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# NUCLEAR DATA NEEDS FOR NON-INTRUSIVE INSPECTION

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**Abstract**

Various nuclear-based techniques are being explored for use in non-intrusive inspection. Their development is motivated by the need to prevent the proliferation of nuclear weapons, to thwart trafficking in illicit narcotics, to stop the transport of explosives by terrorist organizations, to characterize nuclear waste, and to deal with various other societal concerns. Non-intrusive methods are sought in order to optimize inspection speed, to minimize damage to packages and containers, to satisfy environmental, health and safety requirements, to adhere to legal requirements, and to avoid inconveniencing the innocent. These inspection techniques can be grouped into two major categories: active and passive. They almost always require the use of highly penetrating radiation and therefore are generally limited to neutrons and gamma rays. Although x-rays are widely employed for these purposes, their use does not constitute "nuclear technology" and therefore is not discussed here. This paper examines briefly the basic concepts associated with nuclear inspection and investigates the related nuclear data needs. These needs are illustrated by considering four of the methods currently being developed and tested.

## 1 Introduction

There is no doubt that detailed and accurate knowledge of nuclear data is important for successful application of nuclear techniques to non-intrusive inspection. That having been said, in our experience we have observed the emergence of two fundamental truths: First, it is often very difficult to specify exactly what data are needed, and to what level of accuracy, until the development of a particular technique is well in progress. Second, it is amazing how many gaps still exist in what should be very basic - and often not so difficult in principle to determine - knowledge about the interactions of neutron and gamma radiation with matter. Another point worth mentioning is that often there exist administrative barriers to establishing and communicating specific nuclear data needs that are imposed by security concerns. Nuclear-based

inspection is a field that straddles those research domains that are designated as classified for security purposes and those that are open to broad inspection.

The first point raised above should not surprise the reader. Rarely does one know exactly what problems will emerge in any practical situation until one embarks on investigating the details. In the application of scientific knowledge to technology, there are often large disparities between what is "scientifically feasible" and what can be exploited practically in the field given limitations associated with cost, complexity, size and weight, and overall robustness of a particular approach. Little can be said here about those obstructions to the communication between users and producers of nuclear data imposed by security issues other than to emphasize that it is a reality that cannot be overlooked or avoided.

Continuing the discussion, one should not be puzzled by the gap between what information has been provided from scientific investigations and what is needed for practical applications. The motivations that drive the efforts of basic and applied scientists are quite different. An example: Many basic science studies of (CP,n) neutron-source reactions leading to the formation of product nuclei in discrete excited states have been performed using thin targets. The motivation was, quite reasonably from the perspective of the basic scientists, to learn about the properties of these excited nuclear states. However, in applied science the need is generally for neutron emission information corresponding to thick, stopping-target CP (charged-particle) reactions. Since less can be learned about the physics of these processes from thick target experiments it is not surprising that such information is frequently lacking in the scientific literature. Basic research scientists have often inadvertently discarded "raw" information derived from their experiments even though one day these results might prove valuable for applications. Generally, the intent of their research is to answer a specific scientific question and then to publish these academic results. An example: Establish the spin, parity, and isotopic spin of a particular excited nuclear state. Influenced by pressure from peers and rules fixed by scientific journals, attempts are seldom made to provide what pure-science communities tend to view as pedestrian, non-interpreted data or systematic data of broad scope.

In some cases, there may exist nuclear data that could satisfy the requirements for applications but that have not been adequately evaluated or, if evaluated, not processed into suitable form for use in computer codes such as those that perform Monte Carlo simulations of specific interrogation processes. Clear distinctions need to be made on this issue to avoid launching expensive nuclear data development programs that end up proving unnecessary.

Finally, there exists the well-known problem that there is frequently limited funding available for conceiving and developing new ideas pertinent to nuclear-based inspection. Potential users generally want to be able to acquire and field a device that has already been proven in the laboratory rather than to allocate scarce funding (as well as valuable time) to exploring the potential of a particular concept and eliminating technical "glitches". In short, resources for R&D tend to be limited in the coffers of user organizations. Because of the issues mentioned above, the present authors realized early in their quest to define nuclear data requirements for non-intrusive inspection that it would be difficult to provide definitive lists of universally acknowledged "nuclear data needs".

## 2 Basic Concepts of Inspection

Non-intrusive inspection can introduce a degree of technical difficulty that may not be encountered in non-destructive (*e.g.*, the luggage can be opened) or destructive techniques. All inspection concepts benefit from (or are limited by) the physics of neutron and/or gamma ray production by (or origination from) certain materials, and by their subsequent interactions with other materials as well as their detection. The major physics issues are as follows: radiation types, radiation sources, radiation intensities, radiation coincidences, radiation energy spectra, detector efficiencies, and background sources. The practical issues associated with applications are as follows: cost, complexity, safety, environmental impact, and - yes - political and legal questions. This paper will focus on the physics issues although it is difficult to de-couple the physical from the practical matters. Central to all inspection concepts is the idea of a "signal" or "signature". One defines what attribute of the interrogated object is sought (*e.g.*, type and quantity of contraband material and its location inside the sealed container) and attempts to identify what nuclear process could yield a signal or signature that is clearly discernable above background. Sometimes background issues are relatively minor concerns, but in most cases they are significant and often overwhelming. The reliability of a particular approach generally hinges on the ability to distinguish the signal clearly from the background. The lower the background the greater the sensitivity and specificity of a particular approach.

Passive techniques rely entirely on observing radiation emanating from materials residing in a container and shielded from direct visual observation. This approach is limited to detecting radioactive materials. Usually the signature involves the measurement of characteristic gamma radiation, but in some cases the observation of delayed neutron emission or spontaneous fission neutrons and $\gamma$-rays provides a signature. There is obviously a need to detect the signature radiation and to analyze absorption and scattering of this radiation.

