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BASIC CONCEPTS UNDERLYING FAST-NEUTRON-BASED CONTRABAND INTERROGATION TECHNOLOGY: A SYSTEMS VIEWPOINT

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All accelerator-based fast-neutron contraband interrogation systems have many closely interrelated subsystems, whose performance parameters will be critically interdependent. For optimal overall performance, a systems analysis design approach is required. This paper provides a general overview of the interrelationships and the tradeoffs to be considered for optimization of non-accelerator subsystems.

INTRODUCTION

This paper uses a systems approach to investigate the physical configuration of a contraband interrogation system based on one or more types of fast-neutron interactions with matter. Most generally, such a system will consist of a pulsed ion source, an accelerator, a neutron-producing target and associated collimation and shielding, a container conveyance system, and a detector array with its associated collimation and shielding. The goal is to optimize the configuration of the components overall (within their technical requirements and limitations) with respect to a specific physical observation and, particularly in the context of present discussion, to arrive at their essential operational parameters. This is rather different from the situation found in the general purpose fast-neutron laboratory, where the accelerator, because of its sheer complexity, is a given, and suitable experimental programs are considered on the basis of the accelerator capabilities.

The recognition of contraband substances within closed containers, large or small, is most commonly based on the detection of H, C, O, N, Cl and, perhaps, other light elements in either absolute or relative quantities [1]. In practice, this is a difficult undertaking, as these elements are the constituents of many items in daily human use. What properties of the fast neutron, whose energy ranges roughly from a few hundred keV to 20 MeV, make it useful in this effort?

Fast neutrons are well suited for non-invasive examination because they easily penetrate deeply into matter. Moreover, the emanations from their interactions with nuclei have this same property: they are primarily scattered neutrons and gamma rays of characteristic energies which escape reasonably unattenuated. Because of this, particularly if the so-called time-of-flight technique [2] and suitable collimation are employed, the point of this prompt interaction is well marked in time and space.

Neutrons of few-MeV energy interact well with light nuclei (i.e., have substantial reaction cross sections), yet with relative simplicity (few reaction types) in general.

Since the corresponding activation cross sections are quite small for fast neutrons [3], compared with those of thermal neutrons, and half-lives are usually very short, the irradiated materials activate little, if at all. This fact in itself may be of essential importance for public perception and acceptance of deployment of nuclear-based interrogation in our transportation system.

Over the years, considerable expertise in handling fast neutrons has developed, not only due to their use as a investigative tool in nuclear structure and reaction research, but also because of the essential role the neutron plays in fission and fusion energy systems. Diverse detectors have been developed in concert with attendant electronic circuitry, all of which are commercially available. Likewise, digital acquisition hardware and software have been perfected. Analytical and interpretive techniques are widely used. Finally, a considerable effort has gone into establishing

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national, as well as international, neutron data libraries [4].

We will begin our discussion with an enumeration of the dominant fast-neutron interactions and attendant characteristic signatures. From this repertoire the inventor chooses that process which most uniquely identifies the substance of interest. The designer then chooses a suitable detection system, as well as a neutron source of required energy, spatial distribution and intensity. This will define the source reaction, target configuration, incident particle, and hence the accelerator requirements.

The focus of this discussion must be of a general nature, since the purpose of it is not to feature a particular method, but rather to describe the decision-making process, interrelationships and trade-offs concerning the various system components. Further, the detailed matters of accelerator type and their relative merits are deferred to papers addressing these issues specifically.

DOMINANT FAST-NEUTRON INTERACTIONS WITH MATTER

Although the fast neutron may induce, generally, a wide variety of nuclear reactions (from simple elastic scattering to fission), for modest incident energies and light nuclei under discussion, the dominant interactions of interest are elastic and inelastic scattering. These are quantified for a given incident energy by either differential or integral cross sections. It may be that a particular interrogation concept does not require such exacting information. It may suffice, for example, to obtain the unnormalized shape of an angular and/or energy distribution of emitted radiation to determine the elemental composition of a volume under scrutiny. This, in general, would relax the demands on the detection system considerably. With this in mind we list the dominant observables in fast-neutron scattering.

