Remote Detection of Concealed Nuclear Material

Dr. Gregory H. Canavan

1. The need to detect concealed nuclear materials became clear on 9/11. My testimony to the Subcommittee on Coast Guard and Maritime Transportation on 27 October 2015 argued that fast neutrons could produce the high signal to noise ratios (SNR) needed for confident detection of nuclear devices in transportation containers. The analysis here indicates that is also possible for devices with significant countermeasures intended to reduce nuclear signatures and energies. Fast neutrons could fill TEU with neurons that penetrate concealing moderators and cores, produce fission, and generate distinct signals at distant sensors. Fast neutrons produce fission neutrons whose energy difference forms the basis for robust detection of nuclear material. Fast neutron diffusion through moderators reduces their number but increases energy differences, which assists detection.

2. Fast neutrons can penetrate ≈ 30 centimeters of moderators deployed to reduce neutrons flux and energy and yet retain enough of each for detection. Thicker moderators produce high SNR signals whose energy bands indicate moderator composition and intensity indicates thicknesses.

3. Adding moderator to an initially sub-critical device shifts it towards criticality and increases external signatures. For a solid-core device with 10% safety margin an additional 15 cm moderator could shift it back to critical, which could be compounded by container materials. Concealment has a price.

4. Neutron multiplication in the core can be estimated with standard models, which indicate that it is well below unity. Thus, neutron interrogation could not induce criticality.

5. Detection depends on the ratio of the difference between source and fission neutron energies to their combined

standard deviation. Those of fission neutrons fall exponentially with the number of collisions they experience in diffusing out through the moderator, so their averages are only ≈ 1% of their peaks, which contributes to high SNR.

6. Source neutron energies over 1 MeV are far above the averages for fission neutrons. Added to the result that fission standard deviations are small, that leads to detection SNR above 100. While source energies are in the MeVs and their collisions occur in microseconds, the measurements for discrimination are on fission neutrons at keV on time scales of milliseconds, which are conventional.

7. An order of magnitude change in fission statistics does not degrade SNR significantly. A 10-fold increase in average fission energy and standard deviation would shift the energy for SNR = 100 from 1 to 3 MeV; a 30-fold increase would only shift it to 5 MeV. A 100-fold increase would shift it to ≈ 10 MeV, but SNR = 100 is apparently possible even there.

8. X-rays can detect but cannot identify mass. Passive sensors do not detect materials with low emissions. Thermal neutrons can penetrate but are easily countermeasured.

9. Fast neutrons can penetrate over 30 cm concealment with currents, energies, and high SNR for confident detection. Their sources could be adapted from conventional well logging devices and their detectors from reactor and high energy instrumentation. They could be deployed on cranes, ships, or in ports for fast inspection of all cargo containers for confident detection of nuclear threats attempting to take advantage of the large number of containers entering U.S. ports.

Figure captions

1. Fast neutrons slowing down in materials resembling the contents of typical TEU (≈ 5% density Fe, for which the mean free path is ≈ 1.5 m) produce a roughly uniform distribution of neutrons in TEU sized volumes. Their energy falls from 14 MeV to 6 MeV in ≈ 1 microsecond where fission neutrons are < 1 MeV. As both slow down they maintain a separation in energy that provides a basis for filtering. Source neutrons must diffuse through moderators, fission, and diffuse out for detection, which happens in less than a microsecond. Fast reactor theory can treat the slowing down of both the source and fission neutrons that represent the signal and noise. (G. Canavan, Remote Detection of Nuclear Material, Subcommittee on Coast Guard and Maritime Transportation, 27 October 2015)

2. Nuclear theory can treat the penetration of neutrons into moderators of varying thicknesses as a function of energy. For 5 cm carbon moderator (essentially a bare device) there is little attenuation. For 15 cm about 10% penetrates with 1 MeV energy left; for 30 cm about 0.1% penetrates. Thicker moderators produce high SNR signals that give information on their composition and thickness (E. Fermi Nuclear Physics)

3. There are constraints on concealment. A device with 4.5 cm core and 11.5 cm moderator radius whose fission probability is reduced 5% for safety would be returned to criticality by an additional 5 cm of moderator. One reduced by 10% would be returned to critical by 15 cm. (R. Serber, Los Alamos Primer, LA-1)

