Alpha Particle Spectroscopy

Week of Sept. 13, 2010

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Atomic and Nuclear Physics Laboratory
(Physics 4780)

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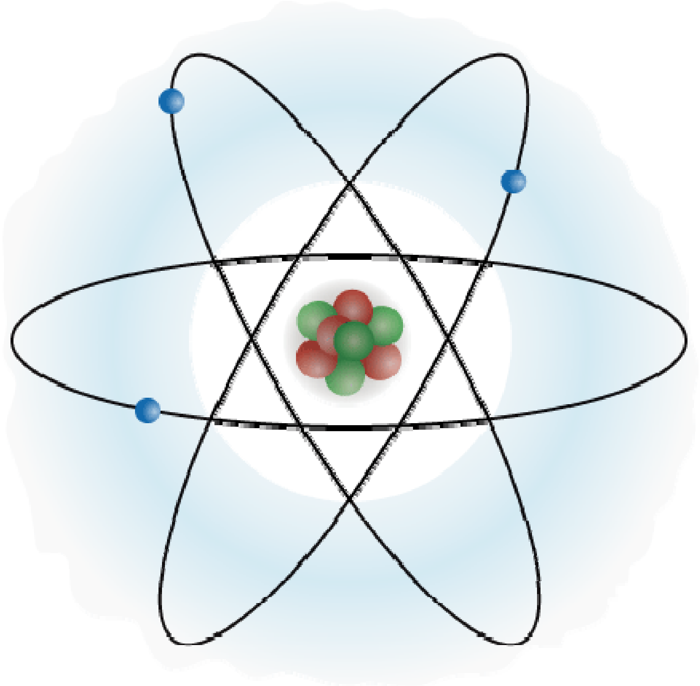
Alpha Particle Spectroscopy

- Alpha particle source – alpha decay
- Context – understanding alpha particles
- Energies
- Interactions between alpha particles and matter (scattering and energy loss)
- Semiconductor “radiation” detectors
- Surface barrier detectors
- Pulse generation (energy resolution?)
- Data acquisition – digitization and “binning” →
- Multi-channel analyzer

Brief Review of Atomic Structure

- Each atom consists of a positively charged core (the *nucleus*, contaning protons and neutrons, held together by nuclear forces) surrounded by negatively-charge shells (electrons).
- Electrons exist in specific energy levels (orbits) around the nucleus.
- Element is determined by # of protons. I.e., atoms of the same element have the same # of protons, but can differ in the number of neutrons. Atoms of the same element (same # or protons) with different # of neutrons are *isotopes*. Since # of protons identifies the element, remember that # of protons is referred to as the *atomic number* (Z).



Masses:

$m_e = 9.11 \times 10^{-31}$ kg

$m_n = 1.67 \times 10^{-27}$ kg

$m_p = 1.67 \times 10^{-27}$ kg

Brief Review of Atomic Structure (continued)

- Charges: electrons (-1*e*), protons (+1*e*), and neutrons (0).
- Magnitude of the charge on an electron = 1.602 x 10^{-19} Coulombs.
- Electrons are bound to the atom's nucleus through the Coulomb force, in which opposite charges attract ("electrostatic force").
- Ions: basically, an atom is uncharged if the # of electrons = # of protons, and if not, you've got an *ion* (a charged atom).
- Terminology for atoms, generalized to isotopes: (what is a nuclide?) A specific nuclide can be annotated as follows:

$$ {}^{A}_{P}X $$

where *A* is the atomic mass number (# of protons + # of neutrons), *P* is the # of protons, and *X* is symbol for the element. Examples:

$ {}^{1}_{1}H $ ("hydrogen-1") $ {}^{4}_{2}He $ ("helium-4")

About alpha particles

α-particles are doubly-charged helium nuclei, written as He^{++}, He^{2+}, or ${}^{4}_{2}\alpha$. An alpha particle (two protons and two neutrons) is emitted from the nucleus of an atom in a radioactive decay event. Typically, only heavy radioactive nuclides decay by alpha emission, as in the decay of Radium-226 as follows:

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$$

The alpha particle source we're using comes from a typical smoke detector, and decays according to the following reaction:

$${}^{241}_{95}Am \xrightarrow[432.2\,yrs.]{} {}^{237}_{93}Np + {}^{4}_{2}\alpha$$

where the half life of the ${}^{241}Am$ is 432.3 years. Note that radioactive decay changes the atom's mass number by four, and the atomic number by two.

About alpha particles (cont.)

