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ASSOCIATED-PARTICLE SEALED-TUBE NEUTRON PROBE

FOR NONINTRUSIVE INSPECTION

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ASSOCIATED-PARTICLE SEALED-TUBE NEUTRON PROBE FOR NONINTRUSIVE INSPECTION*

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The development and investigation of a small associated-particle sealed-tube neutron generator (APSTNG) show potential to allow the associated-particle method to be moved out of the laboratory into field applications. Alpha particles associated with 14-MeV neutrons generated from the D-T reaction travel in the opposite direction and are detected inside the sealed tube. Gamma-ray spectra of resulting neutron reactions in the inspected volume encompassed by the alpha-detector solid angle identify many nuclides. Flight-times determined from detection times of the gamma-rays and alpha-particles not only separate the prompt and delayed gamma-rays but can also yield a separate coarse tomographic image of each identified nuclide, from a single orientation without collimation. A continuous ion beam allows data acquisition by relatively low-bandwidth commercial electronics. This efficient collection of maximum information from each detected neutron by the associated-particle method can allow a much lower source intensity than pulsed accelerator methods, provided a sufficient usable signal rate is obtained. When this method is coupled with a compact sealed-tube neutron generator, a relatively small, inexpensive, reliable, and easily maintainable inspection system can be developed, that is rugged enough to be transportable. Proof-of-concept laboratory experiments have been performed for simulated explosives, drugs, special nuclear materials, and chemical warfare agents. Based on lessons learned with the present APSTNG system, an advanced APSTNG system is being designed and built that will be transportable, yield a substantial neutron output increase, and provide a substantially improved target lifetime.

INTRODUCTION

A recently developed neutron diagnostic probe has potential for a range of van-mobile and fixed-portal applications for NDA (nondestructive analysis). The inspected volume is irradiated by neutrons from a small continuous-beam accelerator. The associated-particle method with flight-time correlation is used to separate the gamma-ray spectra resulting from neutron capture and inelastic scattering in the inspected volume and to provide coarse depth discrimination of the neutron reactions. A position-sensitive associated-particle detector can yield a coarse 3D distribution of materials. The development of a small reliable associated-particle sealed-tube neutron generator (APSTNG) based on the D-T reaction, that provides ion-beam focusing and an interior alpha-particle detector, promises to allow deployment of a fieldable NDA system.

Investigations of applications for verification of chemical and nuclear weapons (1), detection of explosives and drugs (1,2), and extension to large interrogation volumes (2,3) are covered in previous publications. Most recently, application studies have been conducted for detection of cocaine in propane tanks, monitoring for smuggled plutonium and uranium, and characterization of radioactive and toxic waste (4). Land-mine detection is another possible application. A new advanced APSTNG (along with improved high voltage supply and control unit) has been designed and is being constructed. This paper is a review of ANL investigations of this technology.

APSTNG PRINCIPLES OF OPERATION

The neutron diagnostic probe used by Argonne was developed primarily by Nuclear Diagnostic Systems (NDS) (5). Similar associated-particle systems have been developed by others (6,7). The probe operation can be understood from Fig. 1, which sketches a "general purpose" APSTNG system. Deuterons are shown accelerated into a tritium target, producing 14-MeV neutrons isotropically. Each neutron is accompanied by an associated alpha-particle travelling in the opposite direction (in center-of-mass coordinates). The gamma-ray and neutron detectors are time-gated by pulses from the alpha detector, forming a cone of flight-time-correlated neutrons through the object.

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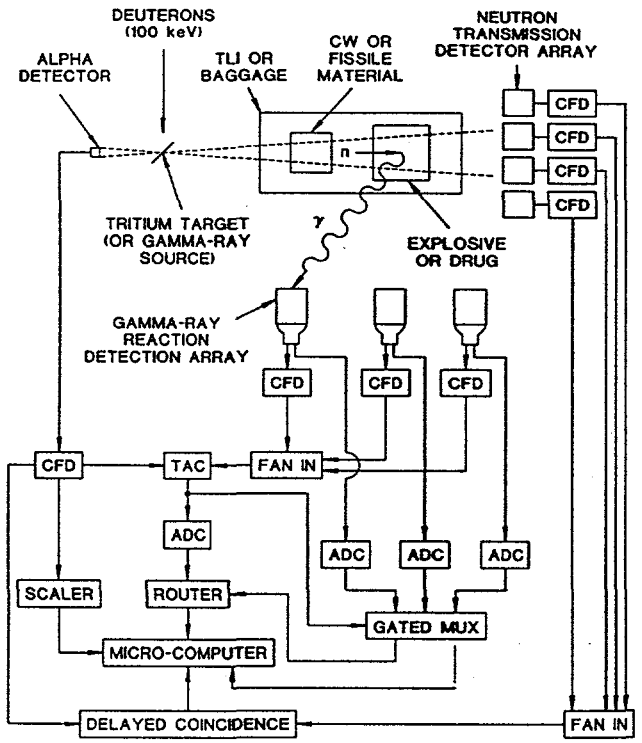

