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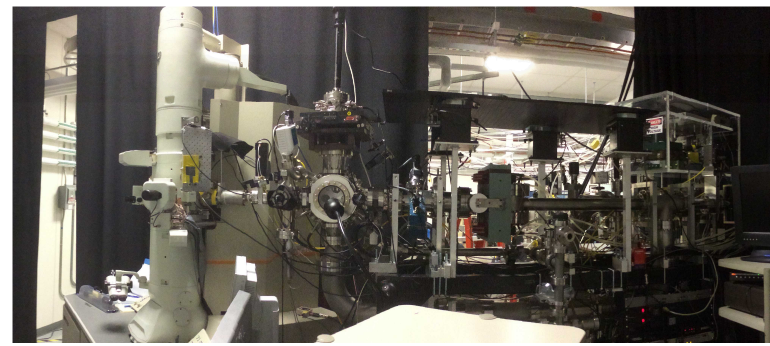


Physics, Nuclear Weapons, and History

Jon Custer

Radiation-Solid Interactions

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

ion beam lab

Outline

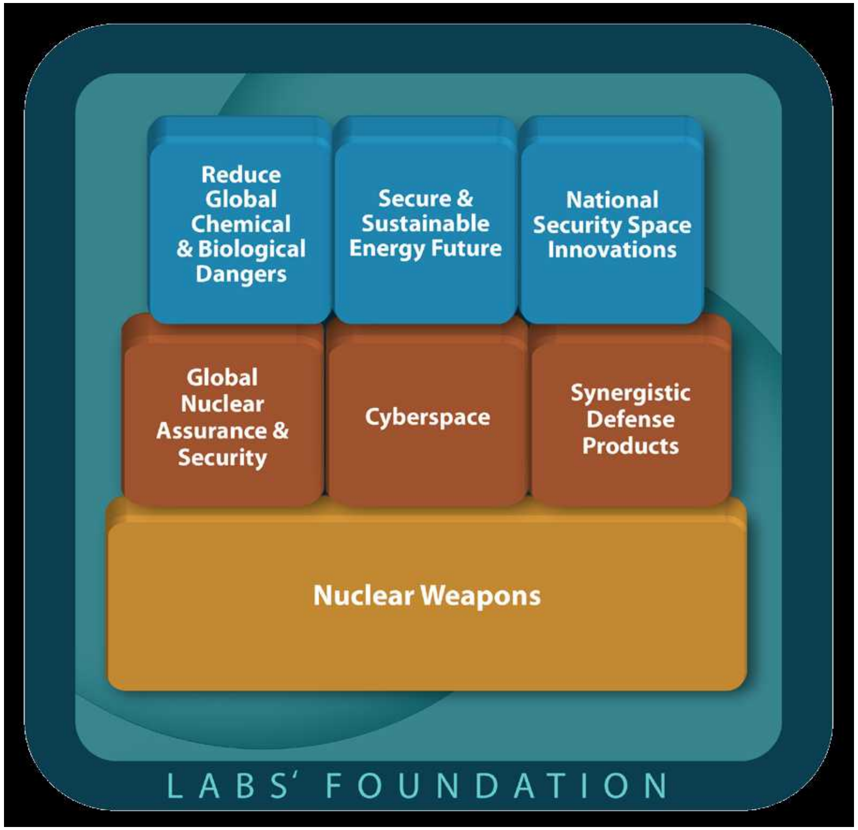
- Sandia National Laboratories – who/what are we?
- Nuclear Weapons –
  - Physics of nuclear weapons
- Hostile Environments
  - Threats to nuclear weapons
  - Dive in to Physics of Radiation Effects

- Focus on the physics
  - But all with an ion beam twist

Sandia is an NNSA National Laboratory

Sandia is a Multi-mission Laboratory

- "National Security Laboratory"
- 12000 people at multiple sites
  - Albuquerque NM; Livermore CA; Tonopah and Nevada Test Site NV; Kauai, HI; Amarillo, TX; Washington DC
- Nuclear Weapons has varied been 45-60% of lab funding over the last decade+
- Non-proliferation, work for DOD and Intelligence, other DOE areas, …



Sandia and Nuclear Weapons

- Los Alamos & Livermore do the bits that go BOOM!
- Sandia does just about everything else
- Design Agency Mission:
  - Arming, Fuzing, and Firing Systems
  - Gas Transfer Systems
  - Neutron Generators
  - Surety Systems
  - Systems Engineering and Integration
- Systems, sub-systems, components must be
  - Designed or specified
  - Manufactured (SNL, KCP) or acquired (specialty, COTS)
  - Qualified
  - Surveillance over system lifetime

Need Science to support Engineering

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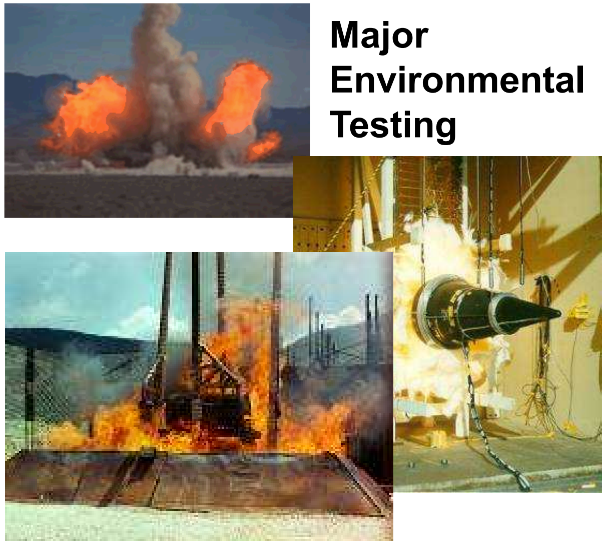
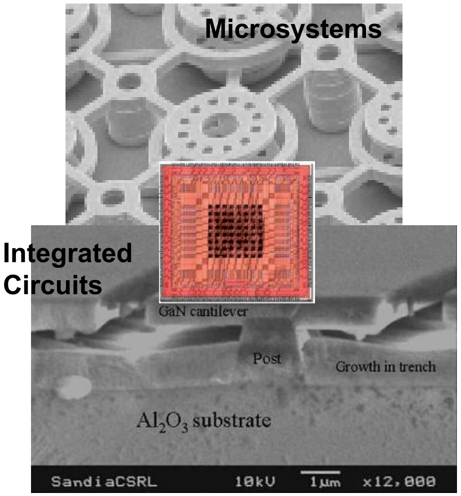


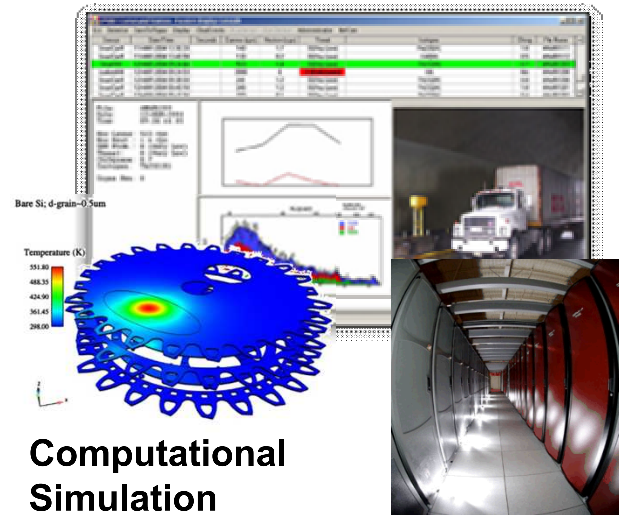
Major Environmental Testing

Microsystems

Integrated Circuits

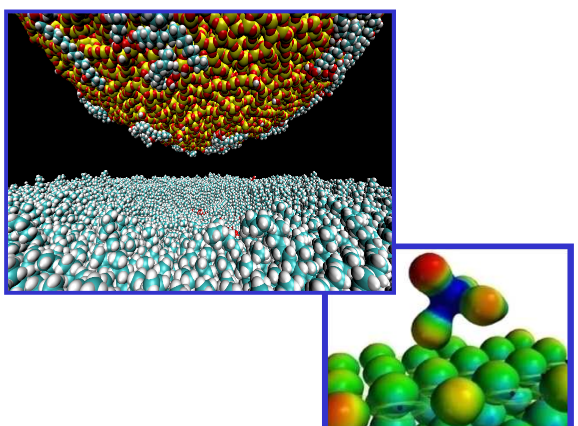


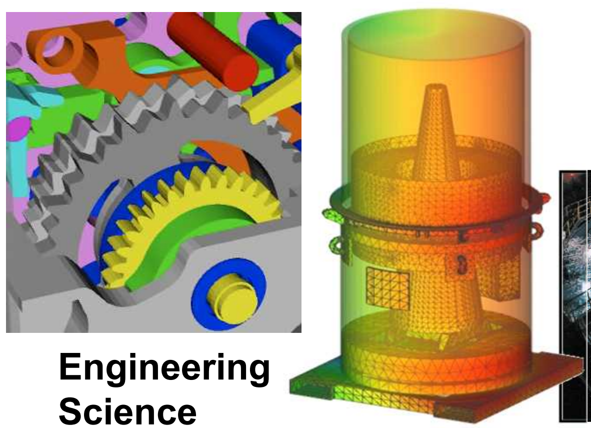
Microelectronics and Microsystems



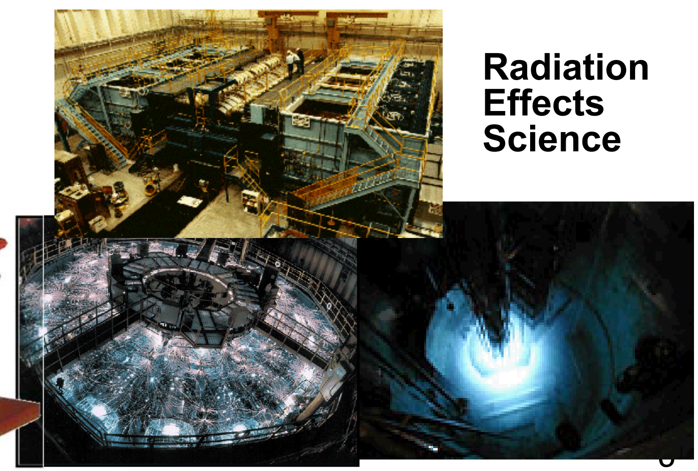
Computational Simulation

Materials Science





Engineering Science



Radiation Effects Science

Nuclear Weapons

- 72 years of nuclear weapons – Trinity test July 1945
- Remain the ultimate strategic deterrent to threats to the US

- Current weapons:
  - B-61, B-83 – bombs (Air Force and NATO platforms)
  - W-80 – warhead (Air Force, *Navy* cruise missiles)
  - W-78, W87 – warheads (Air Force Minuteman missiles)
  - W-76, W88 – warheads (Navy Trident missiles)

Nuclear Weapons require a Nucleus

On a Diffuse Reflection of the α-Particles.

