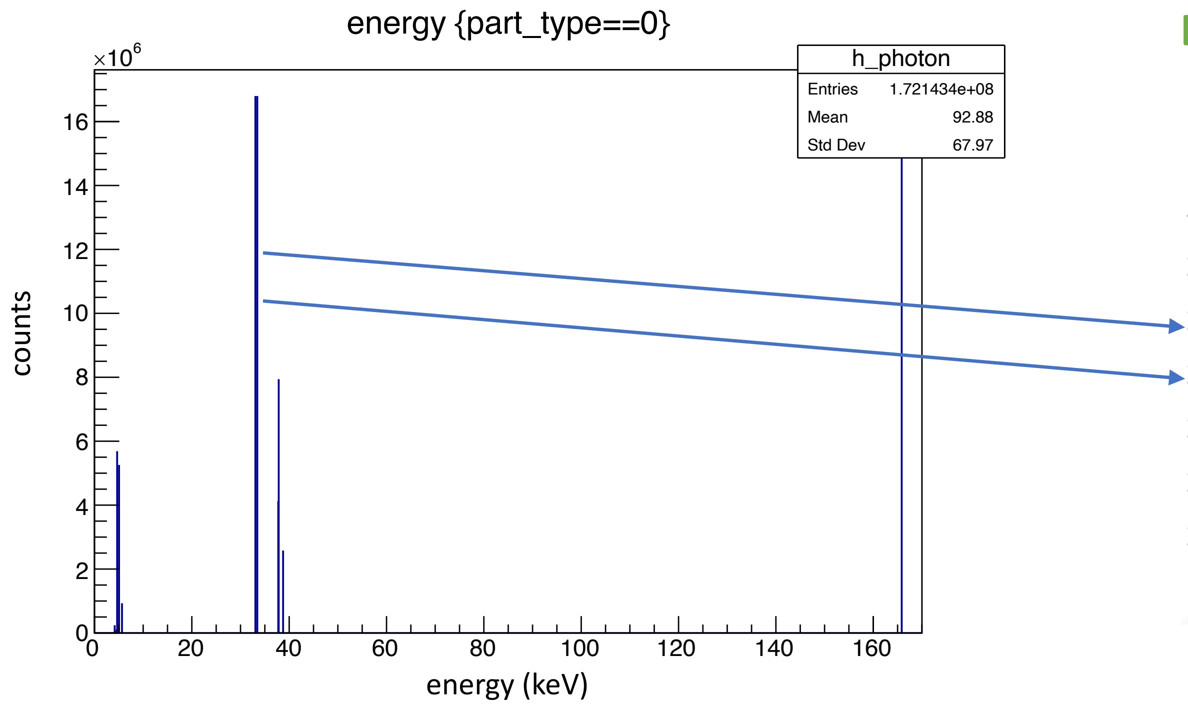


Energy spectrum matches reference data

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
Auger L	3.8	90.7 % *8*	0.00345 *3*
Auger K	27.4	8.4 % *4*	0.00229 *10*
CE K	126.9329 *12*	17.69 % *21*	0.0225 *3*
CE L	159.5912 *12*	2.38 % *4*	0.00380 *6*
CE M	164.4962 *11*	0.494 % *7*	8.13E-4 *12*
CE N	165.5871 *14*	0.1085 % *16*	1.80E-4 *3*
CE O	165.8371 *11*	0.0177 % *3*	2.94E-5 *5*