FIGURE 1. Schematic layout of "general purpose" APSTNG-based interrogation system, with EGRIS and FNTI modes.

Detector pulses are time-resolved by CFD's (constant-fraction discriminators). Flight times are determined by a TAC (time-to-amplitude converter), digitized by an ADC (analog-to-digital converter), and recorded. (In the actual NDS APSTNG accelerator, a Penning ion source emits a continuous mixed beam of deuterium and tritium ions that is accelerated and focused on a spot ~ 1 mm in diameter on the target, tritiating the target; the small spot is necessary for spatial resolution.) A single specially configured gamma-ray detector is employed in the current ANL APSTNG system. A NaI(Tl) crystal 10.16 cm × 10.16 cm in cross section and 40.64 cm long is coupled to two fast photo-multipliers, one at each end. Improvements in time and energy resolution are obtained by combining the timing and energy data from the two ends, while the large detector provides relatively high efficiency for the high-energy gamma rays.

When a reaction occurs in the object along the cone that results in a detected gamma-ray, the time-delay from the alpha pulse yields the position (depth) along the cone where the reaction occurred, since the source neutron and gamma-ray speeds are known (5 cm/ns and 30 cm/ns, respectively). By using a 2D position-sensitive multipixel alpha detector, transverse and depth coordinates of reaction locations can be mapped, providing coarse 3D emission imaging of reaction densities from measurements at a single orientation. (The present NDS system uses a PM tube to detect alpha scintillations, but can provide 3D imaging in the laboratory by restricting the alpha window view field and scanning the interrogated object transversely.) Depth resolution along the cone axis is limited by the ~ 1 ns time resolution of the flight-time electronics and detector signal pick-off to no better than ~ 5 cm. In applications requiring coarse imaging (materials distributions), systems would include a 2D alpha detector, as well as an array of gamma-ray detectors, so as to maximize information obtained from each interacting neutron and sufficiently minimize measurement time. The PC calculates positions and displays data and images.

DETECTION MODES

Fast-neutron inelastic scattering reactions in the object provide prompt gamma-ray spectra that can identify many nuclides. By choosing gamma lines of specific nuclides, a coarse 3D image of each identifiable nuclide in the time-correlated spectrum can be mapped. By choosing appropriate nuclide intensity ratios, coarse 3D images of compounds can be made (molecular bonds are not identified). The use of the time-correlated gamma-ray spectra is denoted the EGRIS (emissive gamma-ray imaging and spectroscopy) mode. If fissionable materials are present, neutron detectors may be used to detect emitted fission neutrons in the ENIS (emissive neutron imaging and spectroscopy) mode. Nearly all nuclides with atomic number above boron have distinctive gamma-ray spectra for the EGRIS mode, with reaction cross sections of ~ 0.5 barn for 14-MeV neutrons (predominantly inelastic scattering).

For gamma-rays above ~ 1 MeV, background is greatly reduced since background counts can only be accumulated during the nanosecond-range correlation interval. Because neutrons are emitted isotropically, the source and emission detection systems can be located arbitrarily, and can be on the same side of the interrogated object when access is restricted. Regions behind walls, under floors or roadbeds, or above ceilings could be inspected nonintrusively. The high-energy neutrons and gamma-rays will penetrate large objects and dense materials. The EGRIS mode is generally the primary detection mode.

Shown in Figs. 2 and 3 are EGRIS mode spectra obtained for an explosive and a drug simulant. Conventional explosives are identified by high proportions of nitrogen and oxygen and high density (although the APSTNG system is not limited to detection of conventional explosives). Narcotic drugs are identified by high carbon content and low oxygen content, and for cocaine HCl by chlorine (the spectral lines below carbon in energy in Fig. 3). The ability to measure concentrations of a range of elements yields strong discrimination against false positives and negatives and provides multipurpose detection capability.