By H. GEIGER, Ph.D., John Harling Fellow, and E. MARSDEN, Hatfield Scholar, University of Manchester.

Proc. Royal Soc. 82(557) 495-500 (1909)

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester**.

Phil. Mag 21(125) 669-688 (1911)

- Ions have been at the heart of understanding the properties of matter since the invention of the atom.
- Natural α sources were quickly deemed insufficient

Where did they get α particles?

- "Radium emanations" were the α source of choice in 1909 (well, only source)
- Radium was announced by the Curies in 1898.
- Marie Curie received the Nobel Prize in Chemistry in 1911 for discovery of radium and polonium and study of them
  - Her second after Physics in 1903 – research on radiation phenomena
  - First to get 2 Nobels in different fields
  - Who was the other person?
  - Name the 2-time Physics winner and for what discoveries?
- What if you want something besides α's?

Wikipedia

ion beam lab

Ions for nuclear reactions:

- Cockroft and Walton invented a high voltage supply in 1930
- Van de Graaff in 1929
- Ions besides α now where possible

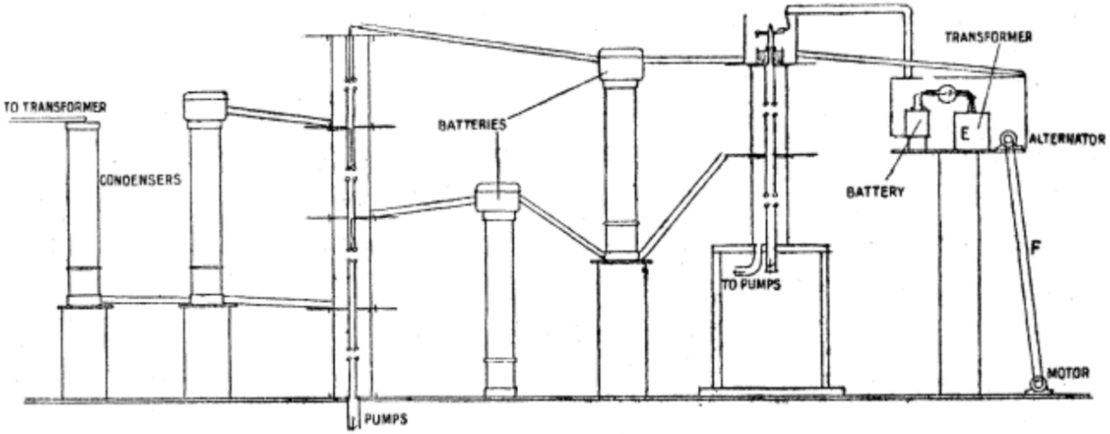
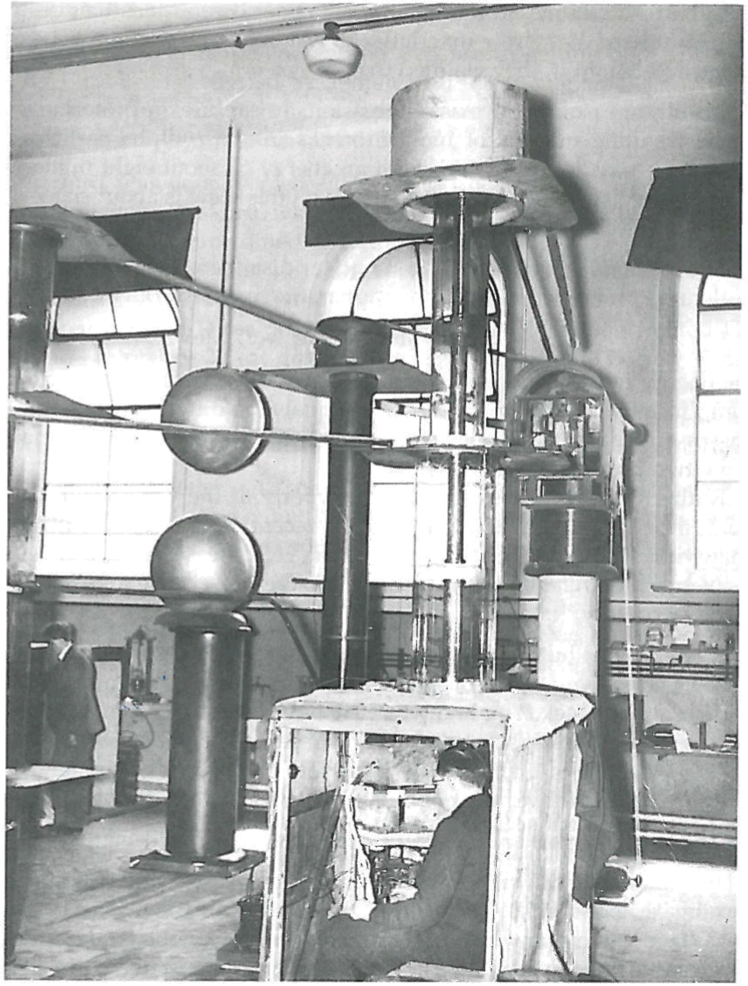


Fig. 6.



In Nuclear Transmutation to Nuclear Fission, PF Dahl, CRC Press (2002), from The Cavendish Laboratory

First Intentional Nuclear Reaction

- $^{7}Li + p \rightarrow 2\ ^{4}He$

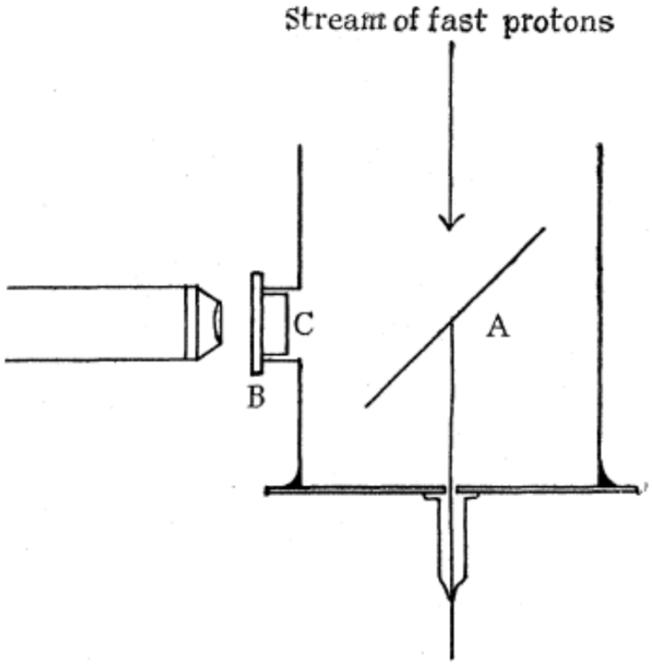


Fig. 1.

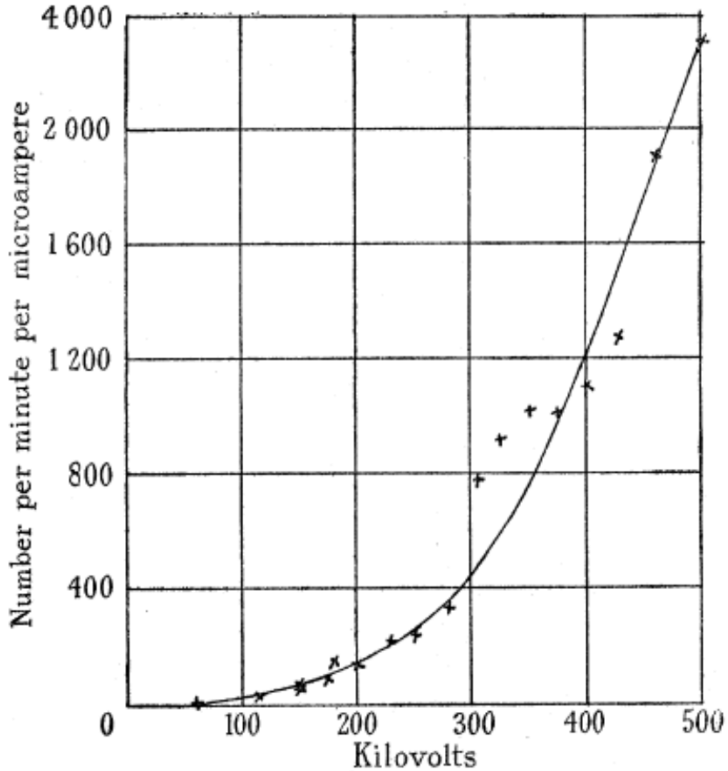


Fig. 4.

