Comparing the response of PSD-capable plastic scintillator to standard liquid scintillator

Richard S. Woolf a,*, Anthony L. Hutcheson a, Chul Gwon a, Bernard F. Phlips a, Eric A. Wulf a

a High Energy Space Environment Branch, Space Science Division, U. S. Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375

1. Introduction

Until recently, the ability to perform pulse shape discrimination (PSD) – a property exhibited by certain types of scintillating material in which incident stimuli (fast neutrons or γ rays) can be separated by exploiting differences in the tail of their light pulses – in plastic scintillator was difficult, if not impossible [1]. A newly developed plastic scintillator capable of PSD [2] is now commercially available through Eljen Technology [EJ-299-33] [3]. Prior to this advent, only certain liquid and organic crystal scintillators (e.g., stilbene, anthracene, p-terphenyl) could perform PSD. Separating fast neutrons from the γ-ray background and performing neutron spectroscopy are important for applications in neutron physics, such as experimental nuclear physics [4], homeland defense [5], and near-Sun observing spacecraft [6]. Using plastic scintillators for said applications, as opposed to the commonly used aforementioned PSD-capable materials, has been desired in the field on neutron physics for the last half century. The downsides of liquid scintillators are that the material is caustic, flammable, and toxic, raising concern for field-deployable systems and spacecraft; organic scintillating crystals are typically more costly than plastics and more difficult to grow to a large size. An understanding of the scintillation light response function is paramount to the full characterization of this novel detector.
This work discusses a campaign that was carried out in December of 2013 to characterize the EJ-299-33 response, complementing work done by others in the community [7–10]. The main goal of this work was to understand the relationship between the amount of scintillation light yielded by fast neutrons interacting with constituent hydrogen nuclei, producing energetic recoil protons in the process. The way to properly investigate this relationship is to characterize the detector response as a function of incident neutron energy. To produce single-energy neutron emission, one must accelerate charged particles and allow them to undergo subsequent nuclear reactions, resulting in quasi-monoenergetic neutrons. By characterizing a PSD-capable radiation detector with quasi-monoenergetic neutrons, along with γ rays (to relate scintillator light output and recoil electron energy from interactions with atomic electrons), one can obtain a relationship between the neutron light output and recoil electron energy from interactions with atomic electrons. The common avenue to obtain a tunable source of quasi-monoenergetic neutron emission is at an accelerator facility, such as a cyclotron [11] or a Van de Graaff [12]. One can also obtain single-energy neutron emission through compact neutron generators that employ fusion reactions, such as deuterium–deuterium (D–D releasing \(E_n = 2.4 \text{ MeV}\)) or deuterium–tritium (D–T releasing \(E_n = 14.1 \text{ MeV}\)) [13].

To better understand the resultant distribution in energy obtained from a measurement with a radiation detector, a simulation of the experiment can be conducted through Monte Carlo modeling techniques. Modeling allows the user to define the details of the experiment (detector setup, spectrum, environment, etc.) and, based on first principles, numerically step through and track each particle, determining the interaction process and energy deposited along the way. By creating an ensemble of these events and applying specific detector resolution (\(s/E/E\)) functions, one can obtain results that can then be compared to the empirical data.

2. Experimental method

Detector characterization was conducted using the 5.5 MV Van de Graaff accelerator located at the University of Massachusetts Lowell (UML) [14] (Fig. 1). The accelerator produces energetic protons that are directed onto a thin (10 μm) Li target, resulting in quasi-monoenergetic neutrons from the \(^7\text{Li} (p, n)^7\text{Be}\) reaction. Typical accelerator current ranged between 1 and 5 μA. The energy spread due to \(dE/dx\) losses in the target is of order 50 keV. The reaction is endothermic with a Q-value of \(-1.644 \text{ MeV}\); thus, the energy of the outgoing neutron is the difference between the proton beam energy and the Q-value. Secondary reactions result from the first excited state of \(^7\text{Be}\), i.e., \(^7\text{Li} (p, n)^7\text{Be}^*\); the Q-value for this reaction is \(-2.075 \text{ MeV}\). At a fixed proton beam energy, different neutron energies are obtained by rotating a neutron spectrometer between 0° (on axis) to points off axis up to 135° – the maximum allowed backward angle. The spectrometer consists of a paraffin and Li\(_2\)CO\(_3\) collimator [15] located 2.6 m from the target.