Active techniques require that the interrogating radiation be produced externally and that the interrogated object, when exposed to this radiation, will generate a signal in the form of emitted, characteristic secondary radiation that then has to be detected. This approach offers many more conceptual options for nuclear inspection, but systems based on active techniques tend to be more expensive and complex to operate and, consequently, somewhat less reliable. In this paper we will consider data needs for these two approaches separately, but sometimes the boundaries are blurred so that similar nuclear data requirements emerge from both passive and active techniques.

## 3 Data Needed for Passive Inspection Techniques

Passive inspection techniques are employed in many applications: routine monitoring of radiation levels at nuclear facilities, assay of new and spent nuclear fuel, characterization of radioactive waste, personnel radiation dosimetry, control of nuclear materials transport, detection of clandestine nuclear materials (*e.g.*, nuclear warheads), monitoring of planned or inadvertent release of nuclear materials from the confines of nuclear facilities, identification of nuclear explosions and determination of the nature of the implicated devices, and general-purpose environmental monitoring of natural or man-made radioactivity to insure the safety of populations. The required apparatus is often relatively simple (*e.g.*, hand-held monitors) but it can be quite sophisticated (*e.g.*, for measurements that involve distinguishing very low-level

signals from background). All of these methods are based on detecting one or more of the following types of radiation emitted directly from suspect materials: α, β, γ, n (delayed), and n (SF). Consequently, the requisite nuclear data are associated with establishing signatures for specific nuclear materials, *i.e.*, defining the energies and the relative and absolute intensities of specific types of radiation, as well as determining the operating characteristics of radiation detectors. Most of these data are related to nuclear structure issues and can be found in the Chart of the Nuclides [1], Evaluated Nuclear Structure Data File (ENSDF) [2], or handbooks based on these sources. It is important that analyses be performed using the most recent evaluated results, wherever possible. The compilation and evaluation of nuclear structure data is an ongoing international activity.

Because of the wide range of applications and associated data requirements, it is difficult to define specific needs in the space allotted to this paper. One aspect of this subject, data needs for safeguards, has already been reviewed quite extensively by Boldeman [3]. Tables 1 and 2 based on his work provide examples of data needs in this area. It is seen that the needs are not very specific but they generally involve fissionable actinides, fission products, and tritium that is inevitably produced when neutrons are present from fission reactors or nuclear explosions.

## 4 Data Needed for Active Inspection Techniques

As mentioned in Section 2, nuclear technologies proposed for active non-intrusive inspection applications tend to be rather complex. The materials most often sought by these techniques are fissionable isotopes, illicit drugs, and explosives. Neutrons or energetic gamma rays are produced externally and in practice impinge on the object to be interrogated in order to stimulate the emission of a characteristic radiation that is detected to provide a "signal" or "signature" of the presence of a contraband material. In some cases, an indication of the quantity and location of this material is also provided. It is immediately obvious that the metrology system utilized must distinguish between the primary and secondary radiation. The former is always overwhelming in intensity relative to the latter. The process of distinction is especially difficult if the primary and secondary radiation is the same, *e.g.*, neutrons. The nuclear data needed for successful application of these technologies fall into three broad categories: production of primary interrogating radiation, scattering and absorption of primary and secondary radiation, and radiation-induced nuclear reactions. These processes must be understood not only for contraband materials but also for the benign materials that accompany them in realistic situations. As is the case for passive techniques, knowledge of nuclear structure and decay processes is required for several of these technologies.

Tables 3 and 4 provides some expressed needs for neutron interrogation and gamma interrogation applications, respectively, as gleaned from the authors' own experiences, private communications, and literature sources. In most cases they are listed here because they have not been satisfied. For neutron absorption, scattering, and induced reactions, one can refer to evaluated nuclear data files such as ENDF [4], JEF [5], JENDL [6], CENDL [7], and BROND [8] to obtain the latest available evaluations. Although these evaluated data libraries are far from complete, their content does offer the possibility of satisfying or nearly satisfying a rather large number of data needs once they are suitably processed for use in analysis codes.

# 5 A Look at Some Active Inspection Techniques

Many different active inspection techniques have been suggested. It would be impossible to review them all in the space and time available. Therefore, four distinct methods have been selected to demonstrate the interplay between concept and nuclear data in practical applications. Three of these methods involve the use of neutrons as an interrogating radiation while the third utilizes energetic gamma rays.

## 5.1 Fast Neutron Transmission Spectroscopy (FNTS)

Argonne National Laboratory [9] and several other laboratories have investigated the use of fast-neutron transmission spectroscopy to locate and reliably identify both explosive materials and illegal drugs in containers by determination of elemental content (see Figure 1). The measurements involve an accelerator, pulsed-beam time-of-flight techniques, and fast-neutron detectors. This technique is heavily dependent on computer simulation and the application of tomographic methods that require two types of nuclear data as input. First, one needs to use energy-dependent spectra and angular distributions of thick-target, light-element, white-spectrum neutron source reactions such as Be(d,n) and (p,n) and $^{7}$Li(d,n) and (p,n) in order to estimate the efficiency of the method. Analysis of the technique at ANL was undertaken using the Be(d,n) source, and at the outset of this project it was found that the neutron-production data for this reaction was not adequately known for deuterons from 0.5 – 10 MeV. Some measurements have been performed that allowed estimation of the effectiveness of the interrogation procedure [10] (see Figure 2). In some applications the Be(p,n) reaction might be a better choice, but knowledge of this reaction remains inadequate pending publication of recent results from Ohio University.

