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# Understanding the physics limitations of PFNA – the nanosecond pulsed fast neutron analysis

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A paper in memory of Zdzislaw Peter Sawa

**Abstract**

The PFNA was conceived by Sawa, Gozani and Ryge, in late 1987 as a means to achieve the highest possible sensitivity for detecting small amounts of explosives concealed in luggage. This could be attained because 1) all the elements present in explosives, i.e., O,N,C (and H, indirectly) can be measured via the (n,n'γ) process with fast neutrons, 2) using nanosecond pulses of neutrons and the time-of-flight (TOF) technique, a full direct imaging of the elements and hence all present materials can be obtained, and 3) the TOF assures the best signal to background ratio, as the signal-stimulated γ-rays are measured before the background – neutron interacting in the detector environment – arrives. The PFNA technology has made great strides since the autumn of 1987. It enables the detection of narcotics, explosives, many hazardous materials and most dutiable goods carried in trucks and containers.

## 1. Prologue

The two sessions on the scientific aspects of contraband detection and this paper in particular were initiated as a eulogy for Dr. Z. Peter Sawa who died on June 26, 1993, at age 70, following a long battle with cancer. Peter was born in Poland and was 16 years old when the second World War started. He suffered immensely during the war, spending most of the time in concentration camps as a member of the Polish resistance movement, sometimes escaping death by shear luck, including his final brush with death at Bergen-Belzen where he was considered dead until the British liberators discovered that he was breathing and rescued him from the dead and dying. Peter's personal war story has been recorded for the U.S. Holocaust Museum. He was sent to Sweden to recuperate – a process that took more than four years. He used the time to teach himself a new language (Swedish) and develop his life-long love for learning and, above all, love of physics. All his undergraduate and graduate studies were accomplished at the University of Stockholm with BS in 1958, MS 1962 and PhD in 1973, while at the same time working as a teacher. He worked about a dozen years at the Nobel Research Institute of Physics and published 23 high quality papers. In the late seventies, he moved to the USA and worked as a scientist at a nuclear utility and in industry in accelerator and radiation physics applications. Since 1987 until his death, Peter was associated with SAIC and worked closely with the Santa Clara group and me. These were among the most fruitful years of his life. Though he soon started his long and heroic battle with cancer, unbeknown to us, a number of patents and disclo-

Peter Sawa (in the middle) with (Peter Ryge on the right and the author on the left) during a dicussion on the application of cyclotrons to PFNA (March 1991).

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sures followed in the area of TNA, FNA, and PFNA. The last one is probably the most important, and we hope will have the most lasting contribution. The story of PFNA was very important for all of us, but had a special meaning for Peter. It allowed him to extend his "borrowed time," as he used to say, to find the inner power to fly to Denton two years ago and present a paper on that topic. The following paper, discussing the limits imposed by the physics on the PFNA technology, is dedicated to the memory of Peter.

## 2. Introduction

The genesis of the nanosecond pulsed fast neutron analysis (PFNA) [1] is rooted in the FNA (fast neutron analysis) technique. The FNA [2] was conceived in 1986 as a possible improvement to the TNA (thermal neutron analyses) for explosive detection. Whereas the TNA is based on the thermal neutron capture of principally one element – nitrogen – the FNA is based on the characteristic $\gamma$-rays stimulated by the (n,n'$\gamma$) inelastic interaction of fast (typically 14 MeV) neutrons, with the three key elements in explosives (and drugs): oxygen, carbon and nitrogen. The fourth element, hydrogen, can still be inferred from the capture of the thermalized neutrons. The ability to distinguish between explosives and benign materials, it was argued, must be far better when all or most of the elements are measured, rather than a single one, important as it is. Indeed FNA has shown some promise [3] but it suffers from a high inherent background. This stems from the interactions of the scattered fast neutrons with the $\gamma$-ray detector materials. It is impossible in practice to shield the detectors from these neutrons without sacrificing detection efficiency. In the fall of 1987, the late Dr. Z. Peter Sawa suggested the idea of separating the interrogating neutrons from the stimulated gamma rays by time, since the fast neutrons are slower (3.9 and 5.2 cm/ns for 8 and 14 MeV neutrons, respectively) by about a factor of 7, than the speed of light (30 cm/ns). This requires first, that the neutrons be mono-energetic to prevent the faster neutrons from reaching the detector and interfering with the $\gamma$-rays stimulated by the slower source neutrons. Secondly, and most importantly, the neutrons must be bunched in narrow pulses compared to the flight time across the inspected object, so that the entire stimulated $\gamma$-rays arrive at the detector before the front of the neutron pulse does. The flight time across the object is of the order of 20 and 60 ns for a suitcase and truck respectively, for 8 MeV neutrons. In further discussions between the author and Sawa, it was suggested that the neutron pulse be narrowed as much as is practical and to use the time of flight (TOF) method to determine where the mono-energetic neutron pulse interacts. The neutron beam is limited, by collimation, in the plane perpendicular to the object movement and thus defines a pixel. The point, or rather the segment, of interaction defines together with the pixel the interrogated volume or voxel. The gamma spectroscopy, which is performed within each time channel (hence voxel) provides information on the elemental composition, and by inference, identifies the materials present there. With the help of Ryge, further refinements, which took account of data acquisition issues, were introduced leading to the practical PFNA concept of late 1988 and a patent filing in January 1990 [4].

