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Design Fundamentals for Cost-Optimized Neutron Detectors Based on an Array of Helium-3 Tubes[1]

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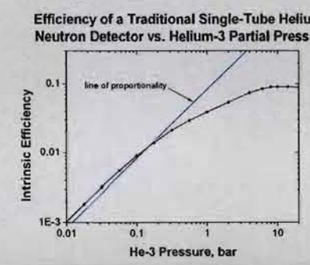
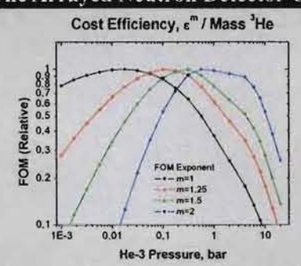
Utilizing He-3 Resources Efficiently

Increasing competition over the world's finite helium-3 reserves has recently created an urgent need to utilize our existing supplies of the gas in the most efficient manner possible. Traditional helium 3-based neutron detectors use high helium-3 pressures (>1 bar) to achieve high efficiency within a small detector volume. This design has the unfortunate side effect of inefficient use of the gas caused by self-shielding and albedo effects.

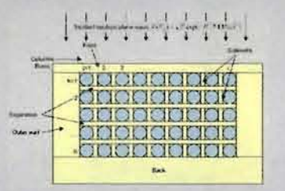


Cost Efficiency and Track Length: The Arrayed Neutron Detector Concept



Cost efficiency is defined as weighted unit detector efficiency per unit helium-3. The figure above shows that the optimum helium-3 partial pressure is less than 1 bar when cost is important (m<2), . The corresponding decrease in detector efficiency is recovered by using an array of low-pressure tubes nestled inside a lattice comprised of thin sheets of HDPE. The incident neutrons are trapped inside the lattice by increasing albedo as they gradually thermalize, passing through several tubes before eventually being captured in the helium-3 gas. The large effective increase in neutron flux results in efficiencies much greater than is possible with traditional helium-3 detectors while maintaining efficient use of the gas.

Optimization of the Lattice

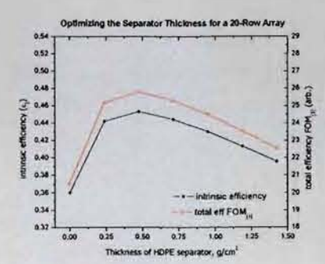


The above figure shows the layout for a rectangular lattice detector. The efficiency of the design was optimized for a plane wave of neutrons incident upon the front face by modeling the detector with MCNPX 2.6.0. A traditional single-tube detector containing 3 bar helium-3 was also modeled for comparison. The FOM used in the efficiency comparison is called the total efficiency figure-of-merit, which is defined as:

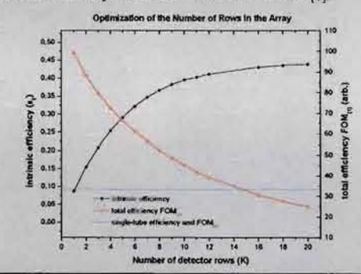
$$FOM_{[m]} = \left(\overline{\varepsilon_I}\right)^m \cdot A/V$$

where ε_I is the intrinsic efficiency, A is the surface area of the detector, V is the STP volume of helium-3 contained in the detector, and m is the cost efficiency weighting parameter. The maximum $FOM_{[1]}$ achieved for the single-tube detector of 33.3, with a corresponding efficiency of around 7.0%.

For the lattice, the helium-3 pressure was selected first by choosing $m = 1.5$, giving $\rho_{He\text{-}3} = 300$ mbar. Next, the HDPE layers were optimized using an iterative approach.



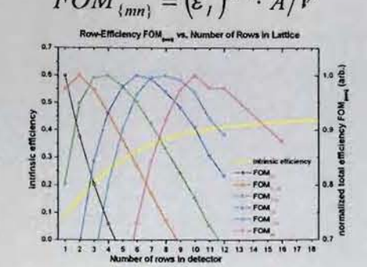
The figure at bottom left shows one stage of the optimization for a lattice containing 20 rows of tubes. Here $FOM_{[1]}$ for the array is slightly lower than that for the single-tube detector, at 25.8, but the efficiency is *much* higher, at 44.3%. This demonstrates that very high efficiencies are possible with array-based detectors if cost is not an issue. However, as the figure below shows, having fewer rows in the lattice is always better in terms of $FOM_{[1]}$



Application to Real-World Scenarios

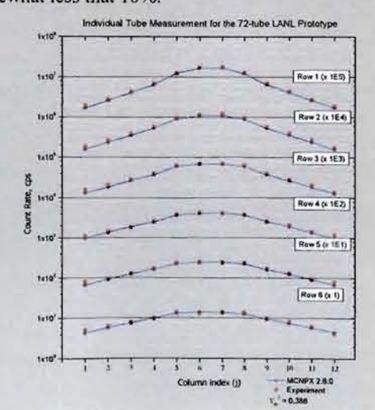
Frequently, a single-row lattice is not sufficient to meet count rate requirements. In this situation, additional rows are added to the detector. The number of rows is determined by introducing a second weighting factor, n, which represents the degree to which total efficiency is preferred over solid angle. This new figure of merit is called the row-efficiency FOM:

$$FOM_{\{mn\}} = \left(\overline{\varepsilon_I}\right)^{m \cdot n} \cdot A/V$$



The ANDY Prototype

A prototype detector was constructed at LANL for supporting homeland security experiments and benchmarking purposes. The prototype consists of 72 tubes, each 2" in diameter and 48" long and filled with 200 -mbar helium-3 and 800-mbar proportional gas. The fast-neutron efficiency (Californium-252 spectrum) is 23.1%.

Results of Benchmarking Experiment

A Californium-252 source attached to the front face of the detector was used in the benchmark experiment. MCPNX 2.6.0 was used to simulate the detector. The count rate was measured for all 72 tube positions, using the same tube for each measurement. A 10% error bar was assigned to the experimental data to account for uncertainties in source position, source activity, and environmental effects. The statistical monte-carlo error was less than 1%. The reduced chi-squared value of 0.388 suggests that actual error is somewhat less than 10%.