Notes from Wikipedia (see Alpha particle) –

- Common smoke detectors use ^{241}Am as the source for alpha particles which ionize air between a gap, allowing a small current to flow. Smoke that enters the air gap reduces the current, triggering an alarm.
- Alpha decay can provide a safe power source for radioisotope thermoelectric generators used for space probes and artificial heart pacemakers.
- Static eliminators typically use ^{210}Po, an alpha emitter, to ionize air, allowing the 'static cling' to more rapidly dissipate.
- Efforts are underway to use the damaging nature of alpha emitting radionuclides inside the body by directing small amounts towards a tumor. Alphas damage the tumor and stop its growth while their small penetration depth prevents radiation damage of the surrounding healthy tissue. This cancer therapy is called “unsealed source radiotherapy”.

^{210}Po was used to kill Russian dissident and ex-FSB officer Alexander V. Litvinenko in 2006.

Alpha particle energies

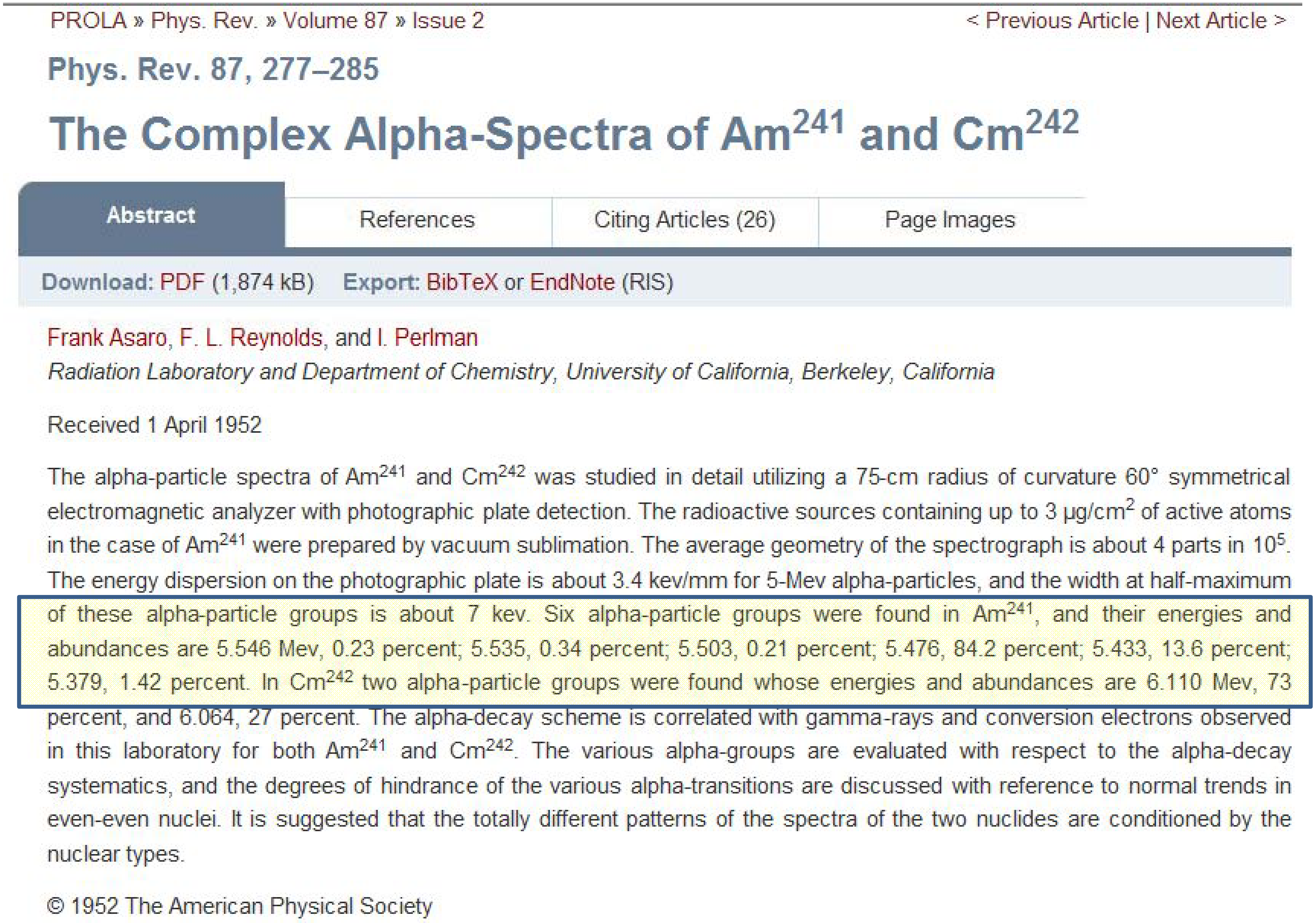
Most α-particles have energy between 3 and 7 MeV, depending on whether the emission half-life is very long or very short, respectively.