4. Neutron multiplication can be estimated with 6-factor models that reduce here to $f = \nu pq$, where ν is the number of neutrons per fission, p is the probability of fission (≈ 1 for highly enriched material) and q is the non-escape probability (1 for infinite media and $\approx 1/\nu$ near criticality.) For stability $f < 1$, or $pq < 1/\nu$, where $\nu = 2.9$ for plutonium and 2.4 for

uranium. The probability of a fission is p; the probability of 2 fissions in sequence is $(pq)^2$; of 3 fissions in sequence is $(pq)^2$; which sums to $pq/(1-pq) < (f/\nu)/(1 - f/\nu)$ fissions, which for plutonium is ≈ 0.5 and for uranium ≈ 0.7. Both are well below unity, so neutron interrogation could not produce criticality.

5. The energy E_F and standard deviation σ_F of fission neutrons fall exponentially with the total number of collisions experienced as they diffuse out through the moderator, by which both E_F and σ_F fall to ≈ 1 keV. Averaged over the slower fission rate collisions, the average E_F and σ_F are ≈ 20 and 6 keV.

6. At energies >1 MeV the source neutron energy E_S is much greater than E_F, and σ_F is small compared to standard deviation of source neutrons, σ_S, so the argument of the energy filter F reduces to $E_S/2\sigma_S$, which is approaches 10 at the far right side of the figure the curve. There the argument including the fission statistics, $(E_F - E_S)/2(\sigma_S + \sigma_F)$, is similar. At energies below 0.1 MeV where the fission statistics become important, it falls rapidly, which defines the region of useful filter gain. The filter is $F = 1 - \mathrm{erf}\,[(E_F - E_S)/2(\sigma_S + \sigma_F)]$; the SNR is S/F, which is presented for signals S = 0.1 for ≈ 15 cm moderators and 0.001 for 30 cm moderators, relative to unit sources. The SNR curve for 15 cm rises from ≈ 0.1 at 0.01 Me to ≈ 100 at 0.5 MeV, and that for 30 cm rises from ≈ 0.01 at 0.1 Me to ≈ 100 at 2 MeV, which are both large compared to those needed for high-confidence discrimination.

7. The signal to noise for the nominal parameters and a nominal signal of 0.1 is at left. The second curve results from increasing E_{SF} and σ_F arbitrarily by factors of 10; the second by 30; and the fourth by 100, which shift SNR = 100 energies to 2, 4, and 10 MeV. While the source interactions take place at MeV energies, the discrimination measurements would be at keV energies at millisecond time scales.

