Nuclear Physics and the Manhattan Project

Oppenheimer & Groves, July 1945

National Atomic Energy Museum, Albuquerque

Two icons of the 20th century, July 1946
Classical versus Modern

- Absolute time & space
- Flat space
- Aether
- Determinism
- Particles or waves
- Observer neutral

- Relative time & space
- Curved space
- No aether
- Probabilities
- Wave-particle duality
- Observer affects outcome
Task of lecture

- From radioactivity to fission
  - Isotopes, neutrons, atomic mass number, half-lives, transmutation

- From fission to atomic bombs
  - Chain reactions, isotope separation, plutonium

- From the Manhattan Project to Hiroshima
  - Physicists as weapons-makers, politicians and geopolitical strategists
  - Passing of the witnesses (Dartmouth’s Leonard Rieser lectures until 1998)
Two visions of the atom

H. G. Wells, 1913 -- the new fire

“We should not only be able to use this uranium; not only should we have a source of power so potent that a man might carry in his hand the energy to light a city for a year, to power a fleet of battleships or drive one of our giant liners across the Atlantic; but we should also have a clue that would enable us at last to quicken the process of disintegration in all the other elements …. Every scrap of solid matter in the world would become an available reservoir of concentrated force …. This would mean a change in human conditions that I can only compare to the discovery of fire, that first discovery than lifted man above the brute …. This is the dawn of a new day in human living.”

Rutherford, 1933 -- moonshine

One might break down atoms by blasting them with particles, “but on the average we could not expect to obtain energy in this way. It was a very poor and inefficient way of producing energy, and anyone who looked for a source of power in the transformation of the atom was talking moonshine.”
Spontaneous radioactivity

- Rutherford, 1898-1904, explores radioactive transmutation of atoms
  - $\beta$-ray emitters become heavier elements
    - $^{14}\text{C}_6 \rightarrow ^{14}\text{N}_7 + \beta$
  - $\alpha$-ray emitters become lighter elements
    - $\text{Th}_{90} \rightarrow \text{Pb}_{82} + 4\alpha$
      - Remember that $\beta = e^-$, and $\alpha = ^4\text{He}_{2}^{++}$
  - But found that only certain carbon and thorium atoms are emitters … did not know why
    - Isotopes not yet understood!
Discovery of the neutron

- Rutherford wonders about neutral protons
  - Had named hydrogen nucleus “proton” in 1911
  - Coined term “neutron” in 1920
- Chadwick discovers neutron in 1932

- Observed by Bothe (1928), Joliot-Curie (1932), who called “strong γ-rays” (wrong!)
Nuclear physics launched

- Protons and neutrons in nucleus
  - \( Z \) [# protons] + \( N \) [# neutrons] = \( A \) [mass]
  - \( Z \) determines chemical behavior of element
  - What holds nucleus together? (strong force)
    - Explains why \(^{238}\text{U}_{92}\) is the heaviest natural element
    - Binding energy = mass of nucleons - mass nucleus \([E=mc^2]\)

- Isotopes: Same \( Z \) but different \( N \)
  - Hydrogen isotopes
    - \(^1\text{H}_1\), \(^2\text{H}_1\) [=deuterium], \(^3\text{H}_1\) [=tritium]
  - Uranium isotopes
    - \(^{238}\text{U}_{92}\), \(^{235}\text{U}_{92}\) [ratio of 139:1 in natural uranium ore]
Collision experiments, 1930s

- Artificial radioactivity in 1934 (Curie-Joliot)
  \[ ^{109}\text{Ag}_{47} + ^1\text{n}_0 \rightarrow ^{110}\text{Ag}_{47} \rightarrow ^{110}\text{Cd}_{48} + e^- \]

- Search for “transuranic” elements
  - Fermi in Rome until 1938 (then to Columbia)
    \[ ^{238}\text{U}_{92} + ^1\text{n}_0 \rightarrow ^{239}\text{U}_{92} \rightarrow ^{239}\text{Np}_{93} + e^- \rightarrow ^{239}\text{Pu}_{94} + e^- \]
    Plutonium has half-life of 24,000 years (does not occur in nature)
  - Hahn and Strassmann in Berlin, 1938
    \[ ^{235}\text{U}_{92} + ^1\text{n}_0 \rightarrow ^{141}\text{Ba}_{56} + ^{92}\text{Kr}_{36} + [3 \ ^1\text{n}_0] \]
    Meitner and Frisch explain above result as fission, 1939
    - Missing mass provides energy, by E=mc^2
      - 60W lightbulb for 1 hr requires 7 billion \(^{235}\text{U}_{92}\) fissions!
    - Number of neutrons released unknown in 1938
Are chain reactions possible?

If 2+ neutrons released per fission!

If “fast,” i.e., unmoderated neutrons in $^{235}$U ... BOOM!

1934: Szilard theory of chain reactions
April 1939: Joliot in Paris measures 3-4 neutrons,
Szilard’s plan for censorship fails
May 1939: British, German & Soviet physicists notify their respective governments about possibilities for atomic weapons!
Wigner & Szilard to FDR, 2 August 1939 (signed by Einstein)
Are atomic bombs possible?

- Einstein-Wigner-Szilard letter, Aug 1939
- Will nature allow a bomb?
  - Fissionable (fast) fuels
    - $^{235}\text{U}_{92}$ requires isotope separation (4 options defined by 1940)
    - “Element 94” (Pu) discovered in Dec 1940
  - Controlled fission in laboratory to measure parameters
  - Critical mass required for bomb (few kgs)
- British MAUD Report optimistic, Oct 1941
“German fear” as motivation

Unsuccessful pile-building (controlled fission of $^{235}\text{U}_{92}$) at Columbia & Princeton

Berkeley cyclotrons produce Pu, is found to be fissionable

Pearl Harbor, Dec 1941

FDR authorizes development (not just research) in Jan 1942, with blank check
MP: industrialization, 41-45

- Army takes control, June 1942
  - Security and compartmentalization
- Chicago pile goes critical, Dec 1942
- Oak Ridge isotope separation factories
  - Redundancy, i.e., 3 methods--gaseous diffusion, thermal diffusion, electromagnetic separation
- Hanford Pu production in 5 massive piles
  - “Poisoning”; chemical separation
  - First Pu becomes available in spring 1945
MP: bomb design, 43-45

- Oppenheimer at Los Alamos
- Russian spies at Los Alamos
- Difficult problems needing solution
  - Assemble critical mass fast enough for complete fission (80 generations)
    - Gun-type (Uranium bomb)
    - Implosion-type (Plutonium bomb)
  - Safe and reliable ignition (provide neutrons)
  - Airplane-deliverable weapons
- Trinity Test, July 1945
- Hiroshima and Nagasaki, August 1945
New roles for physicists

How should the bomb be used?
- Bohr and how to involve the Soviets
- Chicago physicists call for demonstration
- Targeting committee ignores demo idea

US post-war nuclear policy?
- International control vs. nationalized arms race
- Military control of US nuclear research
- Civilian uses of nuclear power
- Federation of Atomic (American) Scientists

Today’s nuclear powers
- Declared: USA, Russia, UK, France, China, India, Pakistan
- Undeclared: Israel, North Korea, Iran? (S. Africa abandoned)