Chapter 12 Tools of Nuclear Science

Presently, the most commonly used tools of nuclear science are accelerators (see Chapter 11), reactors, detectors, and computers. The technological development of these devices has gone hand in hand with advances in nuclear science, sometimes leading and sometimes following closely behind.

Nuclear Reactors

Nuclear reactors created not only large amounts of plutonium needed for the weapons programs, but a variety of other interesting and useful radioisotopes. They produced ^{60}Co, in which the non-conservation of parity was first discovered, and a number of transuranic isotopes that are used to study the limits of the periodic table. Reactors also produce isotopes for commercial and medical purposes:

1. ^{241}Am—used in smoke detectors,
2. ^{60}Co—used in industry to inspect weld quality, also used in cancer therapy,
3. ^{99m}Tc—used for medical diagnosis, and
4. ^{137}Cs—also used for medical therapy.

Reactor neutrons have been used for material studies that involve their scattering from the crystal planes.

Detectors

The interactions of alpha, beta, and gamma radiations with matter produce positively charged ions and electrons. Radiation detectors are devices that measure this ionization and produce an observable output. Early detectors used photographic plates to detect “tracks” left by nuclear interactions. The cloud chambers, used to discover sub-nuclear particles, needed photographic recording and a tedious measurement of tracks from the photographs. Advances in electronics, particularly the invention of the transistor, allowed the development of electronic detectors. Scintillator-type detectors use vacuum tubes to perform the initial conversion of light to electrical pulses. The amplification and storing these data follow the advances in transistor electronics. Miniaturization in electronics has revitalized types of gas-filled detectors. These detectors were developed as “single element” detectors and now have been revived into “multiple element” detectors with more than one thousand elements. Advances in materials, particularly ultra-pure materials, and methods of fabrication have been critical to the creation of new and better detectors.

As the requirements for greater accuracy, efficiency, or sensitivity increases, so does the complexity of the detector and its operation. The following list presents some types of commonly used detectors and includes comments on each of them:

Geiger Counter: The detector most common to the public is the Geiger-Mueller counter, commonly called the Geiger counter. It uses a gas-filled tube with a central wire at high voltage to collect the ionization produced by incident radiation. It can detect alpha, beta, and gamma radiation although it cannot distinguish between them. Because of this and other limitations, it is best used for demonstrations or for radiation environments where only a rough estimate of the amount of radioactivity is needed.

Scintillation detectors: Scintillators are usually solids (although liquids or gases can be used) that give off light when radiation interacts with them. The light is converted to electrical pulses that are processed by electronics and computers. Examples are sodium iodide (NaI) and bismuth germanate (BGO). These materials are used for radiation monitoring, in research, and in medical imaging equipment.

Solid state X-ray and gamma-ray detectors: Silicon and germanium detectors, cooled to temperatures slightly above that of liquid nitrogen (77 K), are used for precise measurements of X-ray and gamma-ray energies and intensities. Silicon detectors are good for X-rays up to about 20 keV in energy. Germanium detectors can be used to measure energy over the range of >10 keV to a few MeV. Such detectors have applications in environmental radiation and trace element measurements. Germanium gamma ray detectors play the central role in nuclear high-spin physics, where gamma rays are used to measure the rotation of nuclei. Large gamma-ray detection systems, such as Gammasphere and Eurogam are made of these detectors.

Low-energy charged particle detectors: Silicon detectors, normally operated at room temperature, play a major role in the detection of low-energy charged particles. Singly, they can determine the energy of incident particles. Telescopes (combinations of two or more Si detectors) can be used to determine the charge (Z) and mass (A) of the particle. This type of detector is used in environmental applications to look for alpha-particle emitters (such as radium) in the environment.

Neutron detectors: Neutrons are much harder to detect because they are not charged. They are detected by nuclear interactions that produce secondary charged particles. For example, boron trifluoride (BF_3) counters make use of the $^{10}B(n,\alpha)^{7}Li$ reaction to detect neutrons. Often one uses a moderator, such as paraffin, to slow the neutrons and thus increase the detection efficiency. These detectors are used to monitor the neutron fluxes in the vicinity of a reactor or accelerator. Liquid scintillators can measure both neutrons and gamma rays. By carefully measuring the shape of the electronic signal, scientists can and distinguish between these two types of particles.