Fig. 1. Slowing down time vs Energy

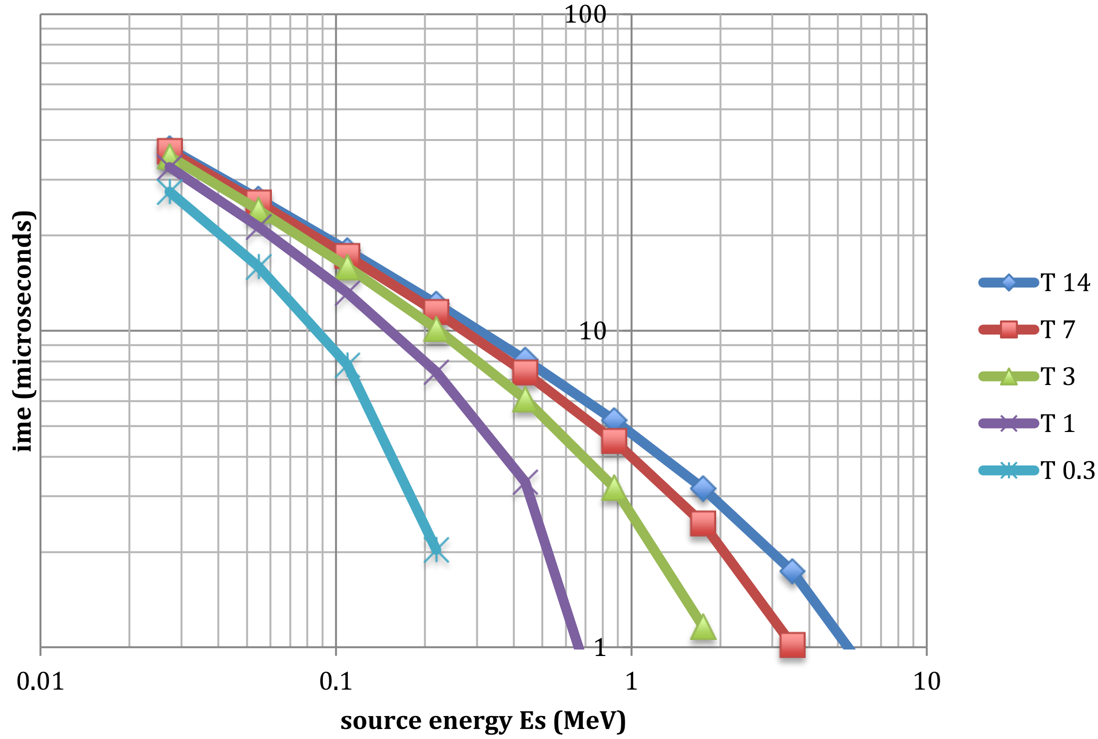


Fig. 2. Penetration to Range vs Energy

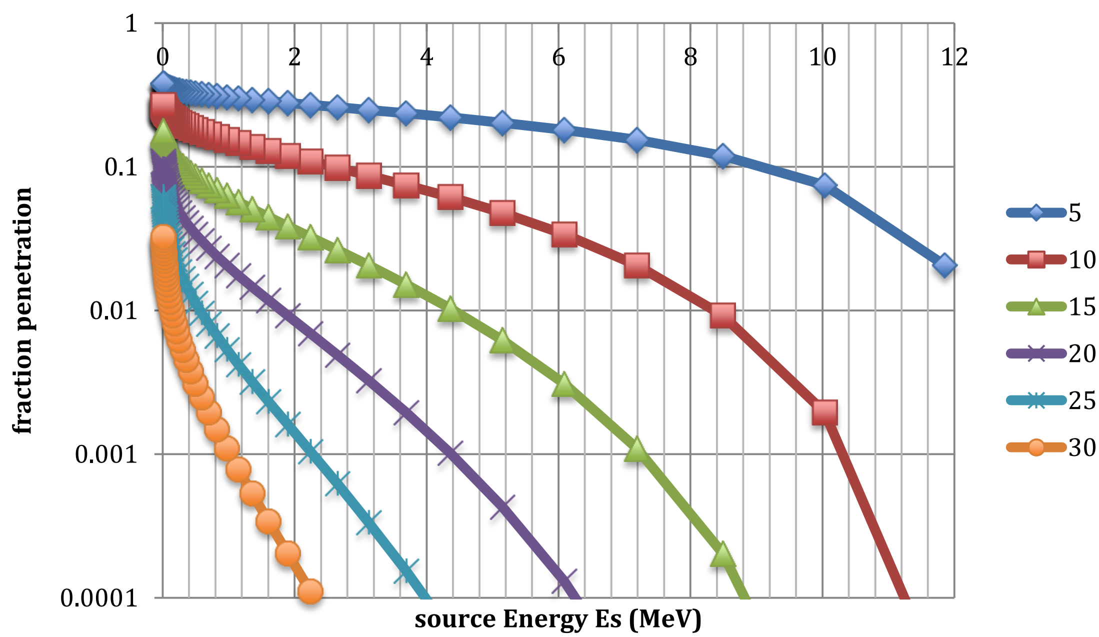