Elastic Scattering

This is the most likely outcome of a neutron colliding with a nucleus. The observed radiation is a neutron of reduced energy to account for recoil. (This kinematic energy reduction increases with decreasing nuclear mass and, therefore, is most dramatic for H, where scattering beyond 90 deg. is impossible.) The signature here would be the angular distribution of the scattered neutrons. (Figure 1 depicts the particularly striking angular distribution of 3.6 MeV neutrons scattered from C [5].) The rapid acquisition of such an angular distribution would require at least an efficiency-balanced detector array subtending a significant portion of the half scattering plane, 0-180 deg., and focused on a small volume element of the space under investigation. The incident neutron field would have to be a mono-energetic, very small angle cone.

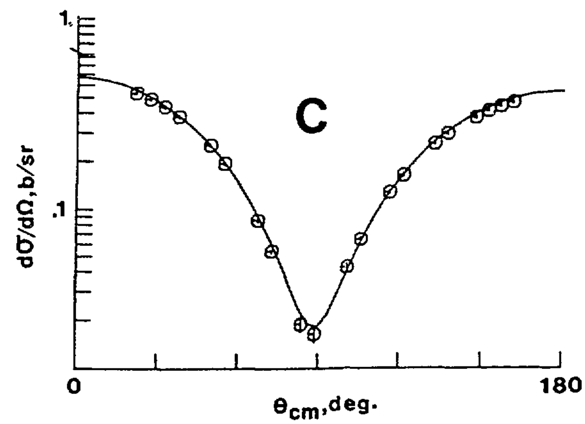

FIGURE 1 Angular distribution of 3.6 MeV neutrons scattered from carbon [5].

Inelastic Scattering

The total non-elastic cross section can be as large as that for elastic scattering [3]. Since, however, the reaction strength will be divided among the "open" reaction channels, the cross sections for the individual processes are much smaller. The signature here is the energy spectrum of either the emitted neutrons or gamma rays. (See figures 2 and 3.) The advantage in observing the neutron arises from the unambiguous identification of neutron peaks with the level scheme ("finger prints") of a given nucleus. In the case of gamma-ray observation, the mix of intra-level decays makes such identification much more difficult. However, state-of-the-art semiconductor gamma-ray-detector energy resolution far outpaces that of current neutron detection