A few MeV represents a lot of energy for a single particle, but a large mass (6.6×10^{-27} kg) means that the alphas are relatively slow at c/20 (~15,000 m/s).

Very high energy particle -- compare to a green photon at $\sim 2.5 \times 10^{-6}$ MeV (2.5 eV). I.e., an alpha particle carries about a million times the energy of a green photon at ~500 nm.

Note the error in earlier version of the ^{241}Am alpha decay particle energy – correct energy is 5.476 MeV (not 5.64 MeV) – see next slide.

^{241}Am decay to neptunium (Np)



Phys. Rev. 87, 277–285

The Complex Alpha-Spectra of Am^{241} and Cm^{242}

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Received 1 April 1952

The alpha-particle spectra of Am^{241} and Cm^{242} was studied in detail utilizing a 75-cm radius of curvature 60° symmetrical electromagnetic analyzer with photographic plate detection. The radioactive sources containing up to 3 $\mu g/cm^2$ of active atoms in the case of Am^{241} were prepared by vacuum sublimation. The average geometry of the spectrograph is about 4 parts in 10^5. The energy dispersion on the photographic plate is about 3.4 kev/mm for 5-Mev alpha-particles, and the width at half-maximum of these alpha-particle groups is about 7 kev. Six alpha-particle groups were found in Am^{241}, and their energies and abundances are 5.546 Mev, 0.23 percent; 5.535, 0.34 percent; 5.503, 0.21 percent; 5.476, 84.2 percent; 5.433, 13.6 percent; 5.379, 1.42 percent. In Cm^{242} two alpha-particle groups were found whose energies and abundances are 6.110 Mev, 73 percent, and 6.064, 27 percent. The alpha-decay scheme is correlated with gamma-rays and conversion electrons observed in this laboratory for both Am^{241} and Cm^{242}. The various alpha-groups are evaluated with respect to the alpha-decay systematics, and the degrees of hindrance of the various alpha-transitions are discussed with reference to normal trends in even-even nuclei. It is suggested that the totally different patterns of the spectra of the two nuclides are conditioned by the nuclear types.

Alpha particle interactions with matter

Scattering

Alpha particles interact strongly with electrons due to their net +2e charge (charge on an electron = 1.602×10^{-19} C) – strong Coulomb interactions with atoms' electron "cloud". In general, their interactions with matter are strong due to their charge and large mass. Alphas can be absorbed by the outer layers of human skin (about 40 μm, equivalent to a few cells deep).[portion from Wikipedia]

Strong probability of electron ejection following scattering event (compare atomic or molecular ionization energy to alpha particle energy).

Based on mass considerations alone, alpha particles will experience little deflection (change in direction) when scattering with an electron. Mass ratio on the order of ~1000:1, with momentum conservation indicating a small deflection in any α - e^- scattering event.

Alpha particle interactions with matter

Energy loss

Radioactive nuclei undergoing “natural” decay emit alpha particles with energies typically in the range of 3 - 7 MeV. The β-factor (β =v/c) of these alpha particles is very small. In this case, the nonrelativistic formula for energy loss *dE* of charged particle in matter of length *dx* can be written as:

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} n_e \ln\left[\frac{m_e v^2}{\bar{I}}\right]$$