The accelerator nominally ran with proton beam energies of 3.0 and 4.0 MeV. Tables 1 and 2 show the angle of the neutron spectrometer with respect to the beam and the resulting neutron energies obtained for 3.0 and 4.0 MeV, respectively. The angle of the spectrometer with respect to the beam was determined by markings on the rail along which the spectrometer rotated. There is an offset of 0.06 m between the location of the Li target and the axis of rotation. The angles listed in Tables 1 and 2 were corrected for the offset. The angle-dependent neutron energy was determined by previous work done on the angular distribution of the \(^7\text{Li} (p, n)^7\text{Be}\) reaction in the laboratory system [16]. A set of Legendre functions were fit to these data to derive a functional form for the energy-angle relationship (Fig. 2). The fourth-order Legendre polynomial that provided the best fit to the empirical data was formed by a 4th order Legendre polynomial to derive a functional relationship.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Angular dependency of the ground and first excited state neutron energy for a 3.0 MeV proton beam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected angle (degrees)</td>
<td>Ground state neutron energy (MeV)</td>
</tr>
<tr>
<td>0°</td>
<td>1.306 MeV</td>
</tr>
<tr>
<td>43.9°</td>
<td>1.144 MeV</td>
</tr>
<tr>
<td>74.5°</td>
<td>0.920 MeV</td>
</tr>
<tr>
<td>88.4°</td>
<td>0.819 MeV</td>
</tr>
<tr>
<td>133.9°</td>
<td>0.579 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Angular dependency of the ground and first excited state neutron energy for a 4.0 MeV proton beam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected angle (degrees)</td>
<td>Ground state neutron energy (MeV)</td>
</tr>
<tr>
<td>0°</td>
<td>2.323 MeV</td>
</tr>
<tr>
<td>43.9°</td>
<td>2.079 MeV</td>
</tr>
<tr>
<td>74.5°</td>
<td>1.734 MeV</td>
</tr>
<tr>
<td>88.4°</td>
<td>1.574 MeV</td>
</tr>
<tr>
<td>111.1°</td>
<td>1.348 MeV</td>
</tr>
<tr>
<td>133.9°</td>
<td>1.179 MeV</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental setup at the University of Massachusetts Lowell Van De Graaff accelerator. Shown on the left is the neutron spectrometer, behind which the detector and paraffin wax shielding were placed.

Fig. 2. Neutron energy-angle relationship in the laboratory system for the \(^7\text{Li} (p, n)^7\text{Be}\) reaction for a 3.0 and 4.0 MeV proton beams. Empirical data from [16] were fit with a 4th order Legendre polynomial to derive a functional relationship.
data is given in Eq. (1):
\[ E = aP_0 + bP_1 + cP_2 + dP_3 + eP_4 \]
where \( P_n \) \((n=0, \ldots, 4)\) are the Legendre polynomials and the coefficients are: \( a=1.3\), \( b=8.1 \times 10^{-4}\), \( c=-9.3 \times 10^{-5}\), \( d=3.7 \times 10^{-7}\), \( e=-4.1 \times 10^{-10} \) for a 3.0 MeV proton beam and \( a=2.3\), \( b=1.3 \times 10^{-3}\), \( c=-1.4 \times 10^{-4}\), \( d=5.4 \times 10^{-7}\), \( e=-5.5 \times 10^{-10} \) for a 4.0 MeV proton beam. As shown in Fig. 2, rotation angles < 45° result in a small change in the neutron energy; thus, angles between 0° and 43.9° (accounting for the aforementioned offset) were not used. The spectrometer was stepped in the increments shown in Tables 1 and 2 to obtain a range of neutron energies in approximately 200–300 keV steps. Following the range of angles at 3.0 and 4.0 MeV, the neutron spectrometer remained on axis, and the Van de Graaff accelerator was operated at 4.2, 4.5, 4.7, and 4.9 MeV, resulting in neutron energies of 2.52, 2.82, 3.03, and 3.0 and 4.0 MeV, the neutron spectrometer remained on axis, and 3.23 MeV, respectively. Varying the proton beam energy and the angle of the spectrometer allowed for the range of neutron energies between 0.5–3.2 MeV. The energy spread resulting from the angular acceptance of the spectrometer is of order 1%.