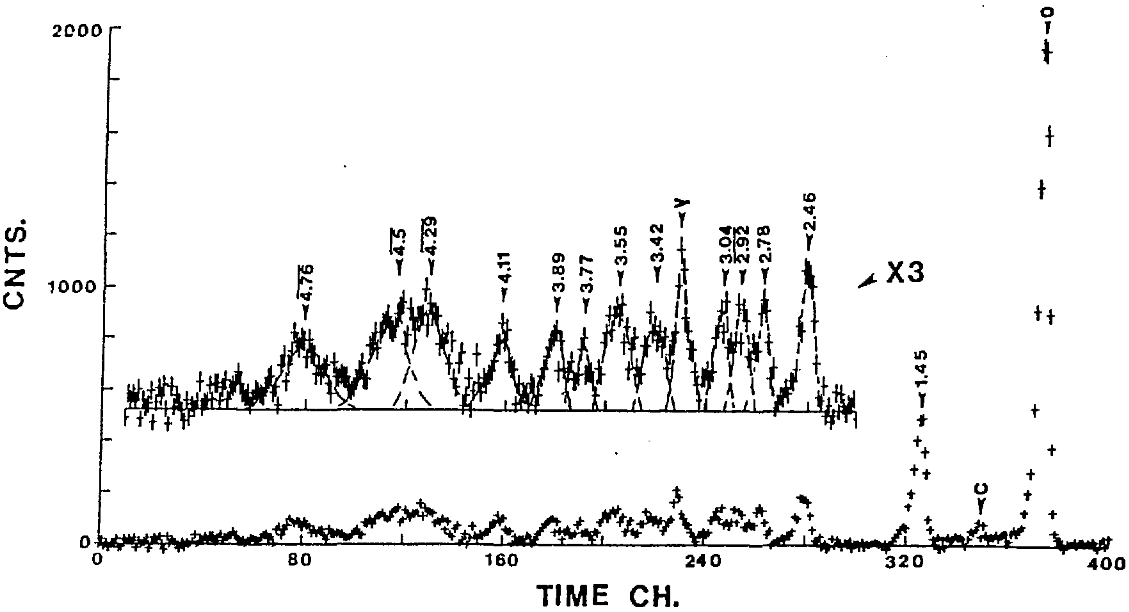

FIGURE 2 A complex time-of-flight velocity spectrum, here due to 8 MeV neutrons on ^{58}Ni [6]. Note neutron groups arising from the excitation of various levels of ^{58}Ni.

methods and, thus, could be more discriminating when dealing with a compound of many elements. Here the minimum detector configuration may be as simple as a single detector whose energy-dependent efficiency is known, thus freeing other detectors for parallel interrogation of other volume elements, or schemes involving verification by redundancy and/or coincidence. This observation method could possibly use lesser incident-energy resolution or even a white source, thus opening the possibility of higher count rates for a given accelerator output. Clearly, an impressive variety of schemes may be imagined using inelastic scattering, and the number of proposals employing this nuclear mechanism bears witness to this fact. Unfortunately, C and O require somewhat higher incident-neutron energies to excite their levels.

Total Attenuation (Transmission)

This process observes the attenuation of an incident-neutron beam by the substance to be identified. It is, therefore, rather different from the previous observations, where radiations emanating from the sample are to be detected. This implies that the detector system will be illuminated with much higher intensities. The signature in this case arises from the characteristic resonances in the total

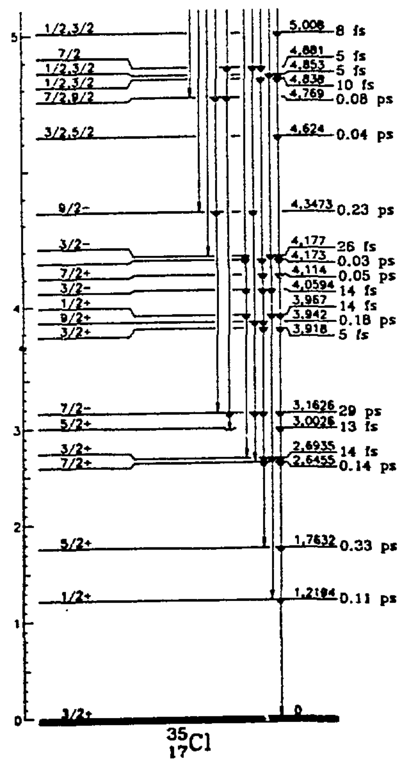

FIGURE 3 The energy-level diagram of ^{35}Cl for excitations up to 5 MeV [7]. Note transitions between energy levels, as well as those to the ground state, which give rise to complex spectra.

crosssection of a particular element. (See Figure 4). Since, for light elements and few-MeV incident-neutron energies, these resonances are widely spaced (typically a few hundred keV), currently achievable neutron-detector energy resolutions can resolve even fairly complex superpositions of materials [8]. A single detector, whose efficiency need not be known, can monitor a given transmission slice. Obviously, an array of such detectors will be required in order to satisfy real-time throughput rates.