Other required data for the application are neutron total cross sections from 0.5 – 10 MeV for H, C, O, N, Fe, Ni, Cu, Cl, S, and other elemental materials found in drugs, explosives, and benign materials included in luggage and containers. As can be seen from Figure 1, the interrogating neutron beams are never perfectly collimated so the neutron transmission through an interrogated object can be affected by small-angle scattering. Thus, effective transmission spectra cannot be adequately reproduced by simply energy-averaging high-resolution neutron total cross section results found in data libraries such as ENDF [4] even though these evaluated results are generally quite well known. Libraries of effective neutron-transmission cross sections for realistic geometries have to be developed, either by direct measurements or sophisticated calculations that take into account small-angle scattering, in order to adequately "unfold" elemental-abundance values for the inspected objects.

## 5.2 Pulsed Fast-Neutron Analysis (PFNA)

In this neutron inspection technique, approximately mono-energetic beams of fast neutrons with energies of $\approx$ 8.5 MeV are produced using the $^{2}$H(d,n)$^{3}$He source reaction [11,12]. There are also variants of the method that have been suggested that employ 14-MeV neutrons from D-T neutron generators. Neutrons impinge on the object to be interrogated and they produce gamma rays by (n,n'-$\gamma$) reactions (see Figure 3). Individual isotopes (and thus elements) are identified and quantitatively measured by observing the characteristic gamma rays that follow prompt de-excitation of specific levels in C, O, N, Cl, and several other elements. The gamma-ray measurements are usually made using NaI scintillation detectors that provide both pulse-height and timing information with good efficiency. In PFNA, contraband objects are

identified by observing signature ratios for gamma ray yields from key elements. The method requires use of an accelerator and pulsed-beam time-of-flight techniques. It is particularly vulnerable to the effects of small angle neutron and gamma-ray scattering as well as absorption.

Properties of the neutron source reaction appear to be adequately known. The inelastic γ-ray yield data available data for C are relatively consistent and may also be adequately known (see Figure 4). However, the angular distribution information available for C in evaluated libraries appears to be inadequately represented. Furthermore, what is clearly inadequately known are the excitation functions for gamma-ray production from O, N, and Cl (*e.g.*, see Figure 5). Finally, angular distributions of the gamma rays are generally not well enough represented for most elements based on the evaluated libraries. As mentioned above, in the case of angular distributions part of the problem may be inadequate formats for representation of these evaluated data, *i.e.*, shortcomings in the Legendre-polynomial representation scheme used in ENDF [4]. The neutron elastic scattering results are probably adequate for the important materials. However, inelastic scattering, which also distorts the primary neutron spectrum and influences background gamma-ray spectra from benign materials, is generally not sufficiently well defined.

### 5.3 Fissile Interrogation using Gamma Rays from Oxygen (FIGARO)

A non-intrusive inspection technology based on use of 6 – 7 MeV gamma rays from the $^{19}F(p,\alpha\text{-}\gamma)^{16}O$ reaction is under development at Argonne National Laboratory [13] and it has been found to be effective in locating fissile material and other nuclear materials such as $^{6}Li$, Be, and deuterium hidden in containers (see Figure 6). Success of this method relies on the fact that photons in the 6 – 7 MeV range can induce photo-nuclear and/or photo-fission neutron production on the above-mentioned nuclear materials whereas neutron emission from most benign materials is not energetically allowed. It is possible to detect the secondary neutrons in the presence of intense gamma-ray fields by using a gamma-insensitive detector system with good efficiency, such as arrays of $BF_3$ counters in a polyethelene moderator.

When this project began it was found that the available thick-target photon yield data from the $^{19}F(p,\alpha\text{-}\gamma)^{16}O$ reaction were completely inadequate to predict feasibility. Therefore they were measured to the required accuracy from 1.5 – 4 MeV [14] (see Figure 7). Full exploitation of this technique is still limited by inadequacy of thick-target (p,n) neutron data needed to assess background neutron-source problems. Furthermore, knowledge of photo-fission and photo-neutron cross sections for actinides is poor in the region below 10 MeV preventing, *e.g.*, a clear distinction between $^{235}U$ (HEU) and $^{238}U$ (DU).

### 5.4 Multi-Detector Analysis System (MDAS)

In this concept, waste containers to be inspected are irradiated with intense low-energy neutron fields (generally, ≤ 0.5 MeV) [15]. The neutrons induce fission in actinide materials and the prompt gamma rays emitted from de-exciting fission fragments are observed with an array of HPGe detectors. Signatures of fission in specific actinide isotopes are provided by observing selected gamma rays emitted from the fragments in pair-wise coincidence. If it is known that a particular gamma-ray line corresponds to prompt de-excitation of a particular FP nucleus, then many gamma rays observed in coincidence should correspond to emission from the other fragment. Relying on conservation of total charge number, one can narrow the range of possibilities to isotopes of a particular element. In principle, by also performing coincident neutron multiplicity measurements, and relying on conservation of total neutron number, one can

identify the specific sister FP nucleus and thereby establish which actinide isotope actually underwent fission. This method relies on use of radioactive (*e.g.*, $^{252}$Cf SF), a reactor, or accelerator neutron source, extensive computer analysis of coincident gamma-ray spectra, and computer simulation to deal with geometry problems, neutron and photon absorption, *etc.*

Obviously, the method requires detailed knowledge of the energies and relative intensities of gamma rays associated with the decay of excited states of FP nuclei. These data may not be well known for many of the FP isotopes far from the line of stability. Knowledge of neutron fission cross sections and prompt neutron (nu-bar) and $\gamma$-ray multiplicities as a function of neutron energy is necessary for all actinide materials likely to be found in interrogated waste containers.

