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Detection of explosives by neutron scattering

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There is considerable interest at the moment in possibilities for using fast neutron beams as non-intrusive probes for detecting hidden explosives or other contraband such as narcotics [1-11], for example in packages such as airline baggage or small cargo containers. Three distinct factors make neutrons of energy 0.1-10 MeV promising candidates for this application. Firstly, neutron beams in this energy range can penetrate such packages without being too severely attenuated. Secondly, the interactions of neutrons with material are very sensitive to the neutron energy and the nuclides in the material, and this makes it possible to determine these nuclides (and hence the corresponding chemical elements) by monitoring the neutron interactions in various ways. Thirdly, the principal constituents of narcotic and explosive materials are the elements hydrogen, carbon, nitrogen and oxygen (HCNO), which differ strongly from one-another in their interactions with neutrons and can thus be characterised via these differences [5].

Two methods for fast neutron interrogation that have been thoroughly explored and are now being implemented are the fast neutron transmission spectroscopy method (FNTS) [6-10] and the pulsed fast neutron analysis method (PFNA) [1-4]. The FNTS method is based on measurements of the attenuation of a pulsed fast neutron beam passing through the interrogated material. The PFNA method uses a pulsed monoenergetic neutron beam and measures the energy spectrum and time of arrival of prompt gamma rays which are excited by inelastic neutron scattering in the interrogated material. Different elements are identified via their characteristic gamma spectra in this method and the time measurement is used to locate the position of the scatterer.

An alternative approach which has received comparatively little attention to date is to use a pulsed monoenergetic incident neutron beam and to detect, *directly*, the neutrons scattered out of the beam [11-13]. Four possible methods are suggested for identifying and measuring nuclides in this way, and they can be used individually or in combination. Firstly, if the energy of elastically backscattered (> 150°) neutrons can be measured sufficiently accurately then the kinematics of this process provides a basis for determining the mass of the scattering nuclide. The operating principle is the same as that underlying the well-known technique of Rutherford backscattering analysis, in which monoenergetic charged particle beams are used to investigate surface regions of solids. Secondly, if inelastic neutron scattering is significant then this will add a low-energy component to the scattered neutron spectrum, which may characterise the scatterer. Thirdly, if the incident energy is suitably chosen and scattered neutrons are measured at two angles, one forward (eg 45°) and the other backward, then the ratio of the forward and backward scattering may help to indicate the scattering nuclide. Fourthly, since scattering cross sections display resonance structure, measurements at two suitably chosen incident neutron energies should also help to identify the scatterer.

We are now developing a fast neutron scattering analysis (FNSA) technique which combines the four approaches outlined above to identify elements and determine their concentrations. Our initial investigations [14] aimed to determine the efficiency of the FNSA method for determining H, C, N and O concentrations in isolated small samples (<0.5 kg). We are now investigating: (i) the complications which may arise, eg from neutron attenuation and multiple scattering, when the sample

is packed, together with other material, in a container; and (ii) various methods that may be used in conjunction with FNSA, to locate the position of the sample in the container. In the past we have worked exclusively with monoenergetic, accelerator-driven neutron sources. Now we are also investigating the possibility of adapting the FNSA method for use with a ^{252}Cf spontaneous fission neutron source, with a view to developing a system which might be used in landmine detection.

Fig 1 shows the experimental arrangement used for the initial studies. A collimated, pulsed beam of neutrons is directed at the sample and scattered neutrons are detected by the liquid scintillators A, B and C at the scattering angles θ = 160°, 160° and 45° respectively. Pulse height L and time-of-flight T are measured from each detector. Monoenergetic neutrons are obtained from the D(d,n) reaction, using a gas target and the neutron energy E is cycled between 6.8 and 7.5 MeV at intervals of about 10 seconds by "flipping" an energy-degrading Havar foil F (fig 1) in and out of the deuteron beam. A scattering "signature" is derived from two-parameter data, counts vs L and T (eg fig 2) measured for each element (H, C, N or O), at each of the two angles θ and two energies E. Fig 3 shows signatures for the four elements. Each is a 400-channel distribution normalized to a standard count in the neutron monitor M (see fig 1) and 100N_A target nuclei in the sample, where N_A = Avogadro's number. Channels 1-200 and 201-400 are derived from the data for E = 6.8 and 7.5 MeV respectively. In each of these sections the first 160 channels correspond to L-spectra for elastically backscattered neutrons, measured by detector B, a deuterated liquid scintillator (NE230, 50 mm diam x 50 mm). A T-cut (see fig 2) was used to select elastically scattered neutrons. The upper 40 channels in each section are T-spectra measured at θ = 45° by detector C, after applying a pulse height cut set at low L (see fig 2).