J.D. Cockcroft and E.T.S. Walton, Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 137, No. 831 (Jul. 1, 1932), pp. 229-242

Induced Nuclear Reaction

Sandia National Laboratories

4. *The Interpretation of Results.*

We have already stated that the obvious interpretation of our results is to assume that the lithium isotope of mass 7 captures a proton and that the resulting nucleus of mass 8 breaks up into two α-particles. If momentum is conserved in the process, then each of the α-particles must take up equal amounts of energy, and from the observed range of the α-particles we conclude that an energy of [redacted] would be liberated in this disintegration process. The mass of the Li_7 nucleus from Costa's determination is 7·0104 with a probable error of 0·003. The decrease of mass in the disintegration process is therefore $7{\cdot}0104 + 1{\cdot}0072 - 8{\cdot}0022 = 0{\cdot}0154 \pm 0{\cdot}003$. This is equivalent to an energy liberation of $(14{\cdot}3 \pm 2{\cdot}7) \times 10^6$ volts. We conclude, therefore, that the observed energies of the α-particles are consistent with our hypothesis. An additional test can, however, be applied. If momentum is conserved in the disintegration, the two α-particles must be ejected in practically opposite directions and, therefore, if we arrange two zinc sulphide screens opposite to a small target of lithium as shown in the arrangement of fig. 5, we should observe a large proportion of coincidences in the time of appearance of the scintillations on the two screens. The lithium used in the experiments

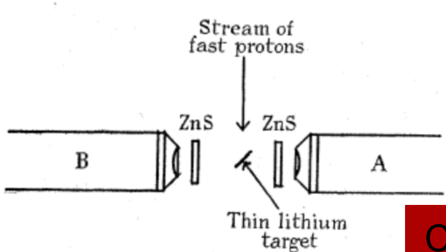


Fig. 5.

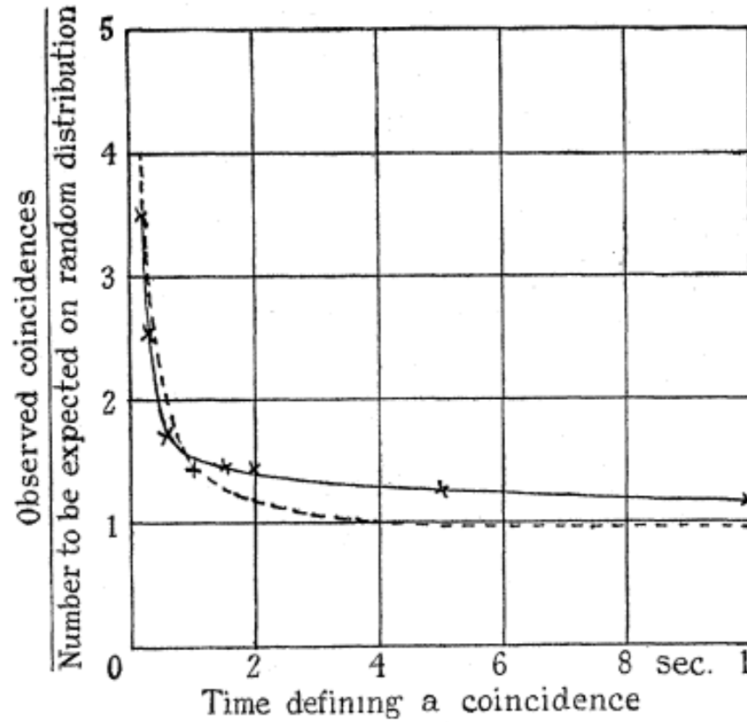


Fig. 6.

Current accepted value: 17.3468MeV

(First observed was $^{14}N(\alpha,p)^{17}O$ in 1919, only explained in 1925)

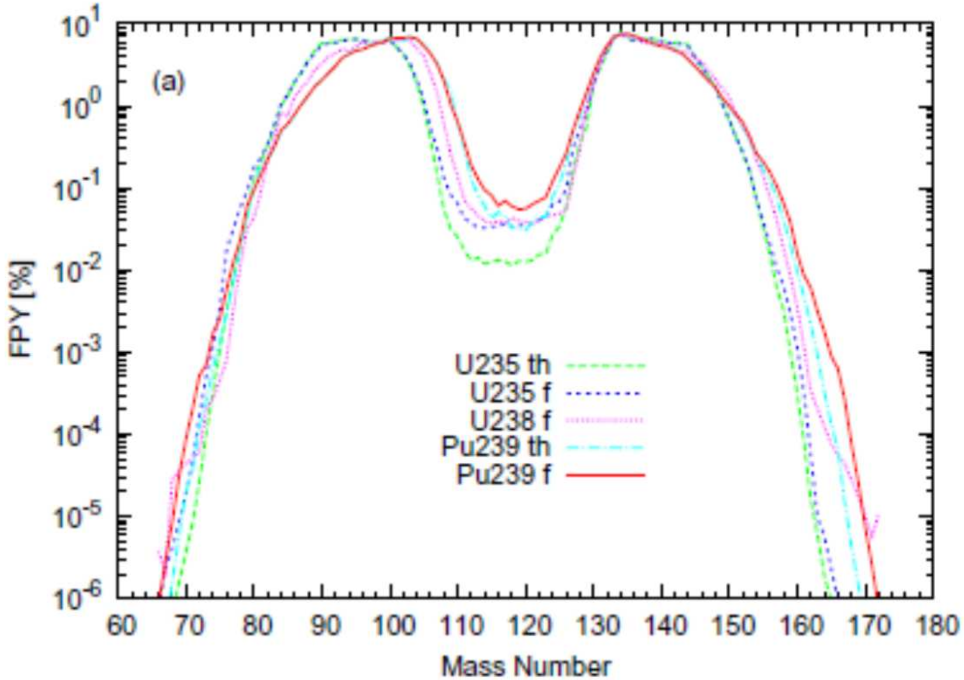
Neutrons and Fission

- Sadly, Ions aren't everything
- Neutrons are the mystery missing mass in the nucleus

- Neutron discovered by Chadwick in 1932
  - Student of Rutherford
  - Went to Germany to study with Hans Geiger
  - Interned in Germany in WWI
  - Worked on the Manhattan Project in WWII, was at Trinity test
- Neutron-induced fission of Uranium in 1939
  - Otto Hahn and Lise Meitner published
  - Lise Meitner had fled to Sweden in 1938 from her position as professor in Germany
  - Did NOT share 1944 Nobel Prize with Hahn (!)

Fission of Heavy Elements

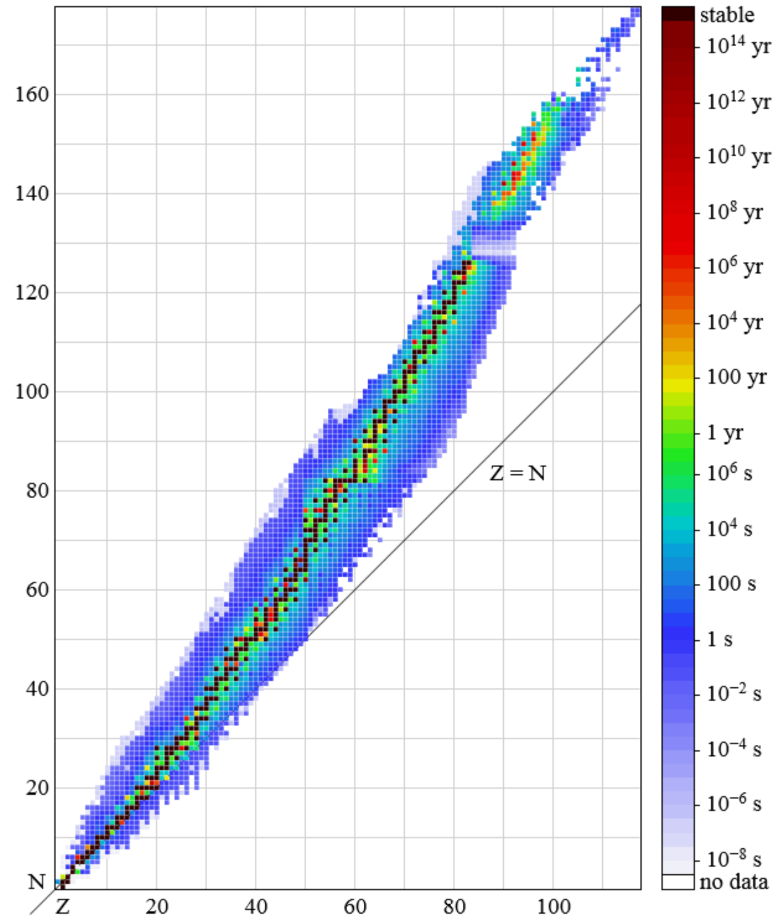
- Nucleus falls apart into two major parts
  - Unequal masses
- Prompt neutrons come out as part of the debris



H.D. Selby et al., Nuclear Data Sheets 1111 2891-2922 (2010)

More neutrons coming…

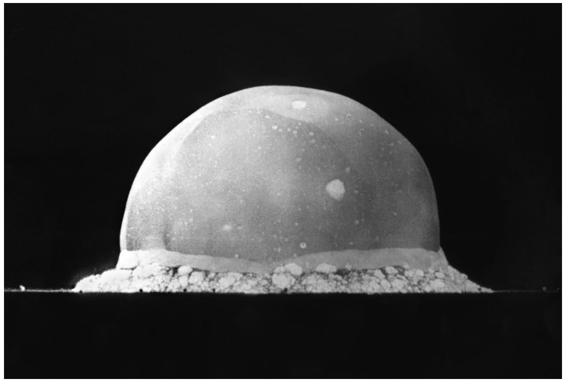
- Additional neutrons ‘evaporate’ from neutron-rich nuclei
- Neutron-to-proton ratio is too high
- Prompt + delayed neutrons can induced fission in other nuclei
- ~180MeV released per fission event