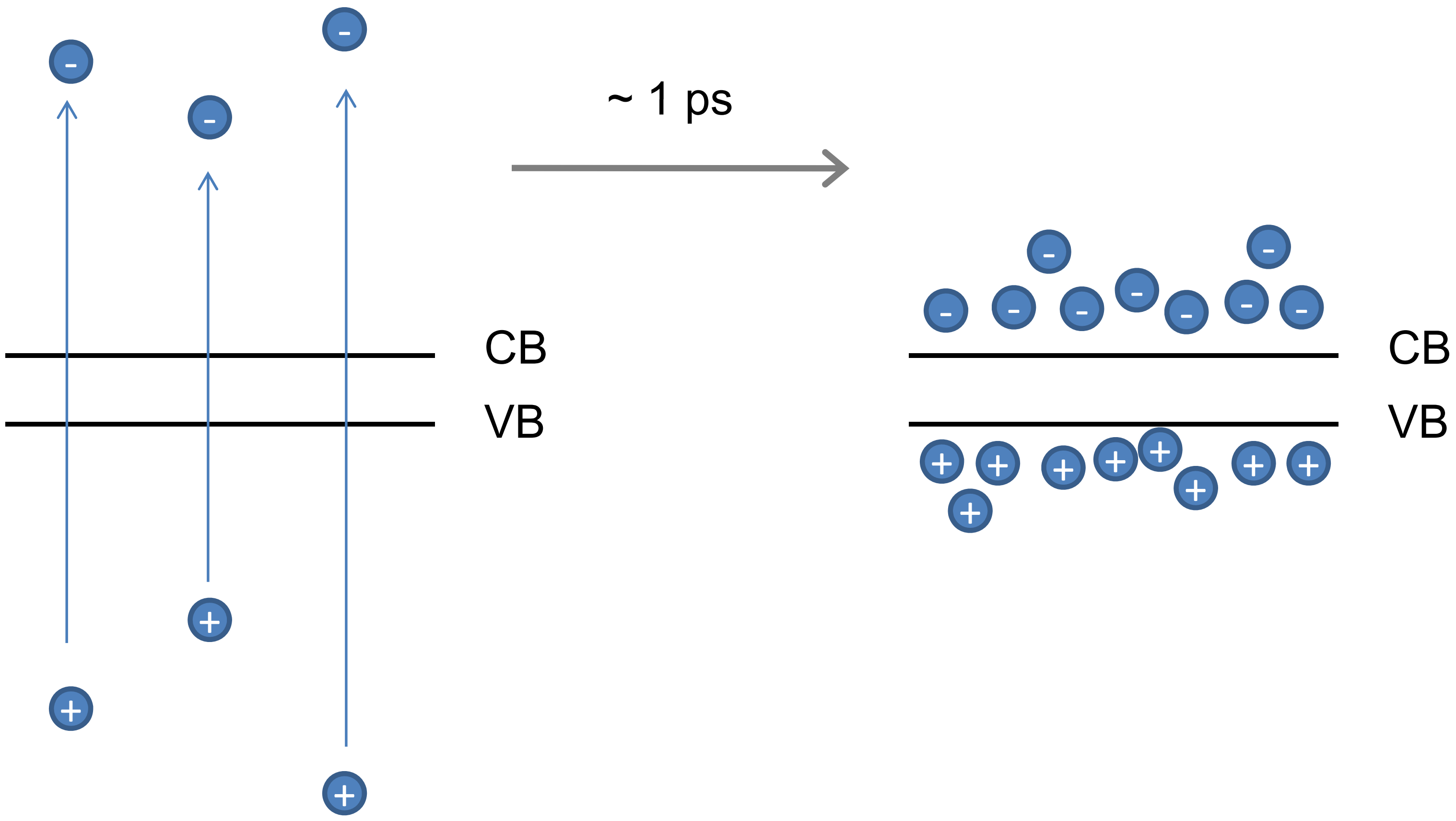
where all units are in c.g.s. system with:

z: charge of the incoming particle (in integral units of the electron charge, e);
v: velocity of the incoming particle;
n_e: electron density of the scattering material;
I: average ionization energy of the scattering material;
m_e: electron mass.

Since the numerical number inside the logarithm changes slowly, the energy loss is characterized as proportional to ($z^2 n_e$) and inversely proportional to (v^2). For a given alpha source then, the energy loss is proportional to the electron density of the scattering material n_e.

Semiconductor radiation detectors

An improvement over "crystal counters" based on a design conceptually similar to a pulse ionization chamber. Ionization yields very high-energy electrons and holes which impact ionize to generate large numbers of e^- - h^+ pairs.