Fig. 3. Criticality vs moderator thickness

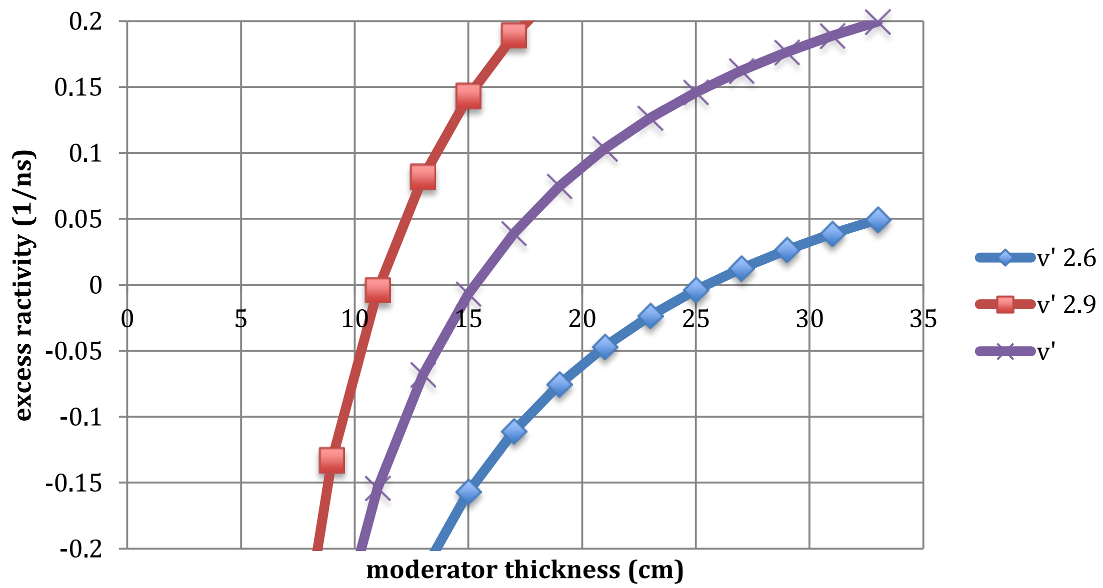
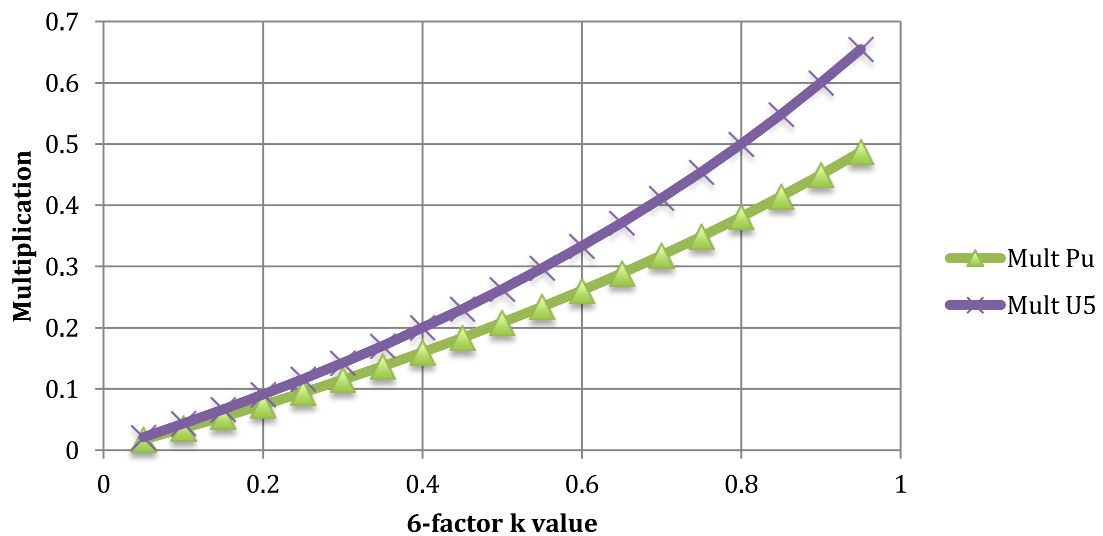