By BenRG - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=7900237

How to make a nuclear weapon

- Need:
  - Enough material (U235 or PU239) that undergoes fission…
  - In a configuration that utilizes most of the neutrons…
  - For long enough to get many fissions before it flies apart
- WWII:
  - Gun type U235 – Little Boy, Hiroshima August 6th 1945
    - Based on 6” naval gun to bring and hold material together
    - No testing required
  - Implosion Pu239 – Fat Man, Nagasaki August 9th 1945
    - Complex explosive lenses to make critical mass
    - Trinity test July 16th 1945



ion beam lab

Side note on history

- William Sterling ‘Deak’ Parsons
  - 1901-1953
- USNA Class of 1922
  - HS in Santa Rosa, NM
- VT fuze work 1940-1942
  - Saw USS Helena shoot down the first enemy aircraft with one, Solomons, January 1943
- Weaponeer on Enola Gay
  - Observer at Trinity test
  - Armed Little Boy in flight
- Rear Admiral at death
  - Never commanded a ship

US Navy

Primary vs Secondary

- Real problem is holding it all together long enough
- Chemical force (gun, implosion by explosives) is only so strong
  - Used for the primary, the first explosion
- Secondary is forced together by the primary
  - Stays together longer, allows for more generations

(Wait, what about Ion Beams?)

- U235 has an isotopic abundance of 0.72%
  - For Little Boy you need highly enriched material
- Ion Beams to the rescue!
- Manhattan Project pursued 3 isotope separation methods
  - Calutrons – mass spectroscopy with ion beams
  - Liquid Diffusion (Naval Research Lab)
  - Gaseous Diffusion (centrifuges, Iran, etc…)
- Gaseous Diffusion now the accepted technique

- All U235 for Little Boy came from the Calutrons at Y12

Physics of Mass Separation

- An ion beam with energy V (and velocity *v*) is sent into a magnetic field
- Force is $q \cdot v \times B$
- Different mass ions have different velocities
- Follow different semicircular orbits
- Capture different isotopes in different buckets

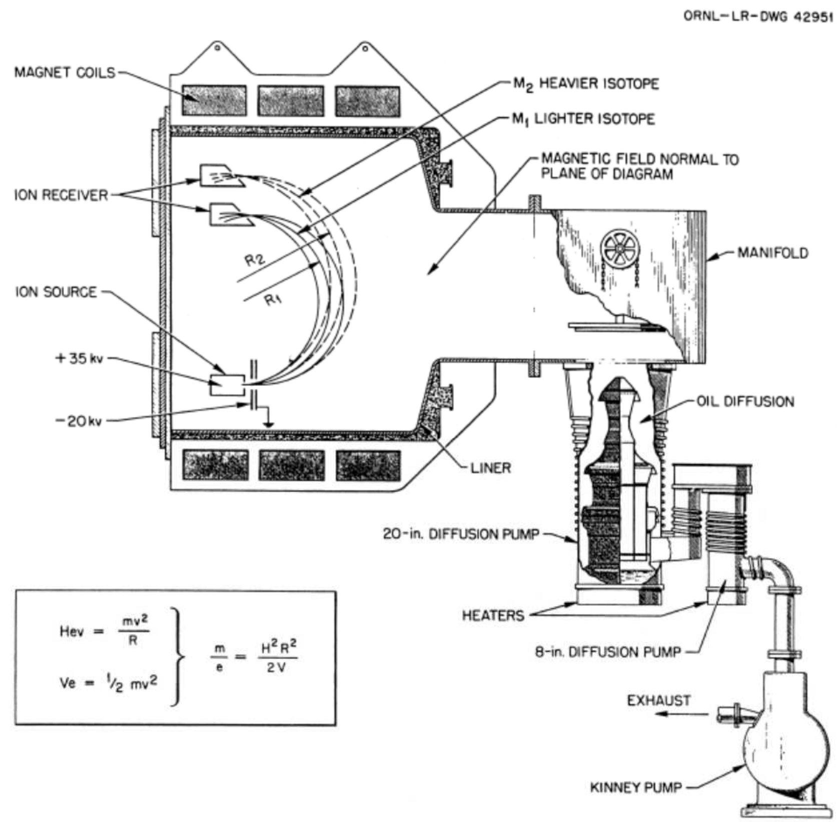
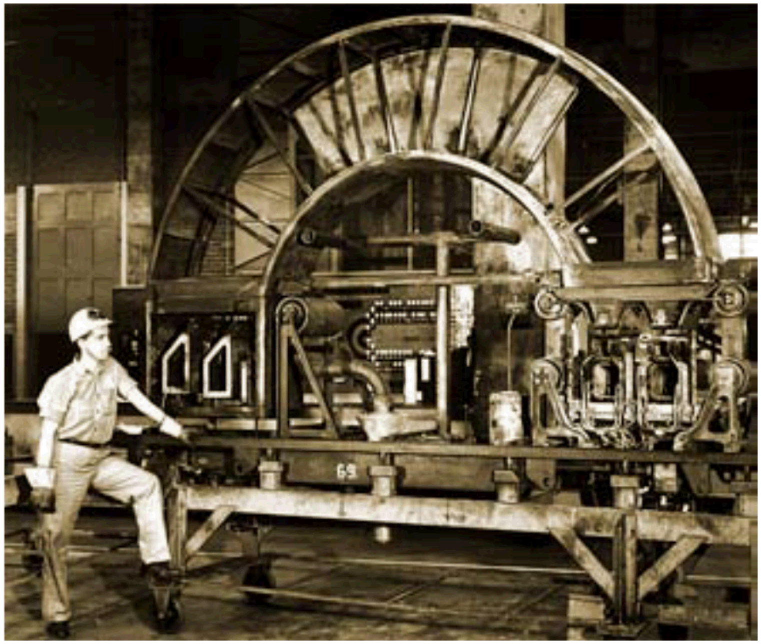


Figure 1. Schematic of second stage, β unit, separator. ORNL Drawing 42951.

Huge industrial enterprise



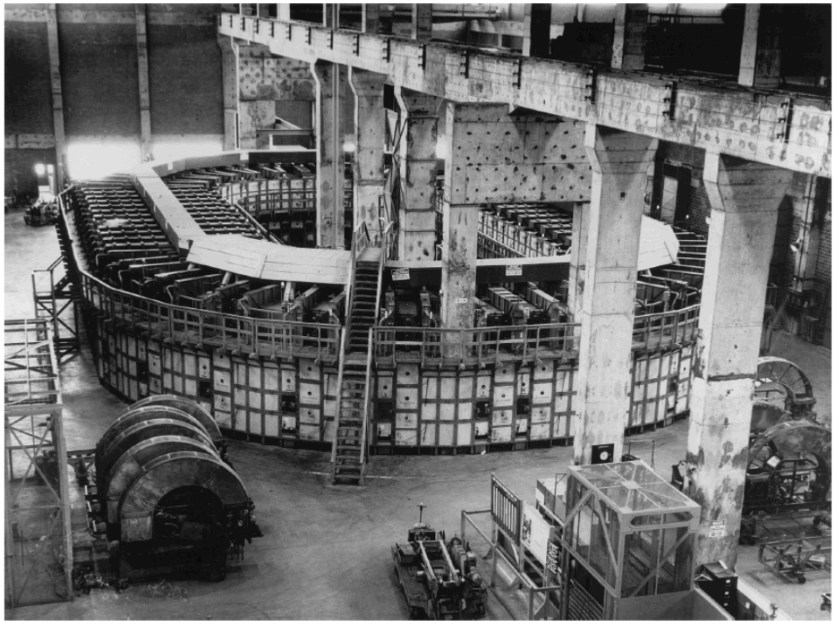


Figure 2. Photograph showing α unit "race track" assembly of calutrons. Photo source: ORD-PRO-2031.

- 1152 Calutrons of 2 designs installed at Y-12
- Sited at Oak Ridge TN because of TVA
  - Used ~ 1/7th of electrical power in the US
- ~42kg of U235 separated ion-by-ion in multiple passes

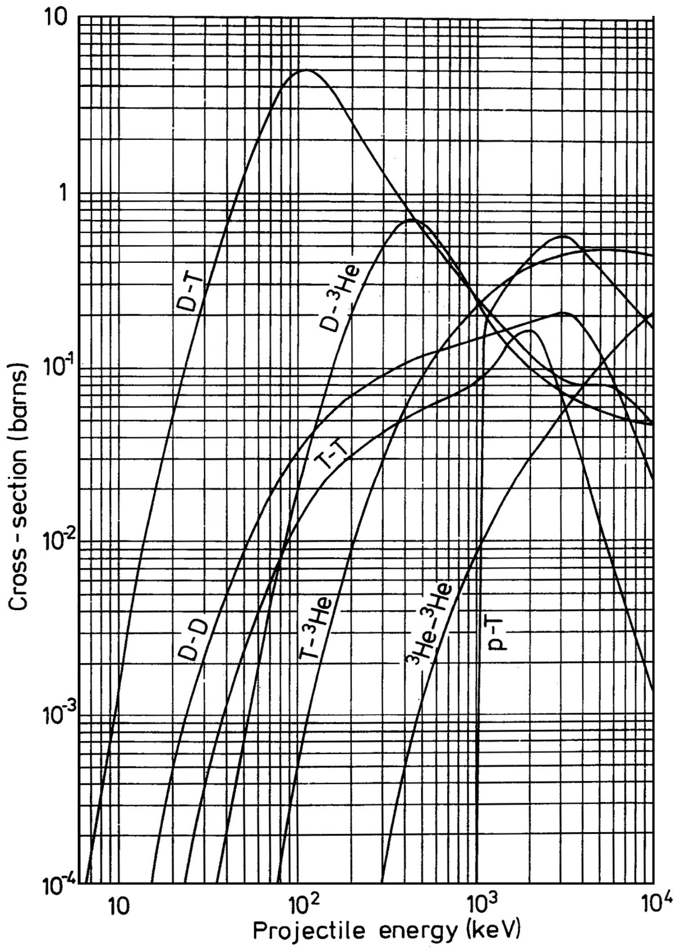
The Treasury's contribution

- Electromagnets need lots of wire for magnet windings.
- Copper a wartime necessity for brass for ammo/shells
- 6000 tons of silver 'borrowed' from the US Treasury (stored at West Point) to make magnet windings for the Calutrons
- All returned (to the troy ounce!) post-war

Figure 7. Calutron silver coils before return to U.S. Treasury. Photo source: Y-12 126949.