## 6 Prognosis for Satisfying the Nuclear Data Needs

Most of the nuclear data needs outlined in very general terms in this paper could in principle be satisfied in a straightforward manner using existing facilities, techniques, and theoretical and experimental expertise available around the world. In some cases, the data needs stated here may have already been met. An example: New evaluations for Bismuth (already released in ENDF) and for Oxygen (soon to be released in ENDF) should lead to improvements in the situation for these elements. However, the overall prognosis for significant progress to made in the foreseeable future is not encouraging. There are attitude barriers to overcome, particularly in the basic research community. Facilities where applied work is usually done are generally under-staffed and under-funded, or their resources are devoted to other tasks. Funding is a key issue. Agencies charged with carrying out non-intrusive interrogation for various purposes generally do not have research budgets that are adequate for this task and they are often inadequately informed concerning nuclear data issues.

Should a turn of events lead to a higher priority being assigned to obtaining nuclear data for nuclear inspection purposes, the first order of business would be to examine very carefully the adequacy of the existing databases in the context of intended applications. This is not a trivial job. To do it right would involve several man-years of skilled specialist effort (not necessarily restricted to a single individual). Due to security issues and the highly diverse nature of the methods and their practitioners in this field, it is not clear whether this review will take place in the foreseeable future. Another problem is that many of the specialists who are skilled in performing the needed measurements, theoretical calculations, and evaluations are retiring and these skills are not being replaced. The longer-term consequences of this evolving situation for the future of all nuclear technologies are potentially quite negative.

## 7 Summary

It is seen that there are extensive nuclear data needs for both passive and active non-intrusive inspection applications. Generally, the requirements are not very carefully defined or documented suggesting that there is a need for detailed sensitivity studies to be performed and reported. However, due to security concerns and funding limitations this important work is not likely to be completed in a comprehensive fashion in the foreseeable future. For passive applications, the needs generally relate to nuclear structure properties and to the decay of

radioactive species. For active techniques, such data are also needed along with information on production, scattering, absorption, and nuclear transmutation information for the neutrons and gamma rays that are both employed as the interrogating radiation and are detected as emitted secondary radiation. In many cases, information that satisfies these needs adequately can be found in libraries of evaluated structure and cross section data but may not be suitably processed.

Decay data are generally reasonably well known for the major isotopes of structural materials such as Al, V, Fe, Cu, Ni, *etc.*, and for the major fissile materials and fission products, as long as the half lives are neither too short nor too long. For less common materials, for cases where the half lives are very short or very long, or for those where the decay schemes do not favor convenient measurement, the information is less reliable. Neutron scattering data for such common elements as C, Al, Fe, Ni, *etc.*, are reasonably well known. It is surprising that similar data for O are not as well known and that the most recent ENDF evaluation for Cl (a major constituent of illicit drugs) dates to 1974 and is both uncertain and incomplete. Gamma-ray production data are generally less well known than neutron scattering data. Neutron and $\gamma$-ray source data, particularly for thick targets are available only in a very limited number of situations. There would be a clear benefit obtained from comprehensive measurements made of thick-target neutron yields, angular distributions and spectra from (p,n) and (d,n) reactions on all stable materials up to Fe for incident particle energies from a few hundred keV up to perhaps 10 MeV. Finally, both photo-fission and photo-neutron ($\gamma$,n) measurements ought to be made on a variety of benign as well as fissionable and other nuclear materials from threshold to about 10 MeV. In particular, the ability to distinguish between $^{235}$U (in HEU) and $^{238}$U (in DU) based on photon-induced neutron production would be extremely valuable.

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Table 1. Some nuclear data needs for passive monitoring of small releases to the environment. [a]

| Materials | Nuclear Data Required | Application |
|---|---|---|
| $^{3}H$, $^{85}Kr$, Pu (α), $^{241}Am$, U, $^{95}Zr$ | Radioactive decay data. [b] | Air |
| $^{129}I$, Pu (α), U | Radioactive decay data. [b] | Deposition |
| $^{90}Sr$, $^{95}Zr$, $^{95}Nb$, $^{106}Ru$, $^{129}I$, Pu (α), $^{241}Am$, U | Radioactive decay data. [b] | Soil/Dust |
| $^{3}H$, $^{129}I$, $^{95}Zr$, $^{95}Nb$, U | Radioactive decay data. [b] | Vegetation (Terrestrial) |
| $^{3}H$, $^{125}Sb$, $^{129}I$, $^{137}Cs$, $^{237}Np$, Pu (α), $^{241}Pu$, $^{241}Am$ | Radioactive decay data. [b] | River Water |
| $^{95}Nb$, $^{110m}Ag$, Pu (α), $^{241}Pu$, $^{241}Am$, Cm | Radioactive decay data. [b] | Sediment (Freshwater) |
| $^{95}Nb$, $^{110m}Ag$, Pu (α), $^{241}Pu$, $^{241}Am$ | Radioactive decay data. [b] | Vegetation (Freshwater) |
| Pu (α), $^{241}Am$, $^{237}Np$ | Radioactive decay data. [b] | Sea Water |
| $^{95}Zr$, $^{95}Nb$, $^{144}Ce$, $^{237}Np$, Pu (α), Cm | Radioactive decay data. [b] | Sediment (Marine) |
| Pu (α), $^{241}Pu$, $^{241}Am$ | Radioactive decay data. [b] | Marine Algae |

[a] Information taken from J. Boldeman [3] and attributed to G. Andrew [16].
[b] Half lives, energies, and intensities of emitted radiation: α, β, γ, n (delayed), and n (SF) as applicable.