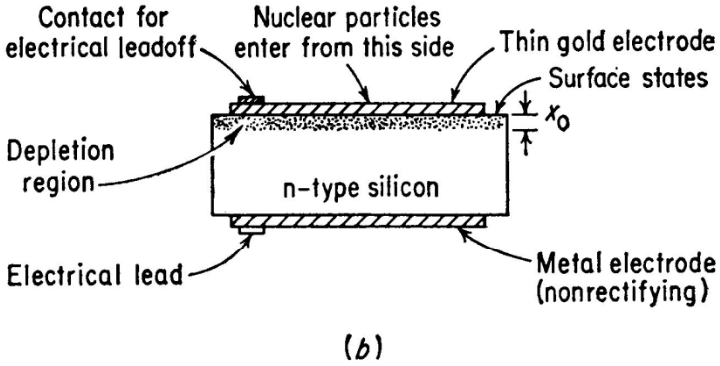
Semiconductor radiation detector – (electrical) pulse generation

The typical energy required to generate an *e*⁻ - *h*+ pair via impact ionization is ~ 3 eV.
→ A single 5 MeV alpha particle incident on a Si-based detector will generate ~ 1.7 million electrons, resulting in total collected charge of:

$$\left(1.7x10^{6}\right)\left(1.6x10^{-19}C\right)=2.7x10^{-13}C$$

A typical transit time for the charge is ~10 ns, yielding a current pulse of:

$$\frac{2.7x10^{-13}C}{10^{-8}s}\approx 25\mu A$$



Surface barrier detector (designed for efficient collection of carriers generated close to the detector surface).

Ortec 142IH preamplifier

SENSITIVITY
Nominal, measured through either output, 45 mV/MeV Si.

Assumed “either output” refers to outputs T (timing) and E (energy), and that Si indicates that a Si detector is applies to the indicated sensitivity.

We can compute the rough pulse height out of the 142IH:
5 MeV * 45 mV/MeV = 225 mV (or slightly less than 0.25 V).