Fig. 4. Multiplication for Pu & U vs 6-factor k



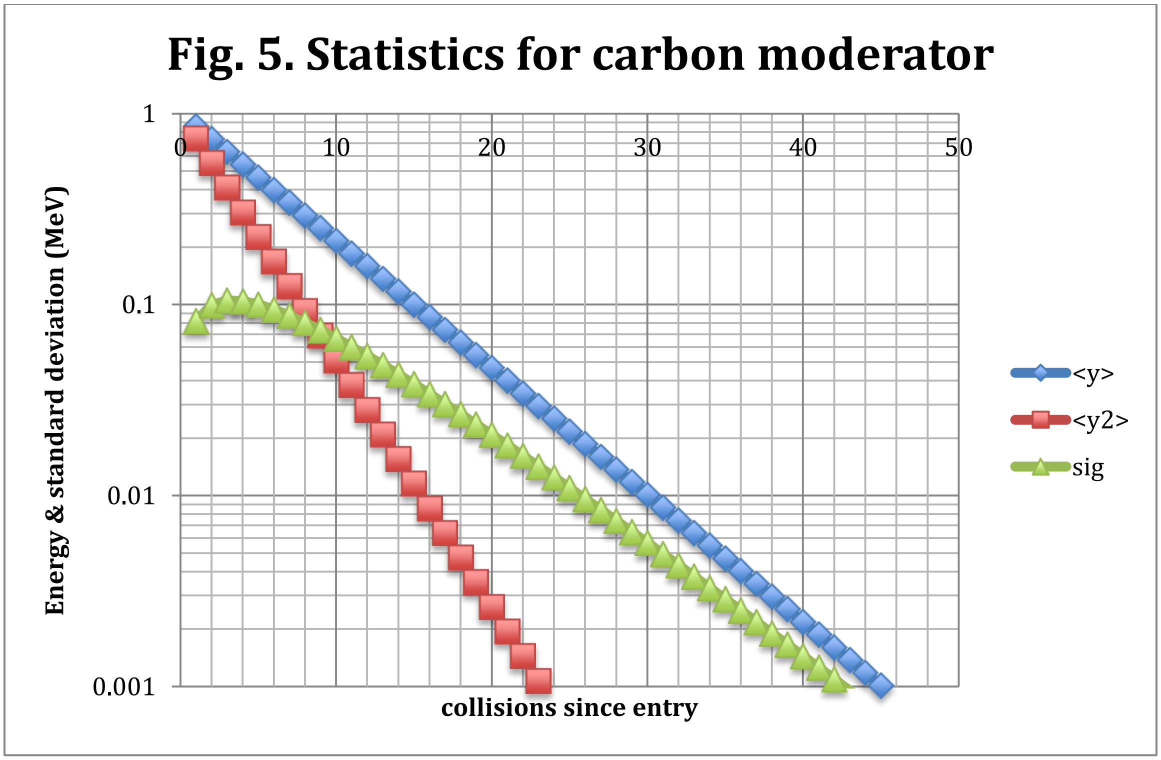


Fig. 5. Statistics for carbon moderator
Energy & standard deviation (MeV)
1
0.1
0.01
0.001
0
10
20
30
40
50
collisions since entry
<y>
<y2>
sig