Table 2. Some nuclear data needs for passive assay of fresh and spent nuclear fuel. [a]

| Materials | Nuclear Data Required | Application |
|---|---|---|
| $^{232}U$ and its daughter products | $^{232}U$ half life. γ-ray energies and intensities fordaughter products. | Assay recycle U fuel. Correction for $^{232}U$ daughter interference with $^{235}U$ γ-rays. |
| Pu isotopes, $^{241}Am$, and their daughter products | Pu isotope and $^{241}Am$ half lives. Energies and intensities of γ-rays from α-decay daughters. | Quantitative analysis of γ-ray spectrum of Pu containing fuel. |
| $^{238,239,240,242}Pu$, $^{241}Am$, $^{242,244}Cm$ | α-decay and SF half lives. Nu-bar for SF. | Passive analysis of neutron emission from irradiated fuel. |
| $^{238}U$, $^{241}Pu$, $^{242}Am$, $^{243}Cm$ | Neutron fission and capture cross sections. | Passive analysis of neutron emission from irradiated fuel. |
| $^{241}Pu$, $^{242}Am$, $^{243}Cm$ | Decay half lives. | Passive analysis of neutron emission from irradiated fuel. |
| $^{18}O$ | (α,n) cross section. | Interference effects in passive analysis of neutron emission from irradiated fuel. |

[a] Information taken from J. Boldeman [3] and attributed to M. Lammer [17].

Table 3. Some nuclear data needs for active neutron non-intrusive inspection applications. [a]

| Materials | Nuclear Data Required | Application |
|---|---|---|
| Bismuth, Cesium, Chlorine, Germanium, Iodine | Neutron activation data from 0 – 16 MeV. | Neutron dosimetry. Neutron activation. For use in analysis of HPGe, NaI, CsI, and BGO detector response and background. PFNA, FNA, *etc.* |
| Bismuth, Cesium, Chlorine, Germanium, Iodine | Prompt neutron-induced γ-ray production data. | Neutron response. For use in analysis of HPGe, NaI, CsI, and BGO detector data. PFNA, FNA, *etc.* |
| Bismuth, Carbon, Chlorine, Germanium, Iodine, Nitrogen, Oxygen | Neutron differential elastic and inelastic scattering data from 0 – 16 MeV. Evaluations for Chlorine and Germanium are incomplete and very old. | Neutron transport calculations. TNA, PFNA, FNA, NES, *etc.* |

| | | |
|---|---|---|
| Nitrogen, Oxygen, Chlorine | Inelastic γ-ray production yields and angular distributions. | Analysis of signature γ-ray production. TNA, PFNA, FNA, *etc.* |
| Major actinide elements | Prompt fission neutron emission data for multiplicity and correlation analysis. Nu-bar and neutron energy spectra. Data are especially poor for $^{237}$Np and $^{232}$Th. | Actinide identification measurements using neutron multiplicity detectors. |
| Major actinide elements | Prompt fission γ-ray emission data for multiplicity and correlation analysis. Gamma-ray energies, intensities and angular distributions. Results for $^{235,238}$U and $^{239}$Pu are lacking and are particularly important. | Actinide identification measurements using γ-ray multiplicity detectors. This may prove to be a more sensitive approach than neutron detection. |
| Germanium | Neutron inelastic and capture γ-ray production cross sections. Activation reaction data. Evaluated data for Germanium are incomplete and very old. | Identification of background interference in monitoring γ-rays with HPGe detectors in the presence of neutrons from nuclear weapons or reactors. |
| C, O, Al, Cl, Fe, Ni, and Hg | Neutron differential elastic and inelastic scattering data. | Characterization of nuclear waste by PFNA, NES and related techniques. |
| C, N, O, Al, Fe, Cu, Cl, and others | Neutron differential elastic and inelastic scattering data. | Monte Carlo simulation in PFNA for the detection of explosives and narcotics. |
| Carbon | Angular distribution of 4.44-MeV γ-ray produced by neutron inelastic scattering. Representation in evaluated files is inadequate. | Signature measurements of the presence of carbon by PFNA. |
| Fission products, light elements and structural materials | Neutron yield from (α,n) reactions. | Data needed to estimate neutron production from α-particle induced reactions on various materials in the presence of α-active actinides. Resolution of background problems. |
| Actinides | Yields of FP nuclei as a function of neutron energy. Of particular interest are thermal neutron fission yields of $^{95}$Zr, $^{95}$Nb, $^{106}$Ru, $^{106}$Rh, $^{133}$Cs, $^{137}$Cs, $^{140}$Ba, $^{140}$La, $^{144}$Ce, $^{153}$Eu, $^{134}$Cs, $^{140}$La, $^{144}$Ce, $^{144}$Pr, $^{154}$Eu. | Data needed for use in active assay of spent fuel. |
| $^{133}$Cs, $^{153}$Eu | Neutron-capture cross sections. | Data needed for the active assay of spent nuclear fuel. |
| H, C, N, O, F, Na, Al, Si, Cl, K, Fe, and Cu | Transmission-derived neutron total cross sections in realistic geometries for 0.5 – 10 MeV. | Unfolding of elemental abundances by FNTS in geometries where small-angle scattering effects are influential. |

[a] Information derived from literatures sources [3,9,11,12,15] and private communications.