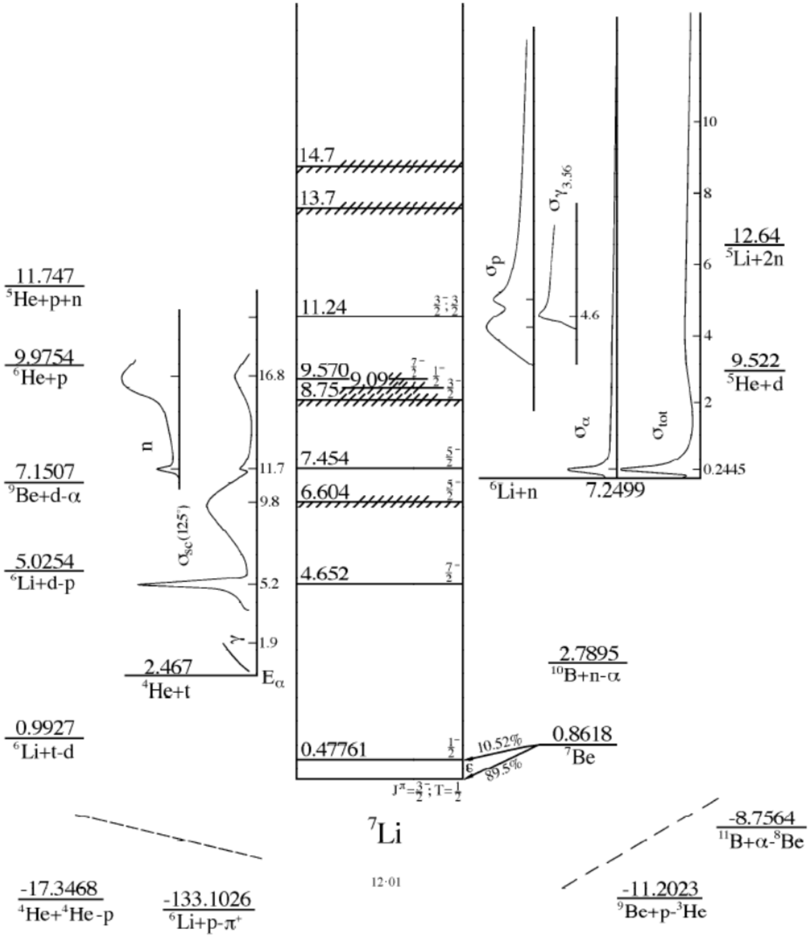
Need 1 neutron to start Primary

- Initiator in WWII
  - $^{9}Be + ^{210}Po$
  - α from ^{210}Po decay
  - $^{9}Be(\alpha,n)^{12}C$ reaction
  - ^{210}Po half-life is 138d
- Modern neutron source
  - $T(D,n)\,^{4}He + 18MeV$
  - 14MeV neutron
  - T half-life is 12.3 years

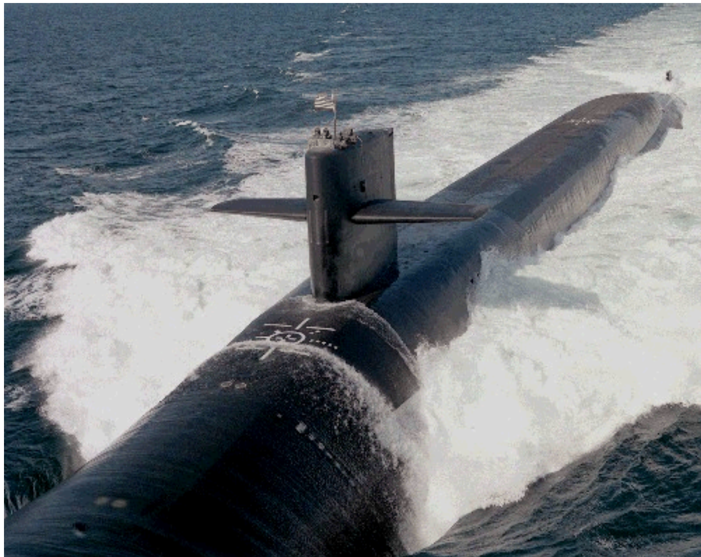


More neutrons are even better

- Time as a critical mass is limited
  - Instead of 1,2,4,8,…
  - Want 256,512,1024,…
- Secondary uses neutrons to make T
  - ^{6}Li (n,T) ^{4}He
- D-T fusion then creates lost of neutrons
- Lots of neutrons means lots of fissions quickly



Navy Nuclear Weapons



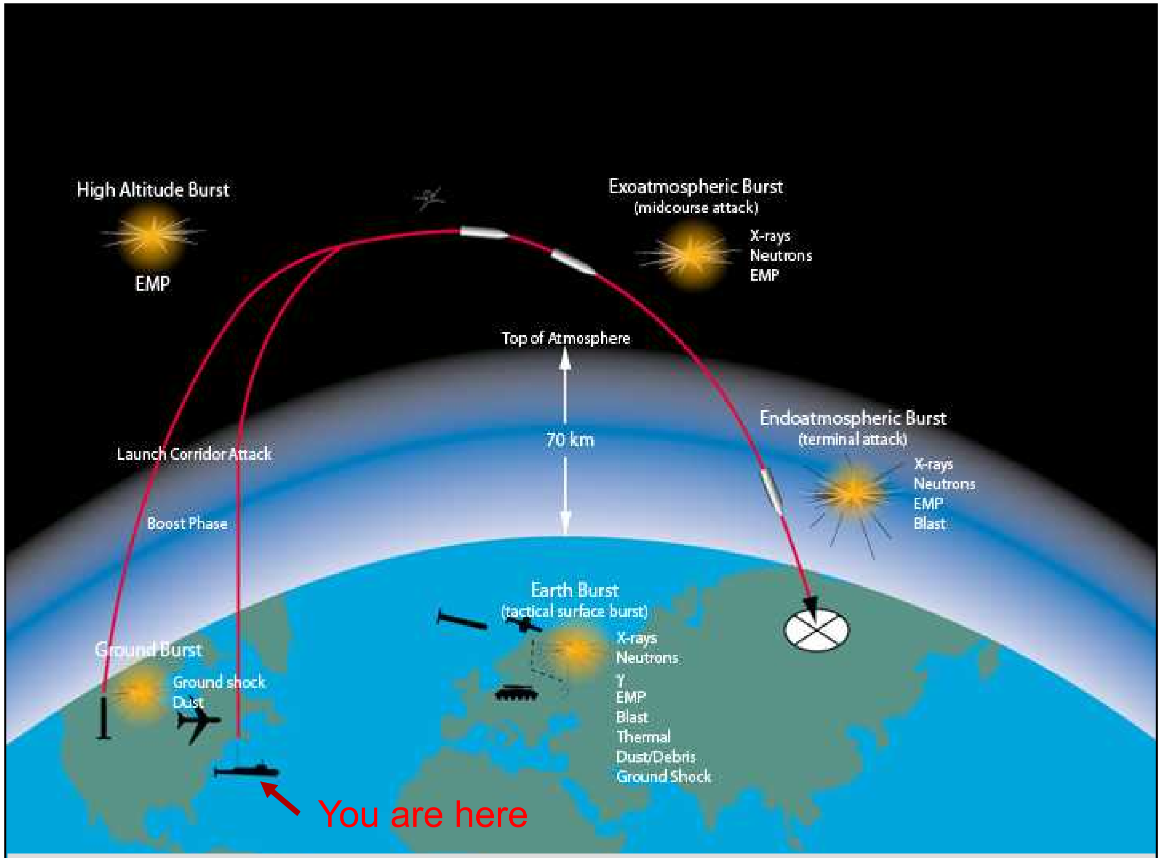
USS Alaska SSBN-732 (US Navy)

Trident launch (Lockheed Martin)

W-87 Peacekeeper Bus on display at USAF Museum, Dayton, OH (picture by the author)

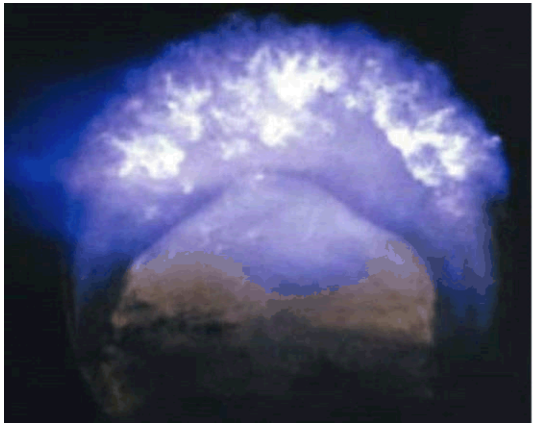
Hostile Environments

- Wide range of hostile environments to weapons in many different scenarios
- STS – stockpile to target sequence – specifies environments that must be survived
- Also have normal and abnormal to consider