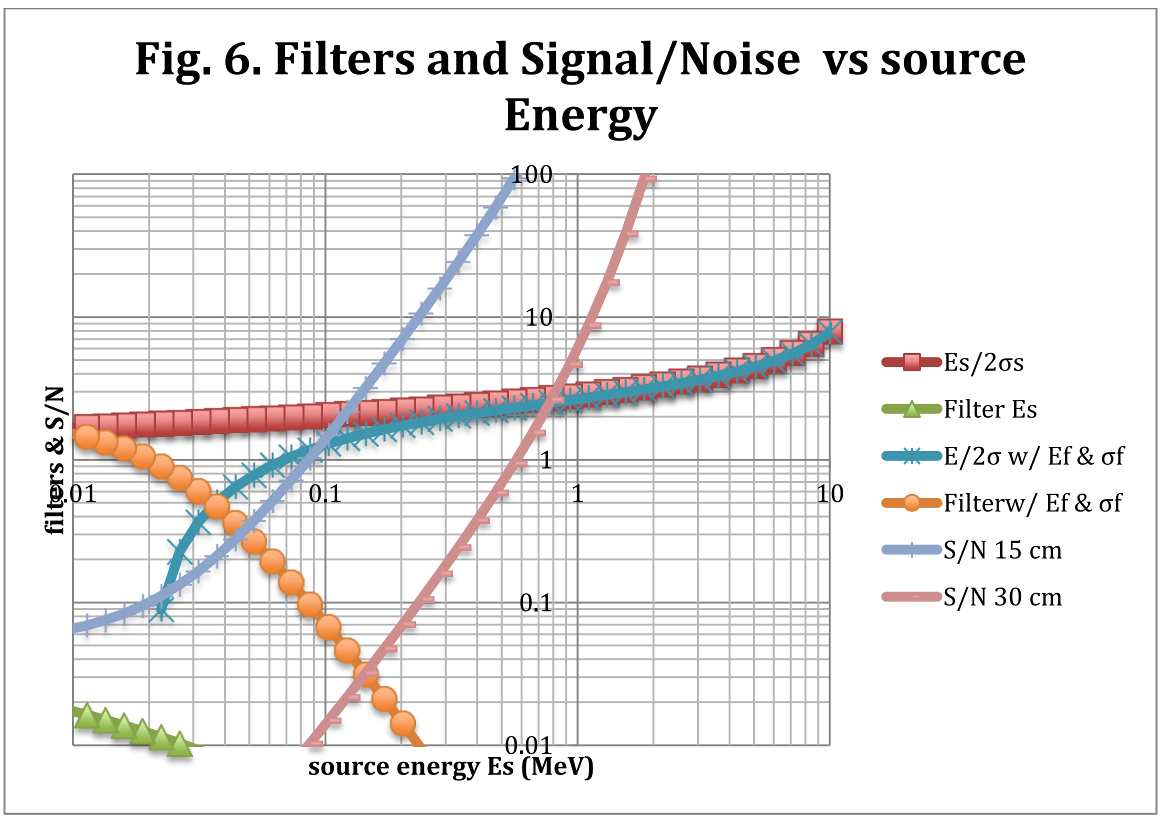


Fig. 6. Filters and Signal/Noise vs source Energy
filters & S/N
100
10
1
0.1
0.01
0.01
0.1
1
10
source energy Es (MeV)
Es/2σs
Filter Es
E/2σ w/ Ef & σf
Filterw/ Ef & σf
S/N 15 cm
S/N 30 cm

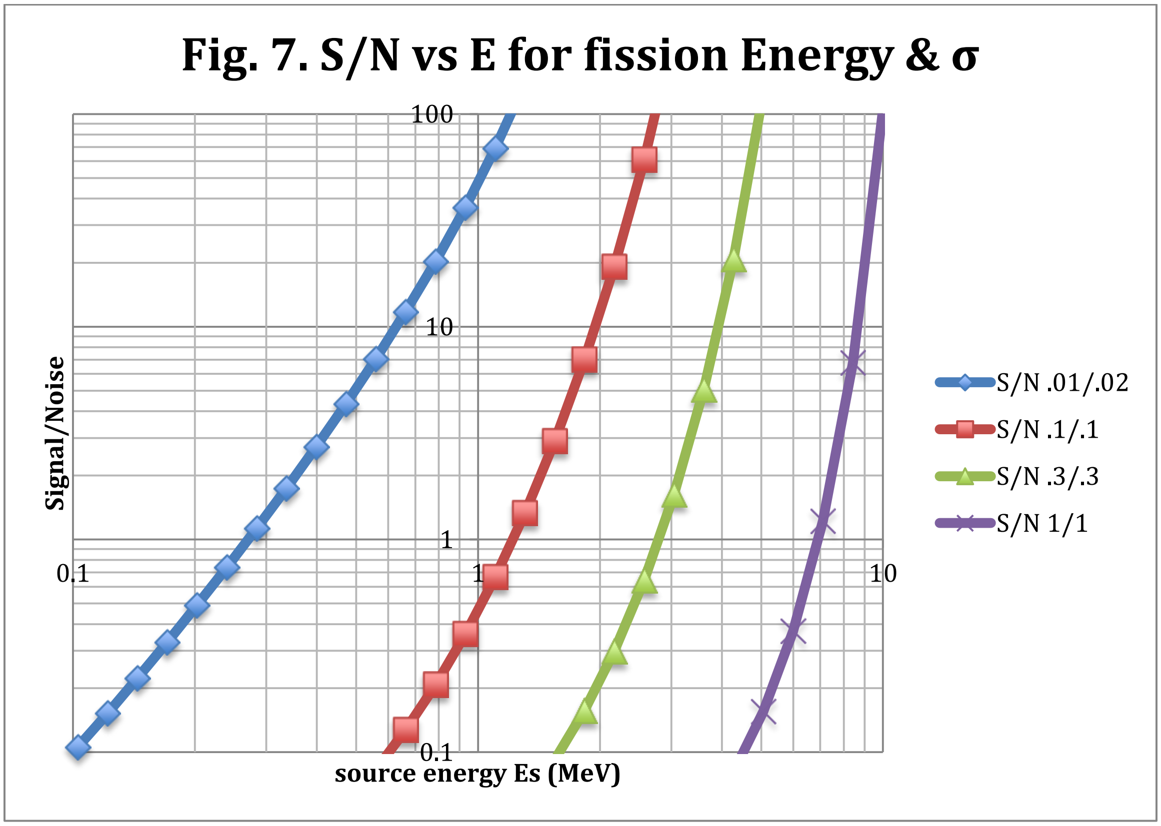


Fig. 7. S/N vs E for fission Energy & σ
100
10
1
0.1
0.1
1
10
Signal/Noise
source energy Es (MeV)
S/N .01/.02
S/N .1/.1
S/N .3/.3
S/N 1/1