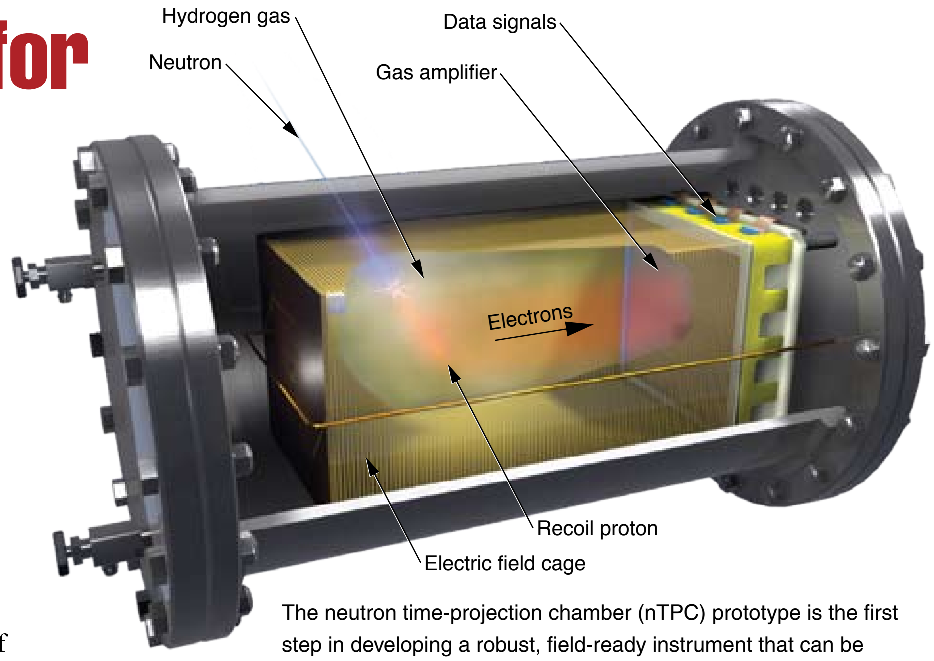
A Time Machine for Fast Neutrons



The neutron time-projection chamber (nTPC) prototype is the first step in developing a robust, field-ready instrument that can be used outside a laboratory to detect neutron sources. (Rendering by Sabrina Fletcher.)

ALTHOUGH time-projection chambers (TPCs) may sound like futuristic time machines, in reality they are unique particle detectors that could help improve national security. Developed in the 1970s, TPCs are gas-filled devices that measure charged-particle trajectories in three dimensions. The instruments are used in high-energy physics experiments to track particles after they are "smashed" together inside particle accelerators. Such interactions produce complex assortments of particles with energies typically ranging from tens of megaelectronvolts to many gigaelectronvolts. Scientists measure the energy deposited in the TPC gas to identify specific particles.

In general, TPCs are highly technical devices with easily damaged components. Until now, they have only been used in laboratories by trained scientists. In collaboration with other research institutions, the Laboratory is developing a neutron TPC (nTPC) that will function in a much different environment to specifically detect neutrons. According to Mike Heffner, a Laboratory physicist who leads the nTPC development team, "We are creating a robust, field-ready nTPC that can be used by nonexperts to locate fissile materials in nonproliferation and nuclear counterterrorism efforts."

The machine is designed to detect fast neutrons—those with an average energy of 2 megaelectronvolts. These particles are naturally emitted by cosmic ray interactions and through the decay of fissile material. Using nTPC, authorized personnel could detect the presence of neutrons emitted from a radioactive source within minutes. In addition, the nTPC prototype can indicate the direction of a neutron source from up to 20 meters away.

Particles on the Move

The nTPC prototype contains hydrogen gas, a lightweight medium that interacts with fast neutrons. When a fast neutron enters the gas, it has a high probability of colliding with a hydrogen atom, which consists of one proton bound to an electron. Similar to the way billiard balls ricochet off the cue ball in a game of pool, the collision causes the proton to recoil away at an angle as the neutron knocks it away from its electron in a process known as elastic scattering.

In the collision, the neutron loses energy and typically leaves the gas unit without inducing further elastic scattering. However, as the newly liberated proton travels along its path, it ionizes the gas, separating the protons and electrons of other hydrogen atoms. This process creates an ionization track as the proton moves through the medium. Every time the recoiling proton ionizes a hydrogen atom, the proton loses energy. Thus, the ionization is proportional to the energy loss of the proton. "After tens of thousands of atoms have been stripped of their electrons, the proton no longer has enough energy to ionize the gas," says Heffner. The nTPC detects the electrons from the ionization track to determine the proton's trajectory and ionization energy loss. This data is then used to help determine the incoming neutron's trajectory and energy.