PFNA makes the best of two well-tested techniques of nuclear physics: in-beam gamma-ray spectroscopy and neutron TOF. It provides directly a three-dimensional map (image) of all the elements that have a significant production of distinguishable and unique $\gamma$-rays. The quality of the spectrum is usually very high because of the time separation between the signal and major sources of background. The smallest size of the image voxel – defining the best spatial resolution – is determined by the size of the collimator opening (defining the pixel) and the neutron pulse width combined with the detection timing uncertainties. The former can be made arbitrarily small by closing the collimator but at the high price of throwing away most of the neutrons. The narrowest neutron pulses – several hundred picoseconds (equivalent to $\approx 2$ cm voxel thickness) – have been obtained but at a heavy toll in beam intensity. Voxels as small as $5 \times 5 \times 5$ cm$^3$ were used in luggage inspection experiments. Larger voxels are normally used when inspecting larger containers.

The PFNA has been studied for detecting small amounts of explosives [5], drugs [6], hazardous and nuclear materials [7], and other cargo materials of interest to customs authorities in various countries.

## 3. Attributes and limits

The PFNA is a very flexible technique and its range of applications is very wide. A thorough understanding of the PFNA principles, discussed in previous papers, and the theoretical and practical constraints they impose on the technique effect a far more efficient use of the technique.

The factors that limit the applications of the PFNA, though well understood, are many and varied as is true for any technique which solves a very complex problem. They range from nuclear physics and neutron and photon transport in bulk media to charged particle accelerators, electronics and data processing issues.

## 4. Key attributes

In this section we will catalogue the physics-related issues and briefly discuss the most important ones. The three key attributes of an effective non-intrusive inspection are:

1) Penetrability – how the thickness of the object affects performance.

2) Sensitivity – the signal magnitude and its statistical significance ($S/N$ – signal to noise ratio).

3) Specificity – the ability to distinguish material of interest from background materials.

To be successful all three attributes should have high values. These features are obviously inter-related, and depend on the various nuclear processes and instrumentation used. Penetrability is affected by a) total neutron interaction cross sections and their angular dependence for all the elements present, b) neutron energy loss per elastic or inelastic interaction, and c) absorption and scattering cross-sections for photons in all elements present. Sensitivity is affected by a) the penetrability, b) production cross-sections and their angular dependence, for the desirable elemental signatures (in the cases of explosives and drugs, they are 4.4 MeV, 6.1 MeV, and 5.1 and 2.3 MeV for C, O, and N, respectively, other signatures exist for other materials), c) type and size of gamma-ray detectors and, d)