3. Equipment

3.1. Detectors

We tested two PSD-capable plastic scintillation (EJ-299-33) detectors of different geometries: 10 cm × 10 cm × 10 cm cube and 10-cm diameter × 10-cm long cylinder. Our group at NRL received the bare scintillator from Eljen Technology then assembled a radiation detection instrument. The plastic was wrapped with a thin, white diffuse reflector material, followed by a layer of pliable black cardboard paper. A 78-mm diameter hole was cut into the wrapping to match the diameter of the Electron Tubes Limited (ETL) [17] photomultiplier tube (PMT); ETL 9265KB (14-pin, nine-dynode stage PMT). The PMT was epoxied (manufactured by EPO-TEK) onto the scintillator surface and allowed to cure for a period of 24 h. The outer layer of material and PMT were then wrapped with several layers of black electrical tape.

For comparison studies, we tested liquid scintillation detectors with well-known response functions: the xylene-based EJ-301 [18], or NE-213 equivalent, (12.7-cm diameter × 12.7-cm long cylinder) and EJ-309 [19] (10 cm × 10 cm × 10 cm and 15 cm × 15 cm × 15 cm cubes). EJ-309 is comparable to EJ-301 in terms of response and light output, albeit with a higher flash point temperature. Table 3 lists the salient properties of each scintillator tested. The liquid scintillation detectors were fabricated by SCIONIX Holland B.V. The EJ-301 liquid is housed in 2-mm thick aluminum with a light-tight fixture for the 130-mm Photonis XP4572B PMT (20 pin, 10 dynode stages). The EJ-309 liquid-based detectors were manufactured in the same manner. The 10 cm × 10 cm × 10 cm EJ-309 cube used the 78-mm ETL 9821 PMT (20 pin, 12 dynode stages); the 15 cm × 15 cm × 15 cm EJ-309 cube used the 130-mm ETL 9390 (14 pin, 10 dynode stages).

At the UML facility, detectors were placed directly behind the opening (Ø 15 cm) of the neutron spectrometer (Fig. 3). To reduce the fast neutron background and the number of down-scattered neutrons, all exposed sides of the detector were shielded with 12-cm thick paraffin wax.

3.2. Electronics

The high voltage was supplied to each detector by either a 32-channel, ISEG high voltage module (maximum output voltage: ± 3 kV; current: 500 μA) [20] or a CAEN SY2527 power supply system with a 12-channel negative high voltage board (maximum output voltage: – 6 kV; current: 1 mA) [21]. The EJ-299–33 detectors were operated with positive biases of 990 V (cube) and 1000 V (cylinder). The 15 cm × 15 cm × 15 cm EJ-309 cube was operated at a negative bias of 830 V. The 20-pin PMT output on the 10 cm × 10 cm × 10 cm EJ-309 cube and 12.7-cm diameter EJ-301 detectors required a higher bias (and thus higher current) to yield comparable gains to the EJ-299–33 detectors and 15 cm × 15 cm × 15 cm EJ-309 cube. The high voltage was provided by the CAEN supply with negative biases of 1900 V (EJ-309) and 1580 V (EJ-301), each drawing in the range of 800–900 μA. Data were acquired by a 16-channel, 250-MHz Struck Innovative Systeme VME flash digitizing ADC (SIS3316) [22], capable of performing digital PSD measurement. The input to each SIS3316 channel is a negative, fast-rise signal, read in from the detector by a 40’ BNC cable.