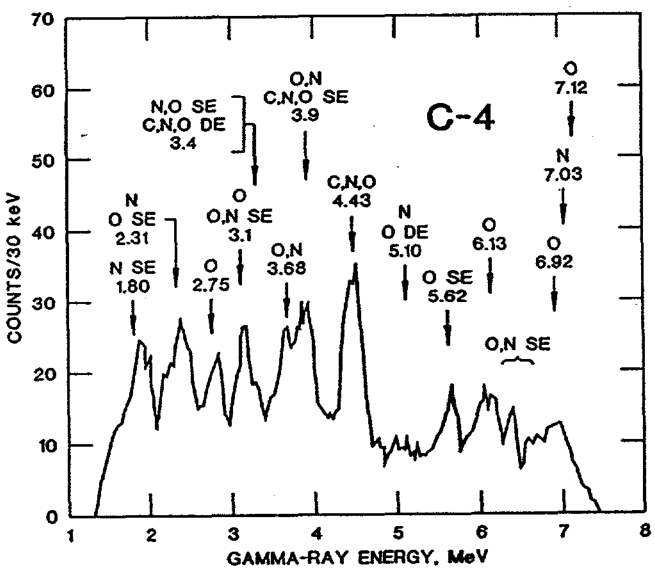

FIGURE 2. EGRIS gamma-ray spectrum of C-4 explosive.

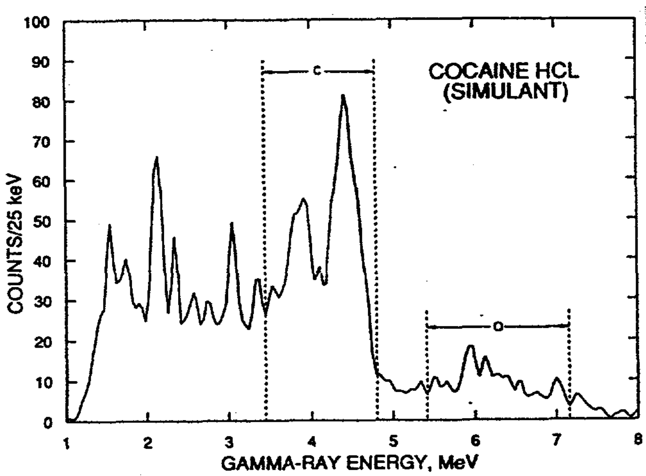

FIGURE 3. EGRIS gamma-ray spectrum of cocaine HCl simulant.

Slow-neutron capture is not time-correlated with the alpha pulses, but provides nonimaging gamma-ray spectra that can aid nuclide identification. Use of non-correlated gamma-ray spectra with the neutron generator on is termed the CGRS (capture gamma-ray spectroscopy) mode. CGRS data can be collected simultaneously with EGRIS data by using a multi-channel analyzer board inside the PC. The thermal neutron capture cross section is small for most nuclides, but is large for nuclides of interest in some applications. The gamma-ray spectra are generally more complex than for EGRIS mode, with much more background. Neutron moderator material may need to be placed between the APSTNG and the interrogated object to get sufficient intensity.

Another detection mode of use is the PGRS (passive gamma-ray spectroscopy) mode, for which the neutron generator is turned off, allowing detection of gamma-ray radioactivity present in the interrogated object and in its vicinity by the sensitive large detector volume, including any activity induced in the object by the neutrons as well as uncorrelated background. Because cross sections for inducing activity with a finite half-life (several seconds or more) are usually very small, the PGRS mode is generally used only when gamma-ray radioactivity is known to be present (as for radioactive waste or nuclear weapons).

As shown in Fig. 1, by discarding detected neutrons not having the proper flight time to be uncollided, one can perform fast-neutron 2D transmission imaging without a collimator (by scanning, using a neutron detector hodoscope array, or using 2D neutron detectors), since scattered neutrons are removed by "electronic collimation". This is called the FNTI (fast-neutron transmission imaging) mode. By measuring at a sufficient number of views around 180 degrees, 3D tomography with relatively coarse spatial resolution is feasible. Transmission imaging (FNTI) can be done along with or instead of emissive reaction-density imaging (EGRIS). No spectral distinction between nuclides is provided, but the neutron attenuation coefficient is mapped over the interrogated object. The FNTI mode is currently used to map and position the neutron correlation cone, and may find use for neutron attenuation corrections or for inspecting extended or highly absorbing objects (2,3).