Table 4. Some nuclear data needs for active gamma-ray non-intrusive inspection applications.

| Materials | Nuclear Data Required | Application |
|---|---|---|
| Common benign materials, especially those with low photo-nuclear reaction thresholds | (γ,n) cross sections from threshold to about 15 MeV. Knowledge of emitted neutron spectra would also be useful. | Photon interrogation concepts such as FIGARO [13] and those which employ white-spectrum gamma sources. |
| Major actinides, especially $^{235}$U, $^{233}$U, $^{238}$U, and Pu isotopes | (γ,f) and (γ,n) cross sections from threshold to about 15 MeV measured with sufficient accuracy to distinguish different actinide species. | Photon interrogation concepts such as FIGARO [13] and those which employ white-spectrum gamma sources. |

| | | |
|---|---|---|
| F, Al, Au, Fe, Ni, S, Ca, Mg and other elements found in target assemblies and target compounds. | Thick-target (p,γ) yields, angular distributions, and spectra. Production of primary interrogation gamma rays as well as background gamma rays | Photon interrogation concepts such as FIGARO [13] and those which employ white-spectrum gamma sources. |
| Target structure, target compound, and accelerator beam line materials such as Fe, C, S, etc., with low (p,n) thresholds. | Thick-target (p,n) neutron yields, angular distributions, and spectra. Data needed to identify sources of neutron background. | Photon interrogation concepts such as FIGARO [13] and those which employ white-spectrum gamma sources. |

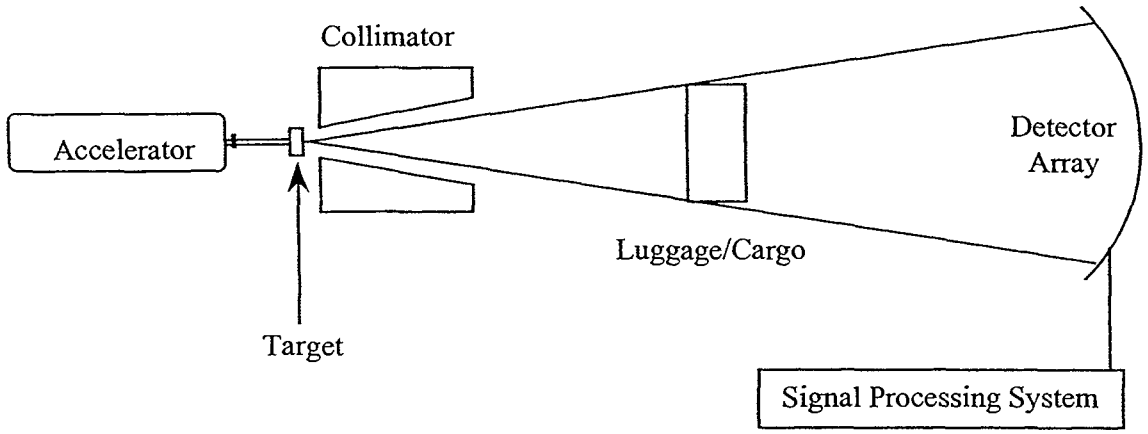


Figure 1. Schematic diagram of Fast Neutron Transmission Spectroscopy (FNTS).

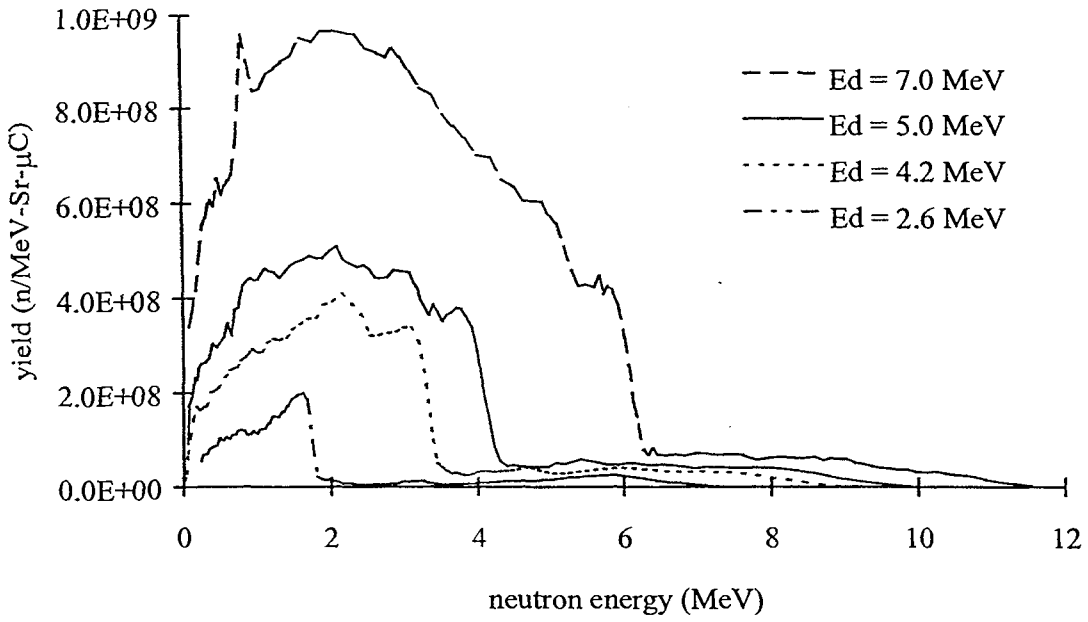


Figure 2. Neutron source spectrum for the $^{9}$Be(d,n) reaction for selected incident deuteron energies.