Hardness against nuclear countermeasures

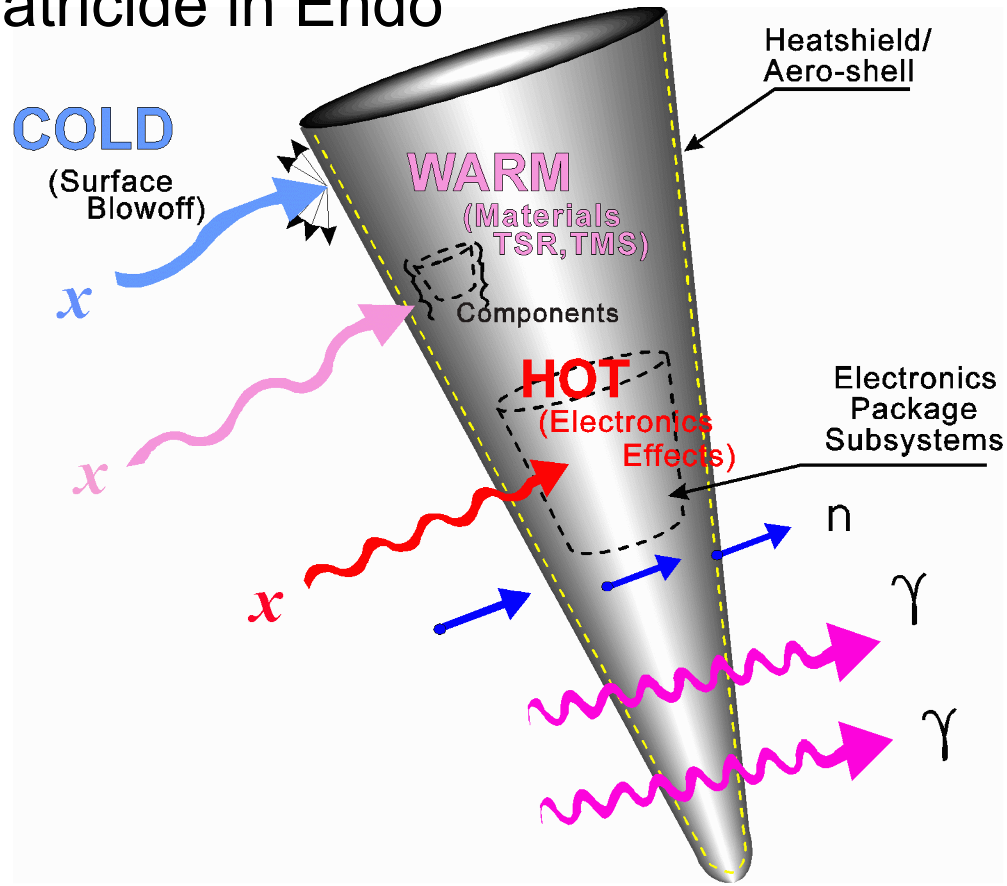
Focus on Radiation Environments



Hardtack-Orange, 3.8MT, Aug 1958 42km

Endo- or Exo-Atmospheric:
ABM in Exo,
ABM or fratricide in Endo

Starfish Prime, 1.4MT July 1962 400km



ion beam lab

Focus down to just one problem:

- Radiation response of microelectronics
  - Still too broad – diodes, CMOS, bipolar, LEDs, …
- Radiation response of bipolar transistors
  - Minority carrier lifetime in base is fundamental to operation
- Radiation response of Si vs GaAs bipolar transistors
- What causes the radiation response?
- Can we simulate it with ion beams?

Sandia and Microelectronics

A survey of literature on the effects of neutron and gamma irradiation of semiconductor materials has been made to determine the present ideas regarding the nature of radiation damage and the effort being applied to the studies throughout the nation.

There is a gap at present between the capability of measuring the bulk properties of irradiated materials and adequately predicting device behavior. Some work at other laboratories is being directed toward closing the gap. It may be valuable to follow experiments and parallel them using high dose rates from Nevada tests and Godiva.

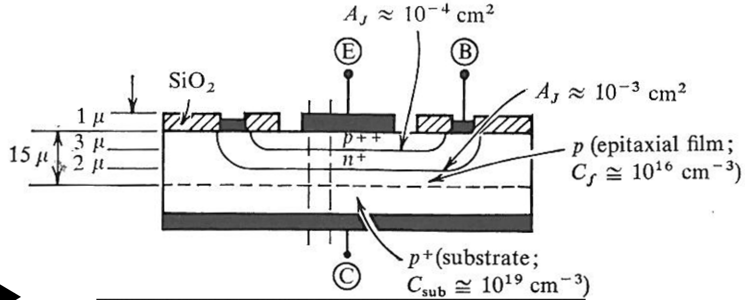
Since Sandia Corporation is in an advantageous position for utilizing high dose rate facilities, we should be capable of making contributions to the existing fund of knowledge on radiation effects to semiconductor materials and devices.

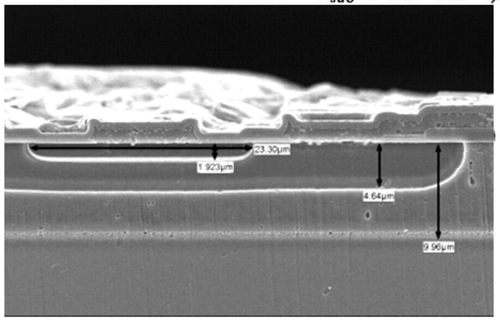
Herman Stein August 28, 1957

Electronics present in many Sandia-designed components

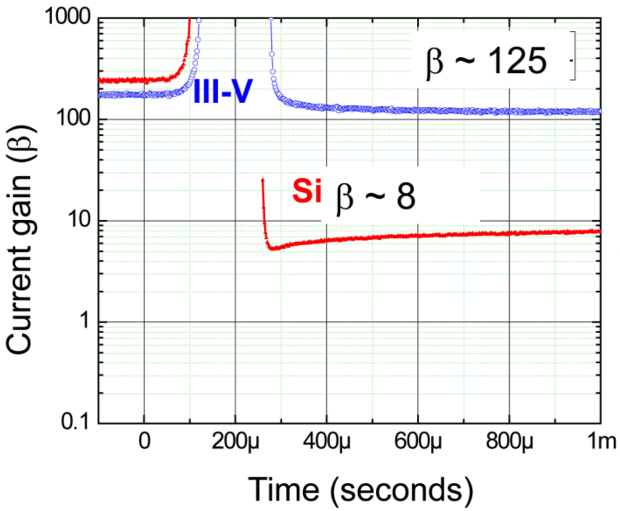
So what happens to transistors?

Neutrons,
Gammas,
X-rays,
Electrons

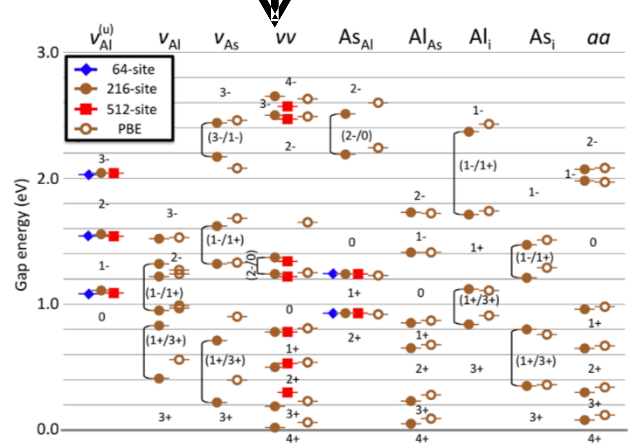




Scattering of:
Electrons – photocurrents
Atoms – **crystal defects**



Minority Carrier
Lifetime Decrease



Defects have states in the gap

Bipolar transistor gain decreases

What is the problem?

- Bipolar transistors and hostile environments
  - Neutrons create atomic displacements
  - Defects reduce minority carrier lifetime
  - Kills transistor gain (minority carrier devices)
  - Si and GaAs devices impacted
- R&D, testing, qualification
  - Historically done on fast burst reactors
  - SPR-III no longer available at Sandia
  - Can we develop a non-reactor simulation facility?
- Ions also generate displacement damage
  - How well can we simulate neutron damage using ions?
  - What else can we do that we couldn't before?