Info from nndc

Ce-139: Produced Photons



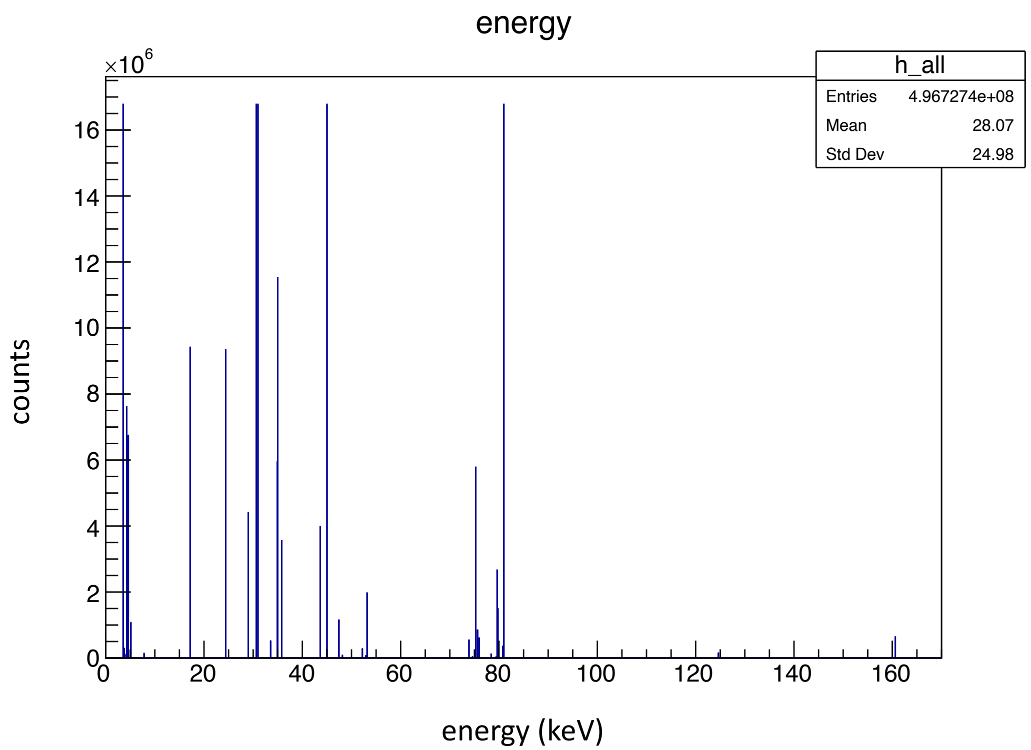
Energy spectrum matches reference data

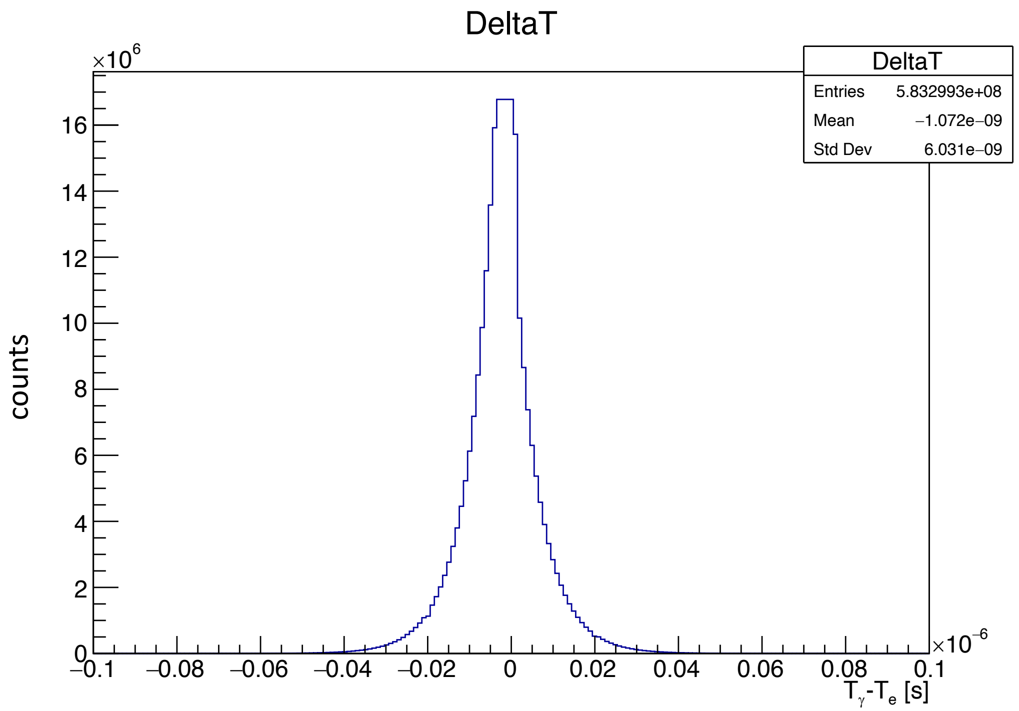
	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
XR l	4.65	12.0 % *5*	5.59E-4 *24*
XR kα2	33.034	22.6 % *6*	0.00748 *18*
XR kα1	33.442	41.2 % *10*	0.0138 *3*
XR kβ3	37.72	3.97 % *9*	0.00150 *3*
XR kβ1	37.801	7.66 % *18*	0.00290 *7*
XR kβ2	38.726	2.48 % *6*	9.59E-4 *22*
	165.8575 *11*	80 % *8*	0.133 *13*