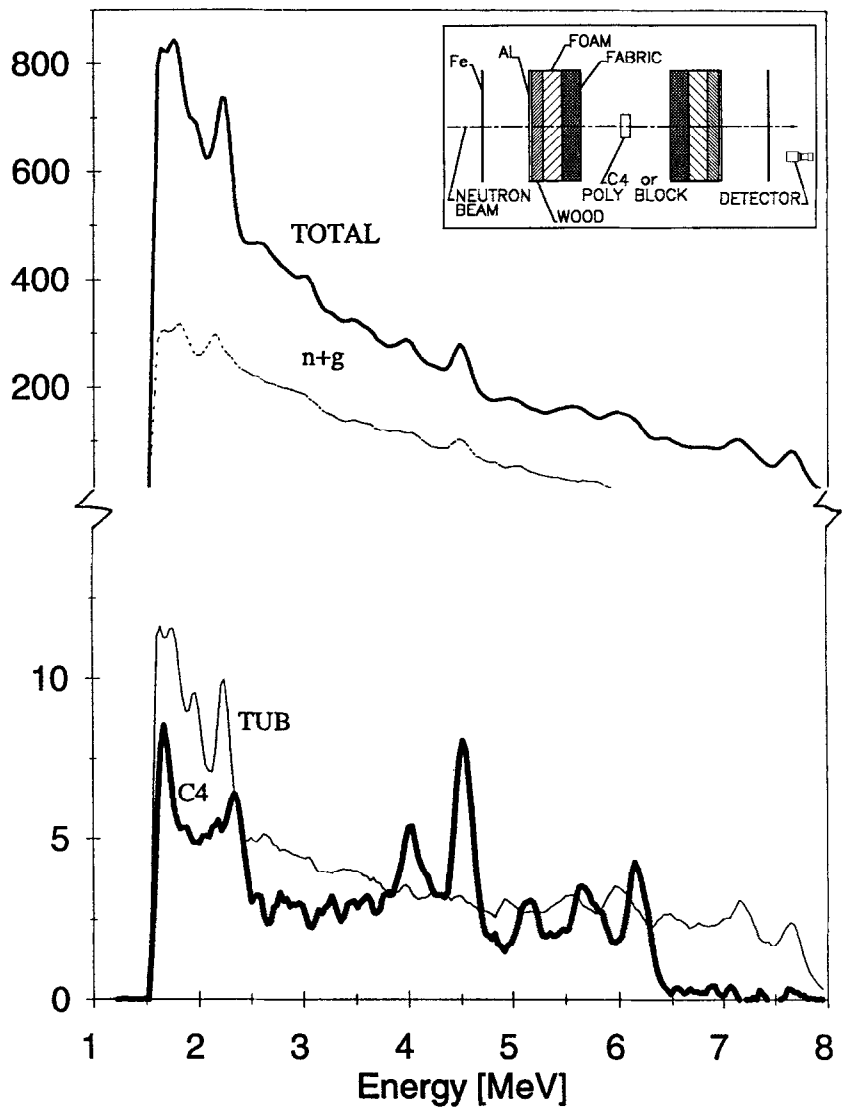


Fig. 1. Signals and backgrounds in FNA and PFNA techniques. The figure shows the pulse height distribution (PHD) measured by the NaI detector located off the pulsed beam traversing a symmetrical object made of metal sheets, wood, fabric with explosives at the center (see inset). The "total" spectrum is time integrated PHD which is equivalent to the FNA [2] signal. The "n + g" spectrum is the result of neutrons interacting inside the detector and the $\gamma$-rays originating in and around the target (e.g., in the collimator), and it constitutes the time dependent background. The TUB (time uncorrelated spectrum) is the measured spectrum due to capture of thermalized neutrons in and around the object. One can discern the Fe $\gamma$-lines at 7.6 MeV, Ca at 6.4 MeV, and the very strong line from H (2.2 MeV). Finally the spectrum taken in the time interval corresponding to the position of the explosive C4, minus the TUB, shows clearly the strong O and C lines and the weaker line from N.

γ-ray energy spectra and production cross-sections in the background elements (e.g., Fe, Al, Ca, etc). Specificity is affected by a) the sensitivity, b) spatial resolution which in turn depends on the time resolution, (accelerator pulse shape and width, and detector time resolution), neutron beam collimation and neutron scattering, and c) detector energy resolution.

The data on various cross-sections and their angular distributions were studied and, when found wanting, were measured and corrected [8]. The various cross-sections and aspects of the detectors were all incorporated in various modeling tools. These range from the general purpose, but slow MCNP code to PFNASIM [9] a specialized end-to-end simulator of the PFNA technology. These tools are then employed to calculate the various deleterious effects, determine estimated system performance and also suggest methods and algorithms to extend the validity of the technique.

## 5. Deleterious effects and sources of background

The various deleterious effects and sources of background are:

1) Neutron attenuation which a) reduces the desired signal and b) distorts the compositional information as a result of the neutron energy degradation.

2) Neutron scattering which effectively increases the inspected voxel size, reduces the density of the elements of interest, and makes it difficult to distinguish it from the prevailing surrounding materials.

3) The finite time-of-flight of the γ-rays, which is different for different detector positions because of the different voxel–detector distances. This effect is however eliminated by building in proper correction for each detector–voxel distance.

The sources of backgrounds as seen by the γ-ray detectors are:

1) Time correlated effects resulting from: a) Compton scattering in the inspected objects and the detectors, b) spectroscopical interference from closely spaced γ-ray lines and high energy "continuum" which is relatively strong in Fe and higher $Z$ elements, and c) neutron induced γ-rays in the detectors.

2) Time uncorrelated background (TUB) which is mainly the result of the capture of neutrons being slowed down and thermalized inside the inspected object and in any other structures including floor, shielding, wall, etc.

3) Finally there is a different type of background, "material background" i.e., γ-rays from O, C, N, Cl (H) and others which are present both in the object of interest, e.g., explosive, and in the benign materials inside and/or nearby the measured voxel.