ADVANCED APSTNG SYSTEM

In order to meet field criteria for a number of important applications, it is necessary to develop an APSTNG system of more advanced design. Although the NDS neutron tube proved to be reliable in the laboratory, time critical applications demand higher neutron output and longer life in terms of integrated neutron output, and field use requires more rugged construction, particularly a rugged accelerator head and HV coupling. ANL is collaborating with MF Physics on a new higher-output longer-life sealed-tube neutron generator and an improved control unit with HV supply, designed to be rugged and transportable and making good use of lessons learned with the NDS APSTNG system. These components will interface directly with the existing ANL single-pixel single-detector system.

MF Physics is designing and building the basic sealed tube to be a welded metal-ceramic unit that can withstand mechanical vibrations and shocks during transportation. A drawing of this new APSTNG tube is shown in Fig. 4, where cutaways reveal the alpha window and beam forming lens configurations. The tube is being outfitted with two getters of an advanced design, with one acting as a backup for the other.

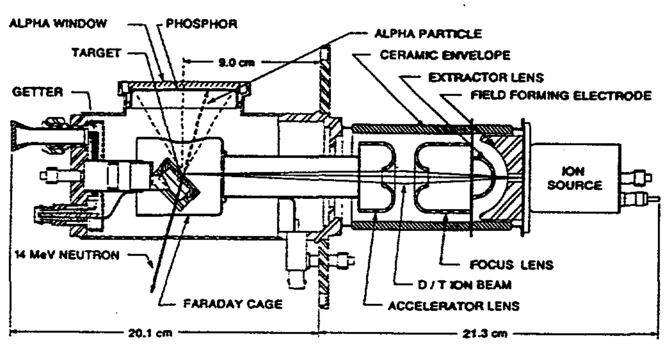

FIGURE 4. Cut-away design drawing of new advanced APSTNG constructed by MF Physics.

MF Physics will warranty the unit to provide a neutron output of at least 10^8 n/s without any target or ion source cooling, for a summed total operating time of at least 800 hours, and a maximum output of at least 10^9 n/s with externally supplied target water cooling. The maximum continuous output rate with no cooling is ~ 10 times that for the NDS APSTNG tube, and the number of neutrons generated during the expected lifetime is ~ 40 times that expected for an NDS APSTNG tube. More than an 8000-hour lifetime at the 10^7 /s output rate needed for many applications is expected. (Also, a spare tube can be kept on hand for immediate replacement, if desired.)

For the planned alpha window solid angle, alpha count rates could reach ~ 7×10^6 per second at 10^8 n/s, so that the alpha window scintillator should have an effective mean light decay on the order of 50 ns or less, with no significant long-persistence light tails. The alpha scintillator rise time should be in the subnanosecond range, in order to maximize flight-time resolution. Therefore the ZnS(Ag) used by NDS has been replaced by ZnO(Ga) as the alpha scintillator.

The HV coupling unit for the new neutron tube will mate to the flange welded onto the accelerator tube shown in Fig. 4, such that the coupling housing is the load bearing surface in a rigid mount. O-rings will seal in pressurized SF_6 insulating gas. The new HV supply and accelerator control system will protect the APSTNG neutron tube against voltage and current surges with limiting circuitry. The design of the new control unit and state-of-the-art HV supplies, with a separate supply for each voltage terminal, is unlikely to malfunction.

The new APSTNG should provide sufficient signal rate and target lifetime that the primary limitation will be accidental counts, which is fundamental to the method and is expected to become a significant problem for inspection volumes on the order of a cubic meter or so. For inspection of items from the size of suitcases to aircraft cargo containers, the new APSTNG can provide significant advantages over pulsed accelerator techniques. The continuous ion beam and time correlation provides significantly higher signal rates for a given neutron source strength and substantially higher signal-to-background ratios, and allows data acquisition by relatively low-bandwidth electronics. The ability to provide coarse 3D material distributions without collimation allows a further substantial reduction in neutron source strength needed for sufficient discrimination against false positives and negatives, leading to the possibility of a significantly smaller and lower cost NDA system, with better reliability and maintainability.

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