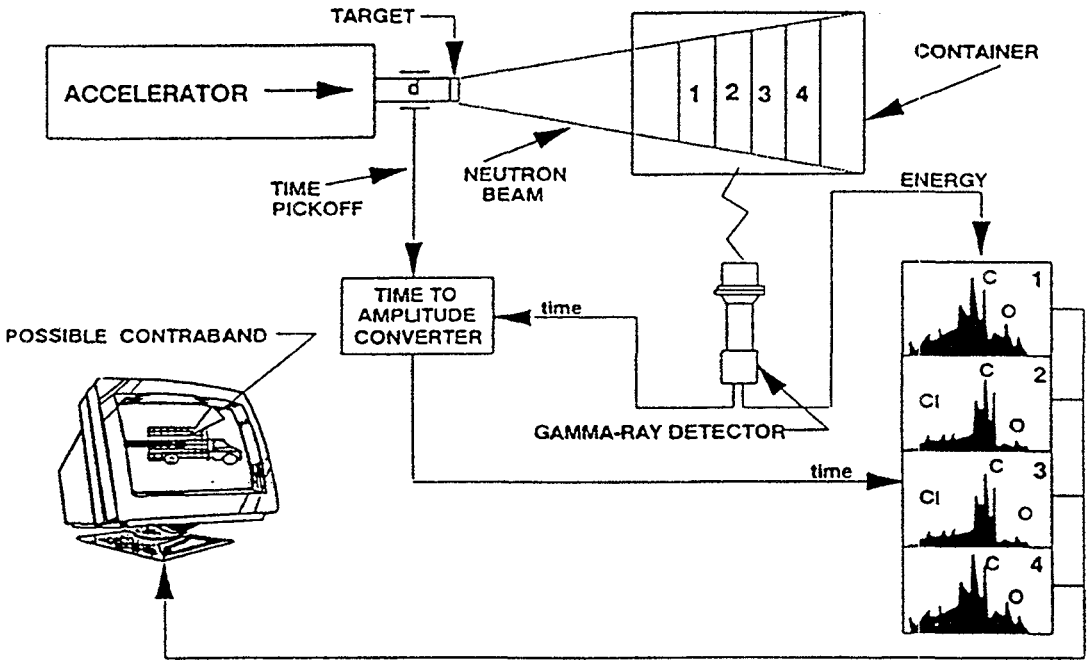


Figure 3. Schematic diagram of PFNA (Pulsed Fast Neutron Analysis).
(Figure published by J. Bendehan *et al.* [11])

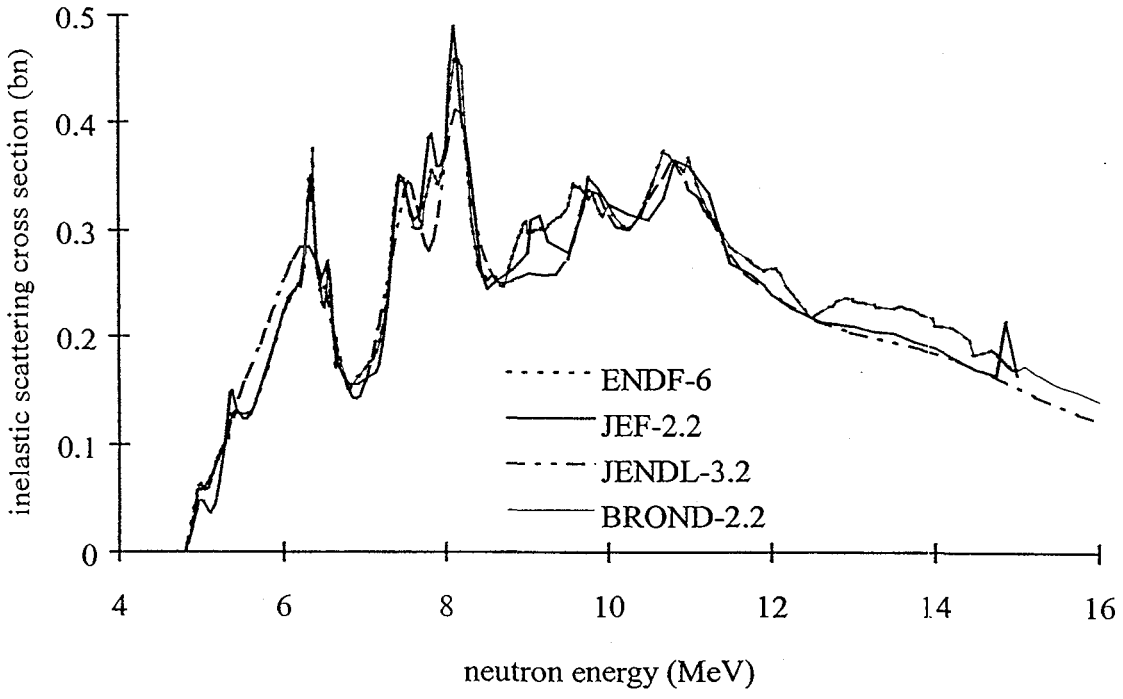


Figure 4. Inelastic scattering cross-section to the first excited state of $^{12}C$.