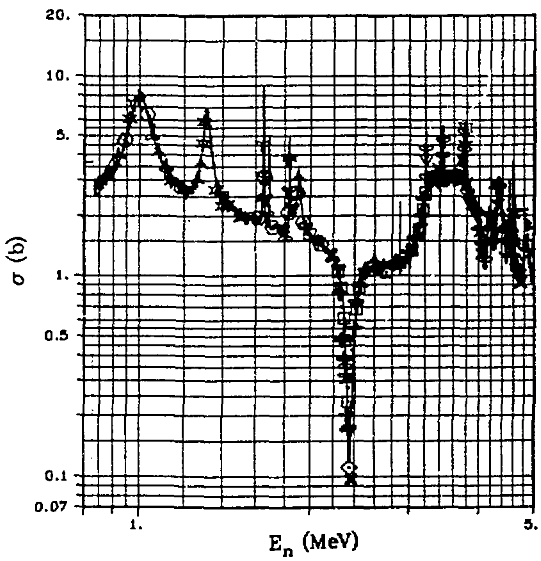

FIGURE 4 The total *cross section of oxygen* for incident-neutron energies between 1 and 5 MeV [3].

The interrogation for controlled substances will make use of one or more of the above principal interactions. (It should be noted, incidentally, that the signatures need not necessarily be the reduced quantities cited above but could be, for example, cataloged responses of the detection system for a controlled substance obtained a priori.) The choice of detection system and neutron source will depend on, among others factors, the radiation to be detected, the strength of the interaction to be observed, the time and energy resolutions required, the real-time demands of the application, the data acquisition and interpretation procedures, the subsequent decision making, and the demands of real-life deployment environment.

We now review some of the requirements, capabilities and trade-offs concerning the subsystem components.

DETECTORS

The review below is not intended to be comprehensive [9], but it serves to illustrate trade-offs experienced in the composition of a practical system.

Fast-Neutron Detection

The most popular detection methods for fast neutrons, particularly when fast timing is involved (such as in the time-of-flight technique) employ either plastic or liquid scintillators mounted on suitably responsive photomultiplier tubes. Both types are reasonably flexible concerning specific shapes and remote access. Plastics tend to be somewhat faster, but it is generally conceded that liquids are more adaptable to neutron-gamma discrimination, which is often essential for optimizing signal-to-noise ratios as well as for confining the data stream to usable information. There are simulative codes available to predict the detector efficiency, but often direct experimental calibration is not only simple, but also more reliable as it may include effects of the detector environment. Generally, the efficiency of the scintillator is readily increased with volume, although this must be done in concert with overall system time and/or energy resolution requirements. These detectors can be reasonably compact, depending on scintillator volume and photomultiplier tube size.

Gamma-Ray Detection

The best efficiencies are attained with inorganic scintillators such as the sodium-iodide crystal. These can be readily machined to reasonably large volumes, although they must be protected with cladding as they are fragile and hygroscopic.

Semiconductor detectors, while less efficient and much slower, have superb energy resolution. Hence their popularity. They are subject to radiation damage and are somewhat bulky due to the required cryogenic cooling. They also suffer from environmental stress. Large devices can be quite expensive.

NEUTRON SOURCE REACTIONS

The interrogation concept will dictate the energy range and intensity of neutrons required. For example, if the concept is based on the transmission of neutrons through the volume element in question, a white spectrum spanning the incident-neutron energy range 1-4 MeV may be obtained from bombarding a slab of ^{9}Be with 4 MeV deuterons. On the other hand, the observation of inelastically scattered neutrons from Cl may require mono-energetic neutrons of good energy resolution from the D(d,n) reaction, produced by bombarding a gas target with 2 MeV deuterons.

Thus, one must first decide whether to use a mono-energetic source or a white source. An excellent review of essentially mono-energetic sources has been compiled by Drosg[10]. Attention has been given to yields, angular distributions, kinematic collimation, etc. Because of the concerns arising from dealing with tritium, the two most benign and useful reactions may be ^{7}Li(p,n) and D(d,n). It should be noted that the ^{7}Li(p,n) reaction may also serve as a pseudo-white source by making the film sufficiently thick.