The elemental signatures (fig 3) are very distinctive and constitute a good response matrix for unfolding elemental components from the scattering signatures measured for different compounds. Unfolding is carried out using the HEPRO program system [15-17]. Fig 3 shows results obtained from scattering measurements made using anhydrous samples of the compounds methanol, ammonium nitrate, acetamide and ammonium acetate. In each case the atom fractions of H, C, N and O determined from neutron scattering (points) are in good agreement with the known values (histograms) calculated from the respective chemical formulae.

The measurements which are planned using a ^{252}Cf source will use either a fission fragment detector or an additional neutron detector immediately next to this source as a reference for the neutron time-of-flight measurement and will employ two or more neutron detectors to monitor the energy and angular dependence of scattering from N and other elements in the energy range 1-4 MeV.

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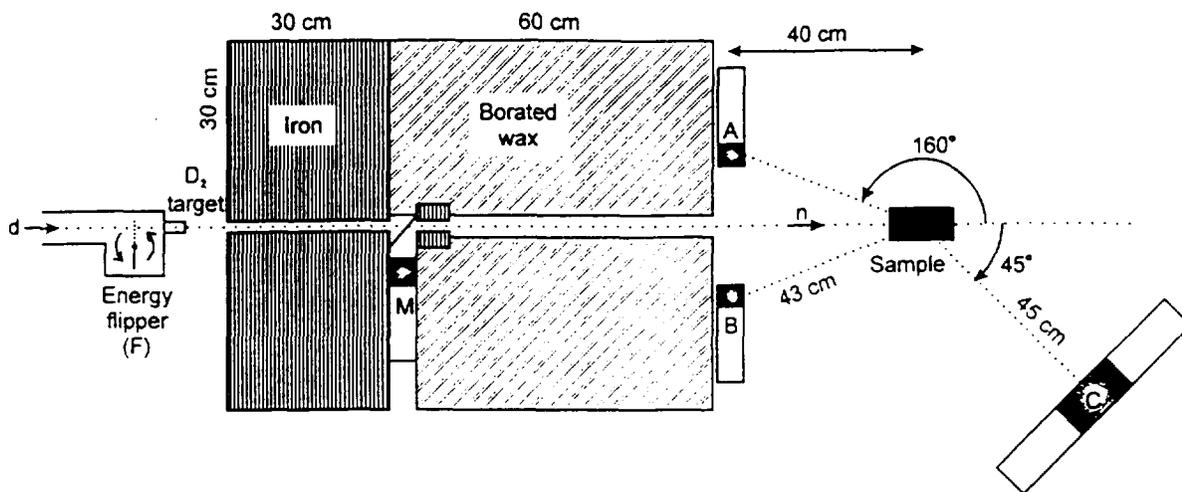
[17] M. Matzke, *Proc. SPIE* **2867** (1997) 598.

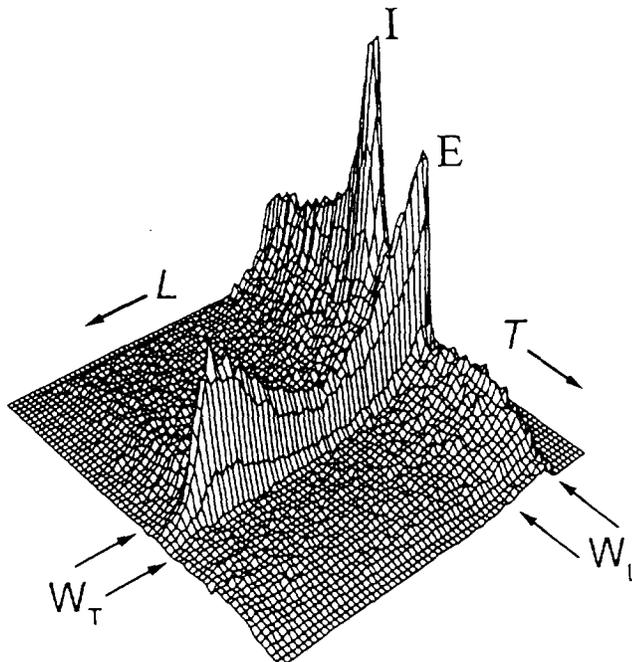Fig 1: Experimental arrangement for scattering measurements