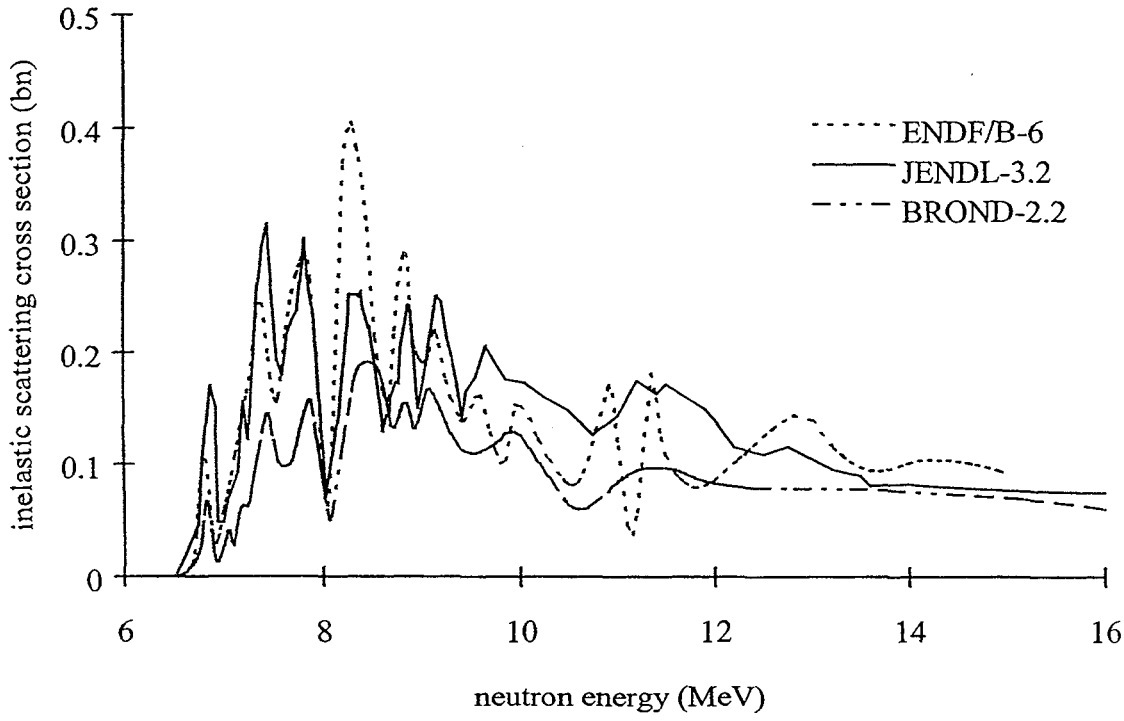


Figure 5. Inelastic scattering cross-section to 2nd excited state of $^{16}O$ (JEF-2.2 is identical to ENDF/B-6).

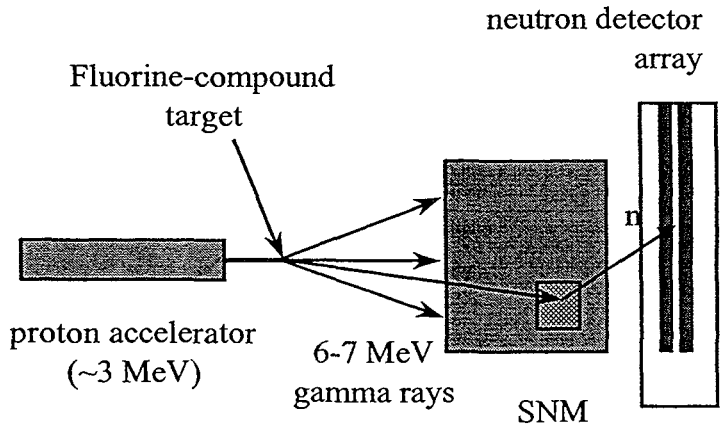


Figure 6. Schematic diagram of FIGARO (**F**issile **I**nterrogation using **G**amma **R**ays from **O**xygen).

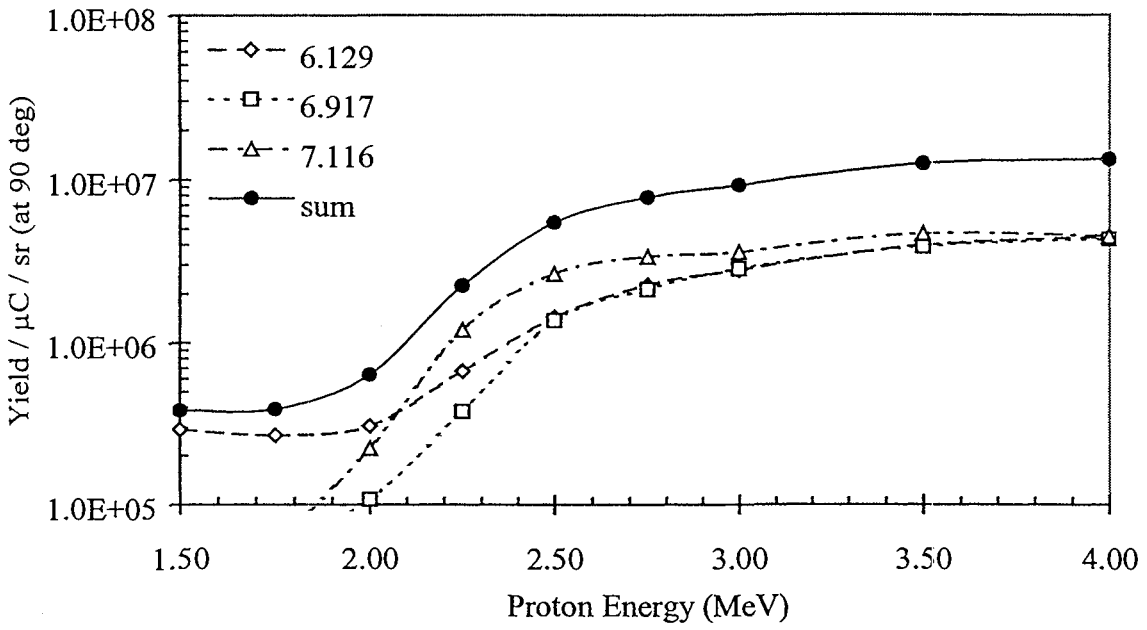


Figure 7. Gamma yield curve for the $^{19}F(p,\alpha\text{-}\gamma)^{16}O$ reaction as a function of proton energy