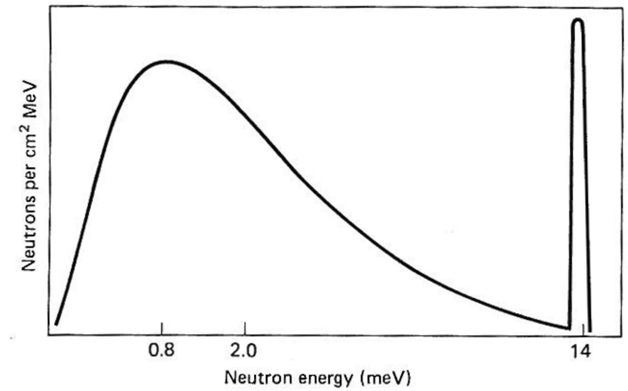
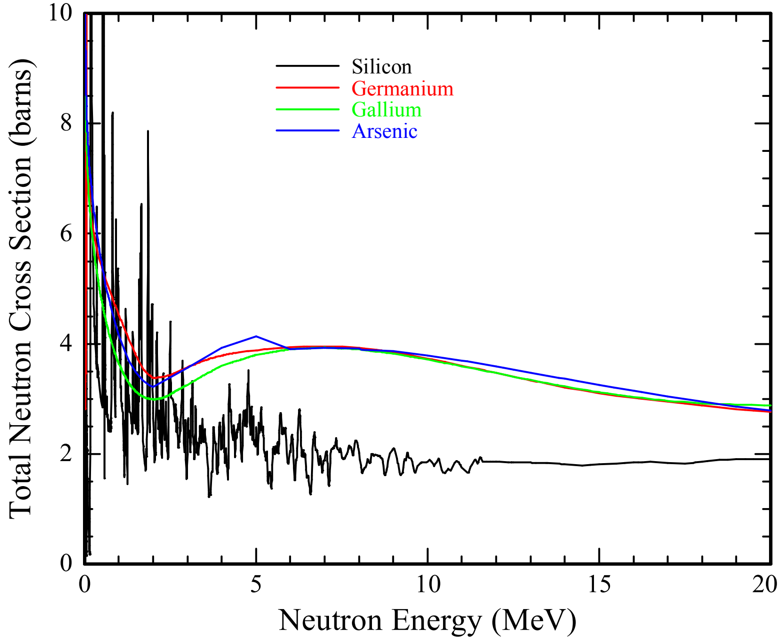


Fig. 4.19 Neutron energy spectrum from thermonuclear detonation.

Messenger and Ash, "The Effects of Radiation on Electronic Systems"

Neutron-Lattice Interactions:

- Mean free path of neutrons:
  - Si: 9 cm, Ge, GaAs: 6 cm
- Much longer than device dimensions
- A neutron might scatter off of one atom in the lattice
  - Recoils have a distribution of energy
  - Maximum energy = $\frac{4m_1m_2}{(m_1+m_2)^2}$
  - n on Si: 13% of n energy
  - n on Ga, Ge, As: 5% of n energy



Data from ENDF/B-VII.1 (www.nndc.bnl.gov)

Can we use ions instead?

- Ions interact strongly with solids
  - Electronic stopping: functions as a smooth “friction” force
  - Nuclear stopping: average over individual ion-atom collisions
- Ion-Atom: Rutherford Scattering cross section:
  - $\sigma_c(\theta_c) = \frac{Z_1^2 Z_2^2 e^4}{16E^2 sin^4(\theta_c/2)}$
  - Low energies, small angles have largest cross sections, lowest energy transferred to target
  - Consequence of long range electrostatic forces

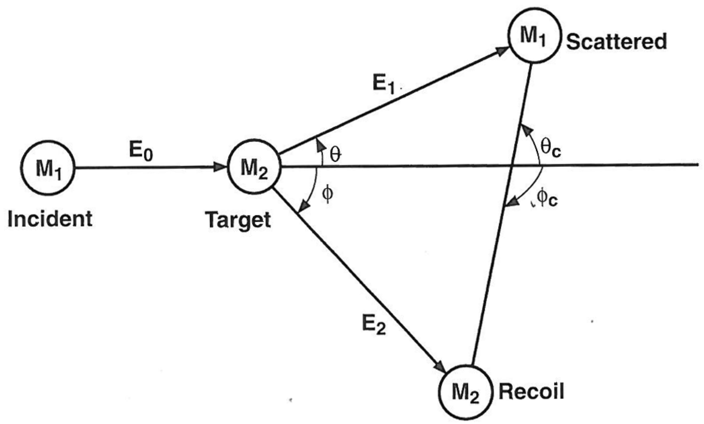
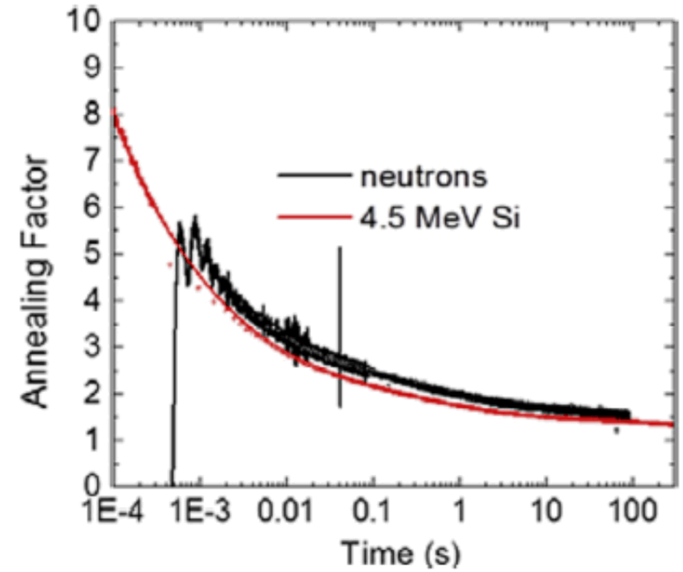


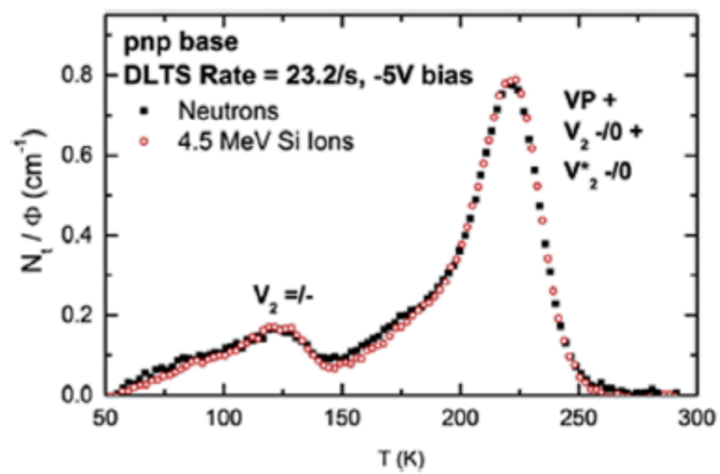
FIG. A4.1. Schematic scattering event as seen in the laboratory and center-of-mass coordinate systems illustrating the angles, energies, and velocities for nonrelativistic elastic collisions.

Tesmer and Nastasi, Handbook of Modern Ion Beam Materials Analysis

Neutron vs Ions

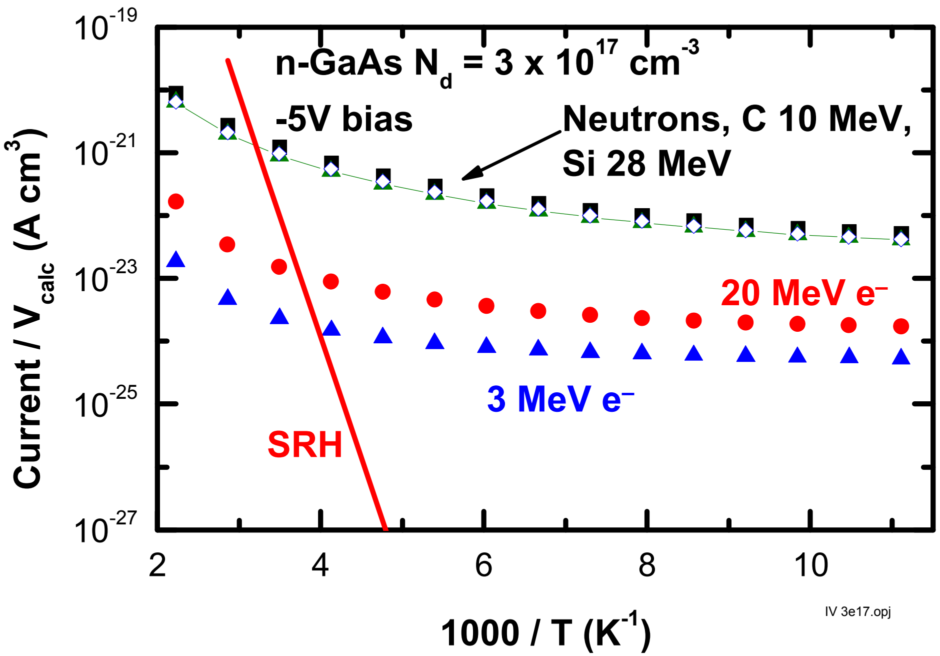
- With care we can simulate FBR neutron response using a fast-pulsed ion beam
- Replicate time response of transistor gain
- Replicate remaining defect population
- Replicate minority carrier lifetime change
- With ions we can probe much earlier in the response
  - No coincident gammas



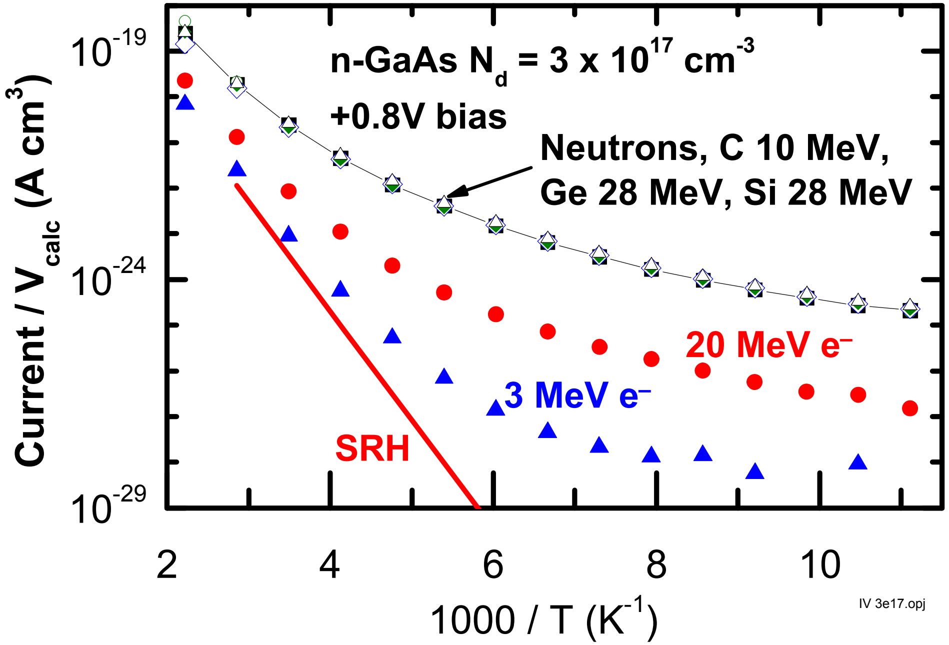


Ion & Neutron Damage Produces the Same Normalized Recombination Currents

Reverse Bias



Forward Bias



Normalized tunneling currents in high doped diodes (defect tunneling), are independent of type of damage for neutrons or ions. Weak temperature dependence.