Fig 2: Counts vs L and T from detector B, using a graphite scatterer, at $E = 7.5$ MeV.
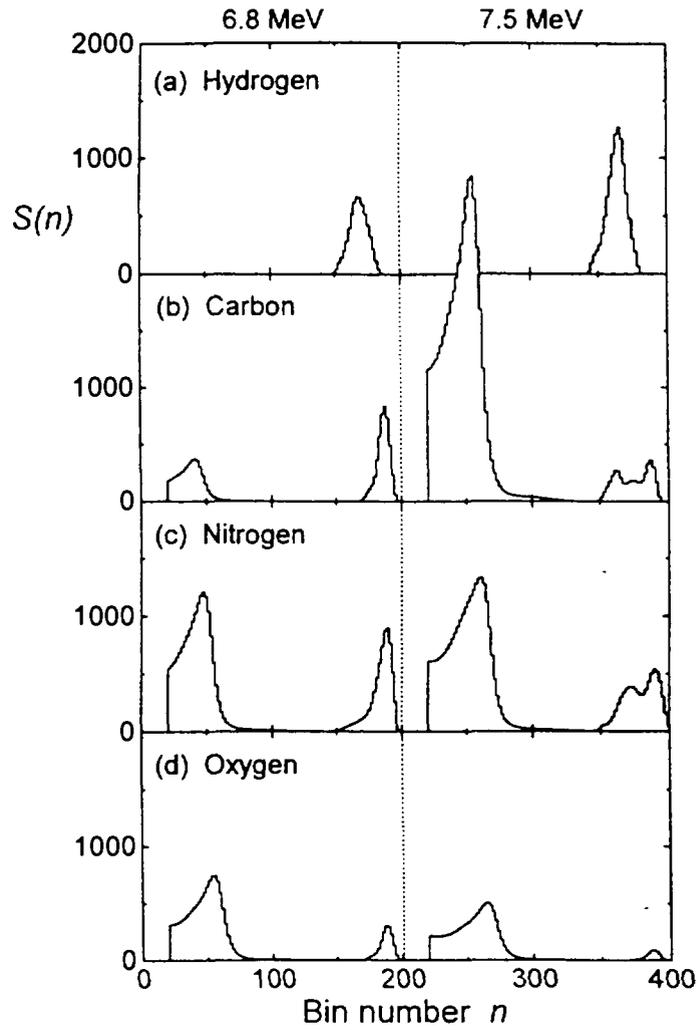
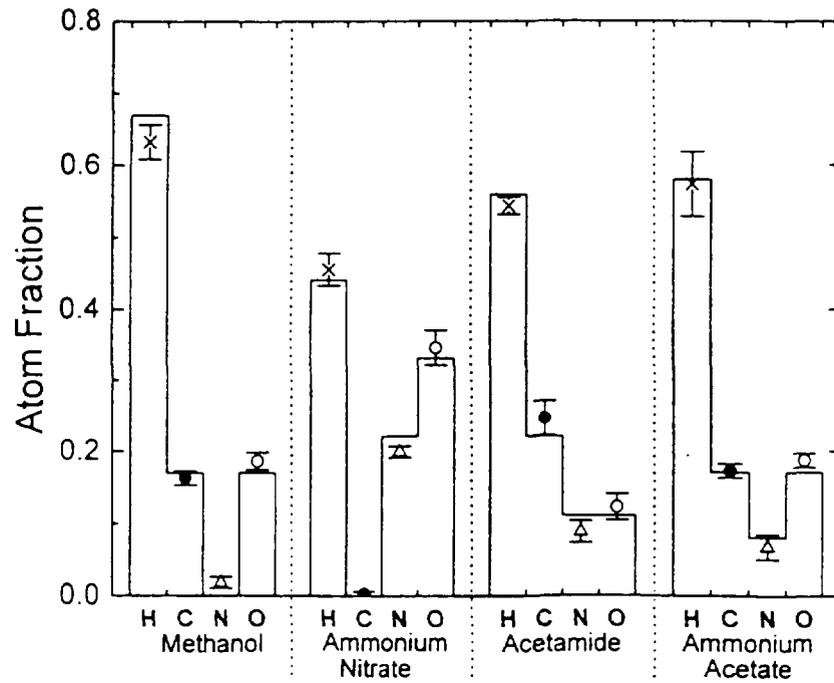Fig 3: Scattering signatures for H, C, N and O

Fig 4: Measured (points) and calculated (histograms) atom fractions for four compounds