Info from nndc

Simulation of Ba-133 Decay

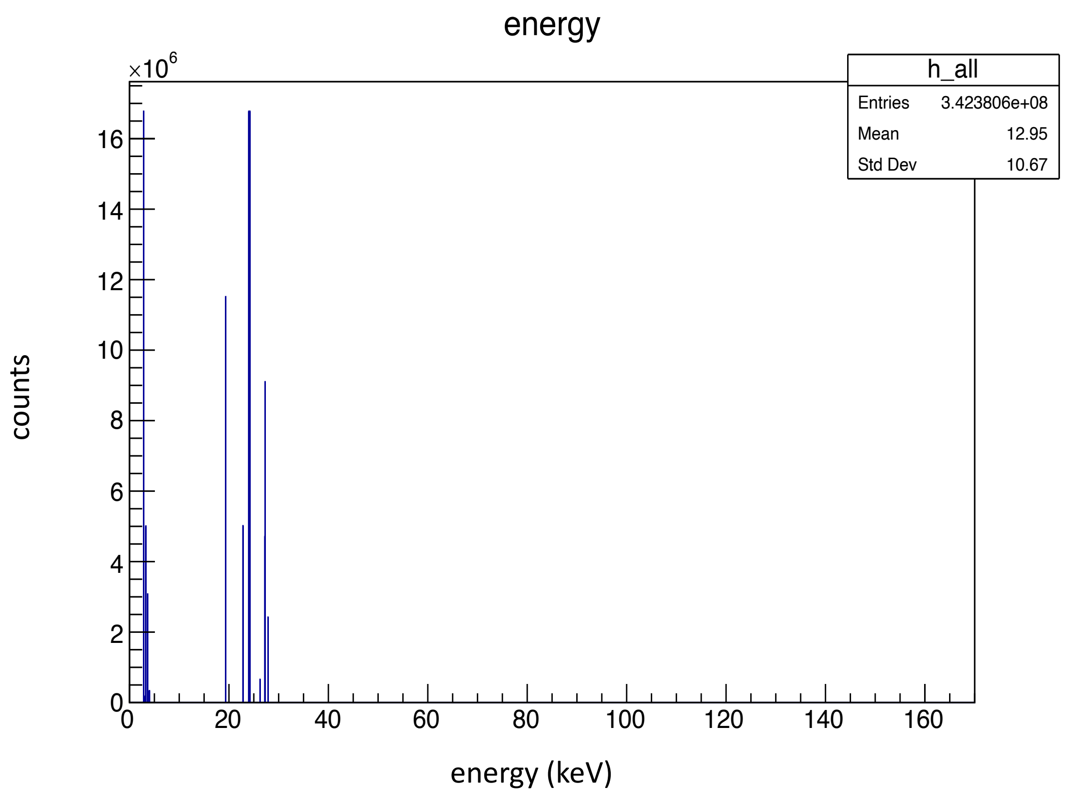
- A test of 10,000 jobs of 10,000 decays was submitted to the SimCenter.
- This simulation took about nineteen hours to complete.

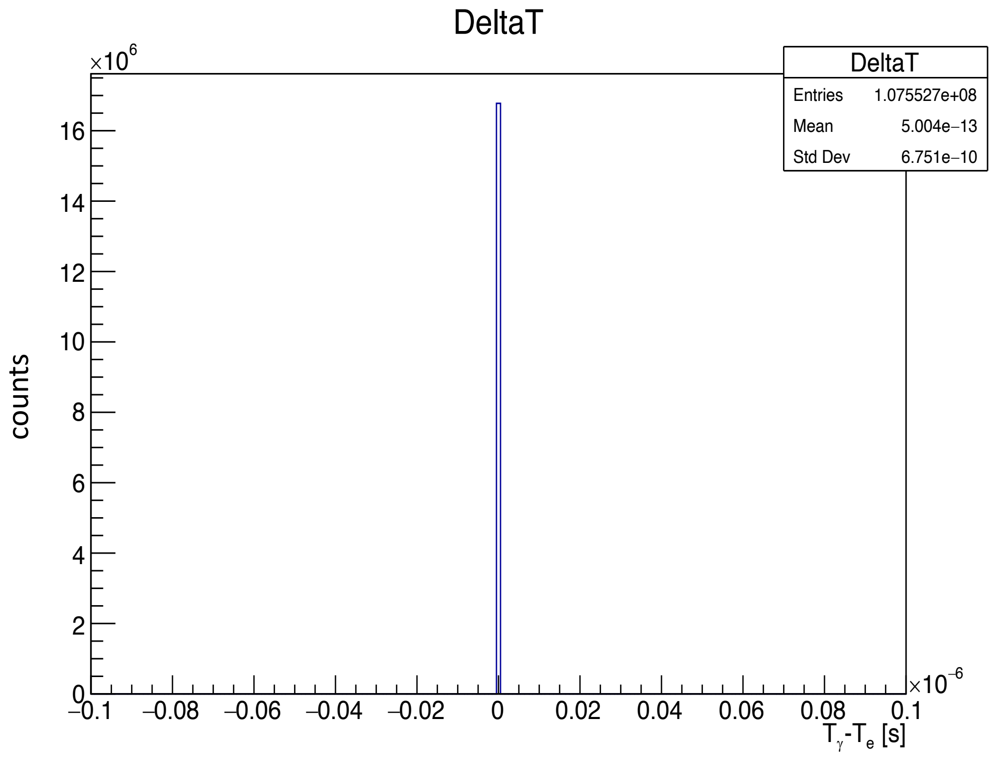




Simulation of Sn-113 Decay

- A test of 10,000 jobs of 10,000 decays was submitted to the SimCenter.
- This simulation took just under twenty hours to complete.
- Sn-113 naturally decays in picoseconds rather than nanoseconds, so the time difference appears to be zero.





Future Projects

Installation and testing of the Nab experiment is ongoing.

There are biweekly video conferences to update collaborators on the progress of the Nab experiment subsystems.

Visualization of the Nab experiment can be simulated using GEANT4.

References and Acknowledgments

- Sonzogni, A. *NuDat 2.7*. Retrieved from https://www.nndc.bnl.gov/nudat2/chartNuc.jsp

- Dr. Ethan Hereth, UTC SimCenter
- Dr. Aaron Jezghani, UK
- Derek Holman, 2018 URP Participant