DFT of defects in GaAs

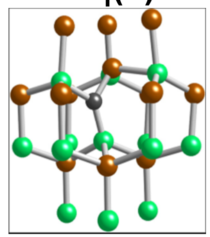
Sandia National Laboratories

Density Functional Theory was used to determine stable charge states of defects and their energies of formation and, migration and reaction including lattice relaxation.

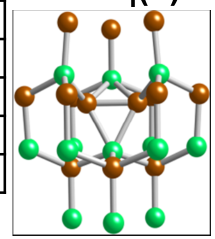
Formation energy (eV)

Charge state	+3	+2	+1	0	-1	-2
Defect type						
As_I	2.32	3.00	2.47	3.43	4.29	
Ga_I	2.03	2.09	2.09	4.05	5.17	
C_I		3.93	4.25	4.89	5.93	7.22
Si_I		1.84	3.09	3.81	5.39	6.87
V(As)			2.55	3.49	4.12	
V(Ga)			2.24	2.82	3.36	
VV				4.19	4.99	5.65
As(Ga)		0.19	0.73	1.49		
Ga(As)				3.29	3.44	3.66
dmg			0	0.52	1.52	

$C_I(0)$



$As_I(0)$



Migration Barrier E_m (eV)

Charge state	+3	+2	+1	0	-1	-2
Defect type						
As_I	0.73	0.17	0.45	0.38	0.72	
Ga_I	1.30	1.26	1.06	0.40	0.60	
C_I		0.90	0.70	0.40	1.20	1.20
Si_I		1.20	0.75	0.60	0.70	0.90

- 10 defect types (38 species), C & Si dopants, e,h
- Only interstitials are significantly mobile at room temperature ($E_m \lesssim 0.5$ eV highlighted).
- Thermal Diffusivity: $D = D_o \exp(-E_m/kT)$ varies with charge state.
- As_I(0/+) also migrates athermally by Bourgoin-Corbett mechanism.
- C and Si interstitials are produced by kick-out reactions between interstitials and dopants.
- Carrier capture rate coefficients (κ) are estimated from DLTS experiments but have large uncertainty.

Defect Reactions

mobile (columns: As_I, Ga_I, C_I, Si_I); immobile (rows); reaction products (cells)

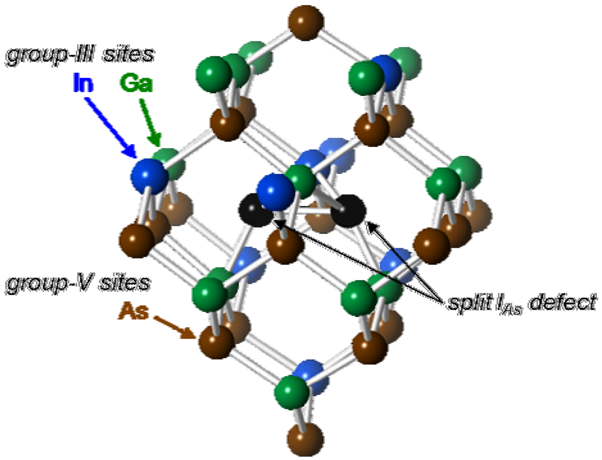
reactant	As_I	Ga_I	C_I	Si_I
C(As)	C_I	CGa(As)	2C(As)	-
Si(Ga)	SiAs(Ga)	Si_I	-	2Si(Ga)
V(As)	0	Ga(As)	C(As)	Si(As)
V(Ga)	As(Ga)	0	C(Ga)	Si(Ga)
As(Ga)	2As(Ga)	As_I	CAs(Ga)	SiAs(Ga)
Ga(As)	Ga_I	2Ga(As)	CGa(As)	SiGa(As)
VV	V(Ga)	V(As)	C VV	Si VV

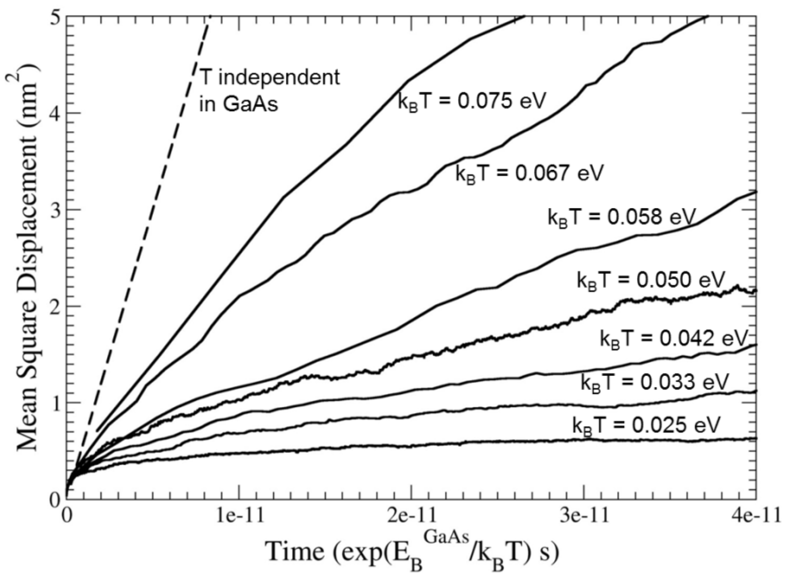
Blue denotes immobile reaction products not explicitly tracked but approximated as a generic defect type dmg.

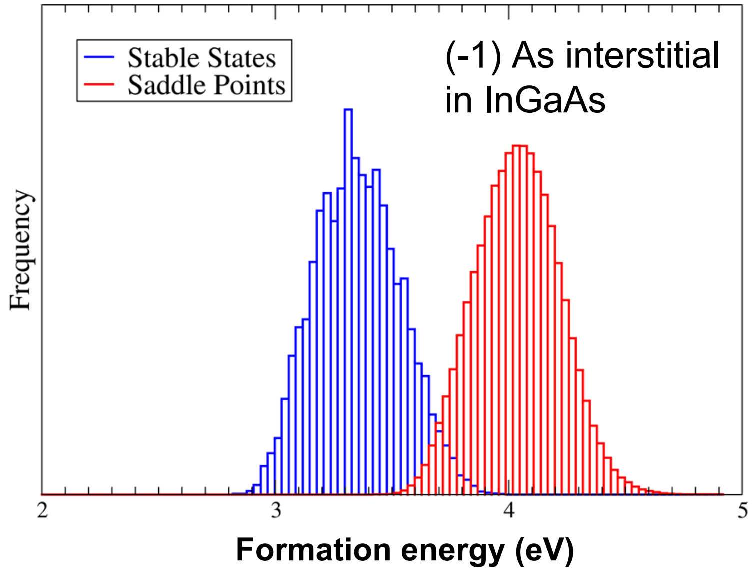
W. Wampler, S. Myers, J. Appl. Phys 117, 045707 (2015)

Defects in ternary III-V alloys

- Present atomistic model is for defects in GaAs (base of Npn HBT).
- However, carrier recombination also in ternary alloys, InGaP emitter of Npn and InGaAs base of PnP.
- Random occupation of nearby group III lattice sites produces variation in defect properties.
- New computational methods (cluster expansion) have been applied to calculate defect properties in ternary alloys (leverages LDRD).
- Kinetic Monte Carlo simulations show defect migration to lower energy sites and time-dependent diffusion rates.
- Impact on device response TBD.







All this goes in to Comp/Sim:

Sandia National Laboratories

Radiation Environment
NuGET
B. Hehr

Defect Production
Cascade/Marlowe
B. Hehr, G. Vizkelethy
Molecular Dynamics
S. Foiles

Defect properties
Density Functional Theory
A. Wright, N. Modine

Device Response
- Carrier Transport
- Carrier recombination

XPD W. Wampler, S. Myers
Charon G. Hennigan

Circuit response
Xyce + Compact models
E. Keiter & circuit analysis team

- Experimental qualification evidence supported by modeling and simulation.
- Difference from 30 years ago is increased physics knowledge
- This is required by loss of high-fidelity testing options (UGT, SPR, …)

Testing an issue even 'back when'

Sandia National Laboratories

Fast burst reactors give intense μs pulses of fission neutrons. The fluence is more than sufficient to degrade both narrow base high frequency bipolar transistors and JFETS. The only source of 14 MeV neutrons sufficient for the complementary experiment is from a nuclear weapon. Unfortunately, the pulse repetition frequency for underground or full scale testing at the Nevada Test Site is quite long. Thus experimenters have devised less direct methods.

J.M. McKenzie, SAND77-0357

Summary

- Nuclear weapons are vital to US security

- The Navy is the ultimate deterrent
  - Lifetime extensions for Navy warheads
  - Columbia-class construction starts ~2021 (why 'Columbia'?)

- Physics broadly applicable to nuclear weapons
  - (And not just nuclear physics)
  - Always be ready to learn (see Deak Parsons)

- (Ion beams continue to be useful)