The properties of white sources are far less well known, and a comprehensive study is lacking. A prolific white source of suitable energy range for the present discussion is the ^{9}Be(d,n) reaction [11], which was used recently in connection with an explosives interrogation scheme at the Argonne Fast-Neutron Generator. The study also compared the ^{9}Be(d,n) reaction with the ^{12}C(d,n) and ^{13}C(d,n) reactions and found it to be superior in uniformity of yield over the energy range of interest.

Clearly, sensitivity of the detection system and the type and strength of the source reaction will have a major influence on the energy and beam output of the accelerator.

TARGETS

The choice of mono-energetic versus white source will have a rather fundamental impact on the target design and the respective yields of these source reactions. Further, depending on specific yields, these structures will have to withstand thermal stress (introduced by requisite beam currents) to provide continued, reliable service (i.e., minimum down time).

A massive structure may introduce unwanted scattered as well as spurious neutrons. In addition, the structural materials and configuration need to be such that activation is kept to a minimum so that maintenance is facilitated [12].

An inescapable trade-off concerns target yield versus energy and/or time resolution. Once again, these parameters must be brought in line with the technical capabilities of the system as a whole and the requirements of the basic interrogation concept.

COLLIMATION AND SHIELDING

Collimation and shielding are of crucial importance in optimizing spatial definition of the incident and scattered neutrons and gamma rays, as well as shielding of personnel against hazardous radiation. They have profound influence on the signal-to-noise ratio. Because interrogation systems will very likely have to be compact and source outputs will most probably be high, innovative approaches will have to be pursued to find minimal bulk, yet adequate protection and beam definition. Detector arrays may pose a particularly challenging problem if space is at a premium.

All these requirements stand in contrast to the average research laboratory environment, and little has been published in this area for many years [13]. The most economical design approach is the monte-carlo simulation technique, which is made possible by the usually reliable neutron-data libraries publicly available [4]. Even so, if ground-breaking designs are called for, the reliability of the data will have to be scrutinized when unusual materials are contemplated.

PULSED ION SOURCES

We will only touch on some general concerns in the overall systems picture and refer for greater detail to other papers of this conference.

It is clear that an on-line interrogation system will have to be extraordinarily rugged to realize satisfactory up-time. Thus the source, whatever its principle, will need to meet minimum system requirements comfortably. If replacements are necessary fairly frequently (say, within hours or days), the design must allow for rapid service and restoration to full operation.

The widespread use of the time-of-flight technique in fast-neutron work virtually guarantees its use in a detection scheme. This is, of course, due to its space/time as well as velocity (energy) tagging capability. Reaching for suitable time resolutions at the detector always involves trade-offs with yield and/or count rates. Considerations here are: the degree to which a pulsing system is able to compress ion-source output to maximize peak currents, beam optics, target design and effective thickness, fight paths, sample size and active detector volumes. Since the time resolution of many of these components are of similar magnitude (typically 1 nsec), straining for ultimate timing in any one particular component may not be rewarding.

Pulsing systems are a subject of continued interest and development. The Argonne Fast-Neutron Generator uses a 2-stage harmonic bunching system with good success [14]. It features automatic phase controls that facilitate its use and provide 50-75% more sharply peaked beam increase. However, perhaps its greatest benefit is the extension of useful source life.

CONCLUSION

We have examined factors in the decision making process which are experienced when, beginning with an interrogation concept employing fast-neutron techniques, one sets out to actualize the concept in a working system composed of current-technology components. Trade-offs considered for various components were demonstrated and discussed. In dealing with single-purpose systems we are confronted with a rather different decision making situation than in a general-purpose research laboratory. A systems approach involving thorough simulation of different component configurations and specifications can place the decision-making process on a sound footing and provide an economical path to optimization. To a large extent, this approach is made possible by the considerable experience accrued over the years in fast neutron physics, both in regard to required technology and understanding of nuclear interactions.

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