As was stated above, many simulations and measurements have addressed the effects and established their range of magnitudes. Most of the radiation transport effects are important for the inspection of large attenuating objects such as fully-loaded cargo containers and not for luggage and other relatively small objects. However, the timing issue is most important for the latter because of the need for a very high spatial resolution.

Fig. 1 is an example of the various sources of background, and the ability of PFNA to isolate the signal. This figure shows the measured pulse height distribution with a 7.5 cm diameter × 7.5 cm NaI detector in a benchmark set-up (inserted in the figure). The outstanding quality of the C4 spectrum is evident, free of all the prevalent backgrounds.

## 6. Attenuation effects

In highly attenuating cargo such as organic liquids or water, the interrogating flux beyond a certain point (normally deep in the container) can be so low that no detectable signal is stimulated. The PFNA system can deter-

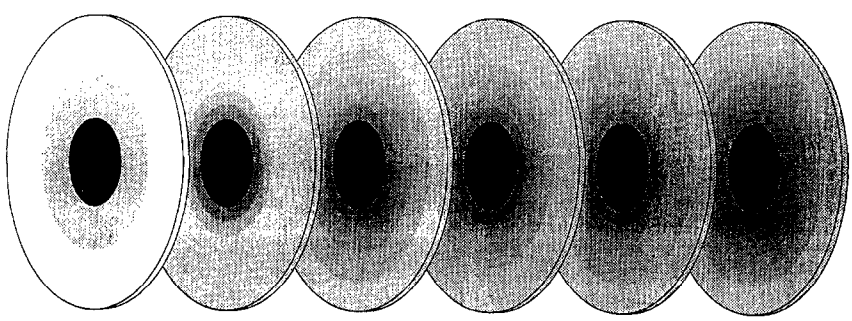


Fig. 2. Schematic view of the neutron scattering as a function of depth in a container with 0.5 g/cm$^3$ cellulose.

mine automatically beyond what point the information is not statistically significant any more by comparing successive voxels. If these volumes are at the center, inspection from both sides of the container will eliminate the problem. Based on the distribution of goods shipped through various ports of entry and cargo weight limitations, this type of cargo (in containers) is not very common. Other complementary means, sometimes simple ones, especially for liquids, can take care of these infrequent cases.

## 7. Scattering effect

The signal in highly attenuating cargos can in principle become corrupted even before reaching the point of "no-signal". This is because scattered neutrons with energies above the threshold of inelastic scattering will stimulate signals in the same elements outside the object as those in the measured object (e.g., contraband). This is the source of the "material background" or material clutter mentioned above. This background degrades the material signature of the specific observed voxel, because the detector gets contributions at the same time from neighboring voxels. Obviously if these voxels contain benign materials with no contraband, elements such as metals, this dilution effect does not occur. The neutron scattering was exhaustively studied by calculations and experiments. An illustrative example is given in Fig. 2. It shows how a narrow (10 cm diameter) beam of 8.5 MeV neutrons penetrates a uniform cellulose-type cargo with a bulk density of 0.5 $g/cm^3$. To obtain the relative contribution of scattered neutrons to the carbon signal from the central beam, the number of neutrons for each slice was normalized to remove the attenuation effect which is given in the figure below each slice. Quite clearly the neutron dispersion increases as the neutron beam penetrates but the dominance of the direct beam is maintained to the center ($\sim$ 120 cm) of the container. While the rings outside the center contribute in excess of 50% to the carbon and somewhat less to the oxygen signal at the center of the container, the overall decrease, in this case of a drug detection feature, (e.g., $c/o$, ratio of carbon to oxygen concentrations) is by about 20%. That is, the exceptionally high observed $c/o$ ratio for cocaine of about 5 is reduced to about 4.2, which is still well above the value in most benign materials of interest. Similar results are reported elsewhere [10]. Numerous calculations and measurements establish that the deleterious effects of scattering, at least to the center of the container even for attenuating organic cargos are manageable. In fact algorithms for correcting for this effect are being developed with the possibility of extending further the range of PFNA validity to cover the fringe cargos.

## 8. Conclusion

The PFNA conceived in late 1987, is a testimony to the insight of the late Peter Sawa. The concept has evolved since then and developed into a fully operational prototype at SAIC's Santa Clara Laboratory. The numerous measurements and simulations have confirmed the power and versatility of the technique as well as its limitations. The latter does not diminish the system's broad applicability, from detection of explosives, drugs, and hazardous materials to cargo manifest verification. The understanding of the strengths and the limitations of PFNA will assure the optimal and most beneficial use of this non-intrusive inspection technique.

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