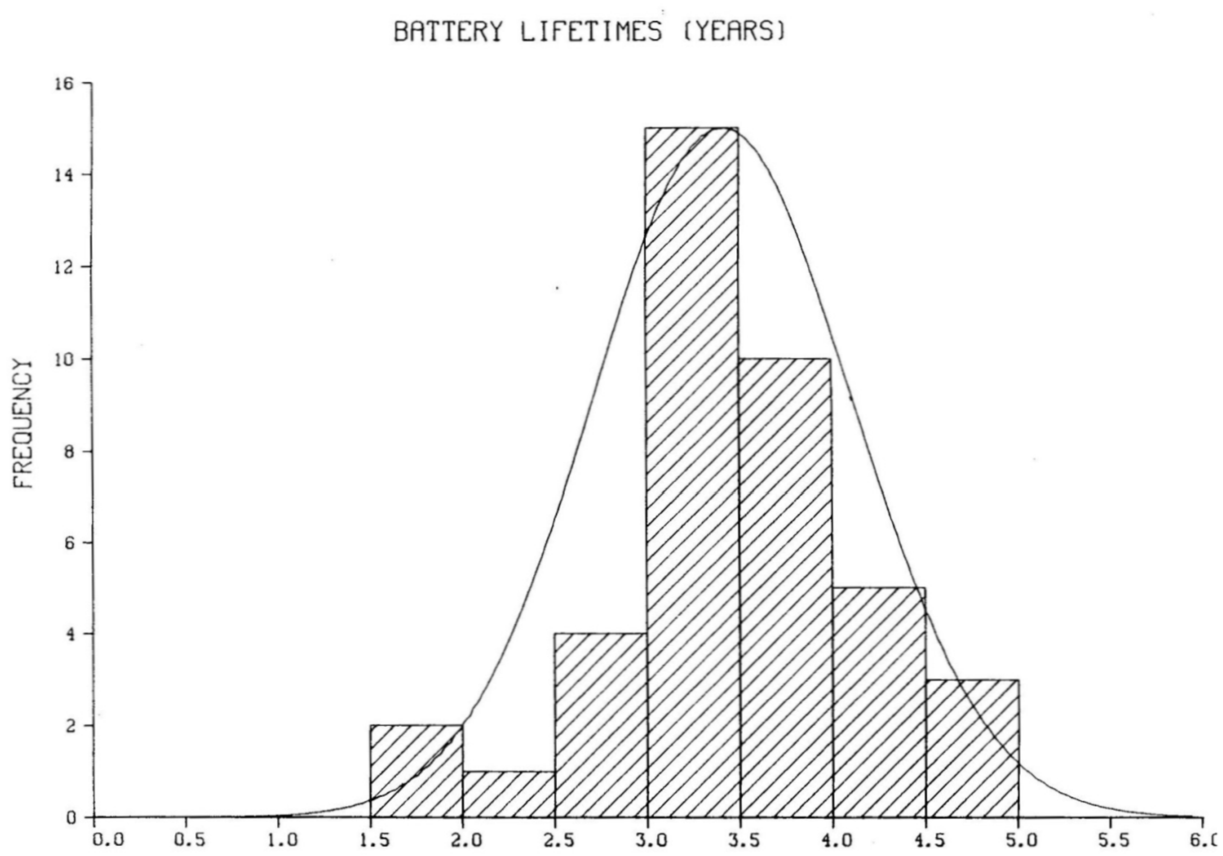
Ortec 575A amplifier

Ortec 480 Pulser

- **Simulates detector output signals**
- **May be calibrated to read directly in terms of equivalent energy deposition in semiconductor detectors**
- **Exponential pulse shape with <10-ns rise time and 200- or 400-μs decay time constant**
- **Line frequency pulse rate**
- **Positive or negative polarity**
- **Direct 0 to 10-V output**
- **Attenuated output with 1000:1 attenuation range**

The ORTEC Model 480 Pulser simulates the output signal from a solid-state or scintillation detector and provides a means of checking electronic instruments in a pulse processing system. It has 1% overall accuracy, good stability as a function of temperature and time, and front-panel controls that allow the instrument to be calibrated to read directly in terms of equivalent energy deposited in a detector. The Model 480 has a stable internal reference voltage that is effectively independent of any modular power supply or ac line voltage changes. Four toggle switches in a pi-attenuator arrangement in the attenuated

Data acquisition and the concept of “binning”



Each voltage pulse has a height proportional to the initial current pulse, which in turn is proportional to the energy of the detected alpha particle.

These digitized voltage pulses can be “binned” by placing them into set voltage ranges (bins); such a set of data then counts the number of events (pulses) which fall into each range. The data can then be displayed as a histogram.

Multichannel analysis for acquiring energy spectrum

A multi-channel analyzer (MCA) does the sorting of voltage pulses into various bins (digital voltage ranges) according to pulse height.

Detectors

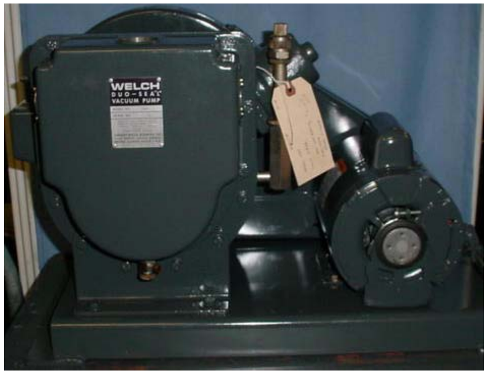
- **Surface barrier detector**: A type of junction detector, used for detections of ionizing radiation, made from a wafer of *n*-type Si which is subjected to etching and surface treatments to create a thin layer of *p*-type material; finally, a thin layer of gold is evaporated onto the detector's surface.
- **Geiger-Müller detector**: these detectors are used to detect ionizing radiation, and operate on the principle that when an ionizing particle passes through the hollow gas-filled tube, the ions produced enable conduction of electricity and generate an amplified current pulse as output. Typical output is in the form of counts per minute, and an audible click is often generated to indicate a detection event.

Geiger counter (based on Geiger-Müller tube)

Vacuum systems

- A vacuum is a volume of space essentially empty of matter, such that the pressure of the volume is considerably less than that of the surrounding atmosphere.
- A **vacuum pump** is a device that removes gas molecules from a sealed volume in order to leave behind a partial vacuum. The vacuum pump was invented in 1650 by Otto von Guericke. (Wikipedia)
- Pumps can be categorized according to three techniques (Wikipedia):
  - **Positive displacement** pumps use a mechanism to repeatedly expand a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere (e.g., roughing pump).
  - **Momentum transfer** pumps, also called **molecular pumps**, use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber (e.g., a turbo pump or diffusion pump).
  - **Entrapment** pumps capture gases in a solid or adsorbed state. This includes **cryopumps**, **getters**, and **ion pumps** (e.g., a cryo pump).

Vacuum systems



Mechanical pump

Cryo pump

Turbo pump

	pressure (Torr)*
Atmospheric pressure	760
Low vacuum	760 to 25
Medium vacuum	25 to 1×10^{-3}
High vacuum	1×10^{-3} to 1×10^{-9}
Ultra high vacuum	1×10^{-9} to 1×10^{-12}
Extremely high vacuum	$<1\times10^{-12}$
Outer Space	1×10^{-6} to $<3\times10^{-17}$
Perfect vacuum	0

* 1 Torr = 1/760 atm, which is approximately equal to 1 mm Hg.