Neutrino Detectors: Neutrinos interact very weakly with matter and are therefore very hard to detect. Thus, neutrino detectors must be very large. The Sudbury Neutrino Observatory in Canada, was developed to understand the solar neutrino problem (too few neutrinos come out of the Sun than expected) and contains an active volume of 1000 tonnes (metric tons) of deuterium oxide (heavy water). This is a Cherenkov counter in which the interaction of the neutrino with the heavy water produces an electron moving faster than the speed of light in the water. The moving electron generates a cone of light that can be observed with photomultiplier tubes. Information from these tubes provide the information to determine the energy and direction of the incident neutrino.

High-energy charged particle detectors: As the energy increases, large and even more complex detection systems are needed, some involving thousands of individual detectors. These detectors typically involve the "tracking" of large numbers of particles as they pass through the detector. Large magnets are required to bend the paths of the charged particles. Multi-wire detection systems with nearly a quarter of a million channels of electronics provide information on these tracks. High-speed computer systems process and store the data from these detectors. Similarly, powerful computer systems are needed to analyze these data so that a scientific discovery can be made.

Table 12-1. A partial list of detectors used in Nuclear Science. Some detectors can be used only in a limited energy range.

Particle Type	Detector Type	Features
Charged		
protons, nuclei, electrons, or pions	Geiger-Müller counters	portable radioactivity detector
	gas ionization counters	gas-filled chamber in an electric field
	multiwire chambers	good position resolution
	semiconductor detectors	good energy resolution
	magnetic spectrometers	good momentum resolution
	scintillators and photomultipliers	good timing resolution
	Cherenkov detectors	good particle identification
Neutral		
photons	scintillators and photomultipliers	good timing, moderate energy resolution
	germanium semiconductor crystals	good energy resolution
neutrons	liquid scintillator or BF_3 tubes	via fission, capture gamma rays, or proton collisions
neutrinos	Cherenkov detectors	via neutrino-electron interactions
	nuclear reactions	detect resultant radiation

Table 12-1 summarizes the information that is presented in this section. It shows the different types of detectors that are suitable for measuring specific particles. When an experiment is designed, first a scientist chooses a particular detector based on the particles and their properties (such as energy, position, or time) that must be measured. Some detectors, such as scintillators, can make accurate time measurements but only a fair position determination. A scientist designs an experiment using an optimum choice of detector system. Cost is a major factor in modern detector design, especially for large systems consisting of a multitude of detectors and associated electronics.

Computers

Beginning in the 1970s, computers played a role in nuclear science that developed from relatively minor to significant. Before this time, computers were used for calculations to develop and refine theories in nuclear science. As computers moved to being interfaced with detectors and accelerators, they became inseparable from the experiment. Indeed, the design of detectors for large experiments includes the integration of computer systems into each detector element. Computers are still used to calculate predictions of experiments based on various theories. Only the most powerful computer systems can generate simulations of the expected data from today's giant experiments. Similarly, only the most powerful computers can process the data that come from these experiments.

Other Sciences and Technologies

While technology has been a driving force for nuclear science research, this field has similarly pushed the limits of technology. Likewise, advances in other scientific disciplines have been important to the progress in nuclear science. Development and advances in chemistry were essential to the discovery of most of the transuranic elements. This technology is still used to separate chemical species and allows studies of nuclei produced in accelerator or reactor experiments. Advances in solid state physics have produced larger and better silicon and germanium detectors for use in x-ray, gamma ray, and particle spectroscopy. Advances in ultralow-temperature physics have produced superconducting magnets. They are used by the Michigan State University Cyclotron, by the superconducting radio frequency acceleration cavities at the Argonne National Laboratory's ATLAS accelerator, at the Jefferson Laboratory, and at the RHIC collider.