An external "cage" surrounding the gas produces a uniform electric field that forces the electrons to drift toward the ground end of the detector, where an amplification structure is located. The amplification structure consists of a grid of anode wires positioned orthogonally to charge-sensitive copper strips. This grid is used to record the amplified electric charges and provide a two-dimensional (2D) set of coordinates for each cluster of electrons. The amplified electric charge is proportional to the energy produced in the initial ionization event. Amplification is necessary because the electron signal produced in the primary ionization event is not strong enough to be detected amidst the inherent noise of the system.

In the nTPC prototype, an electron's velocity is approximately one centimeter per microsecond as it drifts toward the grid. Because the drift speed remains constant, researchers can accurately determine the distance the electrons travel before being recorded by the amplification structure. Thus, time projection chambers get their name from the fact that time is used to project back to where the initial ionization event occurred.

Computers are needed to translate the complex data generated into a 3D representation of each ionization track. "We use compression algorithms to manage the volume," says Heffner. "Depending on the strength of the neutron source and its location, we can estimate the direction of the neutron source within minutes."

"Pointing" to the Source

Kinematics—how particles move through an environment—plays a critical role in determining the direction of a neutron source. The nTPC researchers are particularly interested in the kinematics of the neutron–proton collision. When the neutron hits the hydrogen atom, the proton is knocked out at an angle. "We have no control over how the neutron will hit the proton, so the proton could be knocked out at almost any angle forward of the incoming neutron direction," says Heffner.

For each collision, the nTPC's fast electronics record a set of data, including the proton's angle. Computers transform the data into a histogram, where the x axis represents the angle and the y axis indicates how many collisions have occurred for each angle. Using the histogram, the team can average all of the recorded angles to identify the source's direction. "The greater the number of collisions we record, the more accurately we can detect the direction of the neutron source," says Heffner. "However, just ten neutrons are enough to reduce the directional uncertainty to a 16-degree cone."

From the Lab to the Field

To test the nTPC prototype, Livermore researchers exposed the detector to a californium-252 source equivalent in neutron output to approximately 6 kilograms of weapons-grade plutonium. Inside a laboratory, the team first ran nTPC with the californium source stored in a shielded container to assess the amount of background radiation being generated from neutrons naturally occurring in the environment. The californium-252 source was then removed from the container and placed in various locations several meters from the nTPC. "We detected neutrons from the radioactive source 10 and 20 meters away," says Heffner.

The nTPC has three main advantages. First, the machine provides fast proximity searching because it can "point" in the direction of the sources. Second, it provides improved suppression of background radiation from sources such as cosmic rays and those naturally given off by the decay of isotopes in the environment. Third, nTPC can track multiple neutron sources in the same area.

With innovation and ingenuity, Heffner and his team have found a way to adapt a well-known technology used in high-energy physics experiments to a device for detecting fissile materials. "The prototype nTPC is the initial step in developing a robust, field-ready instrument that can be used outside a laboratory," says Heffner. It may not be a fancy time machine, but nTPC is proving to be a potentially valuable tool for protecting our national security.

—Caryn Meissner

Key Words: detector, fissile material, high-energy physics, ionization track, kinematics, neutron time-projection chamber (nTPC), radioactive source.

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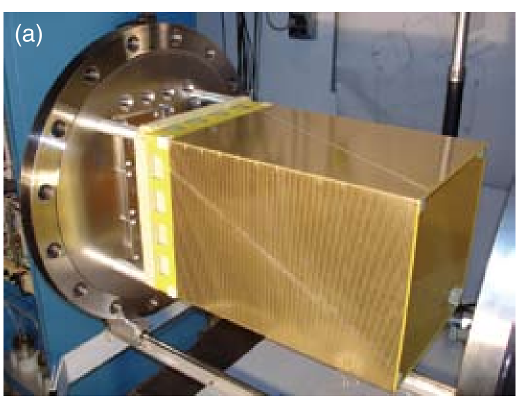

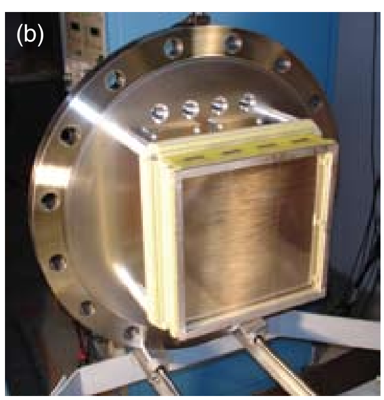

(a) The neutron time-projection chamber contains hydrogen gas, which is surrounded by a "cage" that produces a uniform electric field to pull electrons toward the ground end of the machine. (b) A structure at the ground end of the chamber amplifies the electric charge. The amplification structure consists of a grid of anode wires positioned orthogonally to charge-sensitive copper strips. This grid is used to record the amplified electric signals and provide a two-dimensional set of coordinates for each cluster of electrons.