3.2.1. Digital PSD

The acquisition system performed digital PSD through the charge integration method [23] where the charge pulse was integrated over user-defined gate widths – a short gate (on the order of 50 ns) and a long gate (on the order of 500 ns) – and the

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Salient properties of the organic scintillating material used in the UML test campaign.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EJ-299-33</td>
</tr>
<tr>
<td>Light output, % Anthracene</td>
<td>56</td>
</tr>
<tr>
<td>photoelectrons/1 MeV e⁻</td>
<td>8.600</td>
</tr>
<tr>
<td>Hydrogen-to-Carbon ratio</td>
<td>1.06</td>
</tr>
<tr>
<td>Density, g/cc</td>
<td>1.08</td>
</tr>
</tbody>
</table>
ratio of each gate was compared to reveal differences in the decay of the tail pulse arising from different scintillation mechanisms dependent on the incident stimuli. The pulse shape parameter used was \(1 - Q_s / Q_e\), where \(Q_s\) (\(Q_e\)) is the short (long) charge integration gate window. Fig. 4 shows a representative pulse (rendered using a 5-point running boxcar average) arising from either an incident \(\gamma\) ray or neutron (bold curve); the vertical lines indicate the regions that define the short and long integration gates.

4. Results

4.1. Calibration and initial neutron beam measurements

Various radioactive laboratory check sources (\(^{241}\)Am, \(^{57}\)Co, \(^{133}\)Ba, \(^{137}\)Cs, \(^{208}\)Bi, \(^{60}\)Co, and \(^{22}\)Na) were used to calibrate each detector response to monoenergetic \(\gamma\) rays, obtaining a relationship between the light output response in terms of electron equivalent energy \((E_{e.e.})\). As expected from previous work, the detector light output is linear for increasing \(E_{e.e.}\) based on a measure of the total integrated charge. Data at each energy were acquired for equivalent run times; however, due to variations in the beam current from the accelerator, the counts on the ordinate were scaled accordingly.

To select out neutron events, the common method is to make selections on a 2-d scatter of the aforementioned ratio (the pulse shape parameter) vs. the pulse height (energy). Displaying data in this manner (Fig. 6) show two distinct bands of events corresponding to \(\gamma\) rays (pulse shape centroid \(\sim 60\) ch.) and fast neutrons (pulse shape centroid \(\sim 110\) ch.). Background and 478 keV \(\gamma\) rays (from the \(^7\)Li\(p\),\(^n\)\(^7\)Be reaction) are filtered out by event selections (piecewise cuts in Fig. 6). The pulse shape parameter was tuned by optimizing the PSD figure of merit \((M)\) using a \(^{252}\)Cf \(n/\gamma\)-ray source, where \(M\) is the ratio of the distance between the centroids of the \(\gamma\)-ray and neutron distributions and the sum of the full widths at half maximum (FWHM) of each distribution. Typical values of \(M\) ranged from 0.5 to 2, dependent on energy and detector type. The spectra of the PSD-selected neutron events for each energy are shown in Fig. 7 for the 10 cm \(\times\) 10 cm \(\times\) 10 cm EJ-299-33 cube. Spectra are shown in terms of relative light output based on a measure of the total integrated charge. Data at each energy were acquired for equivalent run times; however, due to variations in the beam current from the accelerator, the counts on the ordinate were scaled accordingly.

To achieve Gaussian statistics \((\sigma \sim \sqrt{n})\) in the neutron-PSD selected band of events and to avoid pulse pile up events, it was requested that the accelerator operate such that each detector would count in the range of 10 kHz (all events) over a five-minute increment by varying the beam current. However, the stability of the accelerator output dictated that it operate with higher beam current (in the 3–5 \(\mu\)A range), and thus count rates of 30–100 kHz were often observed. The typical efficiency of the liquid and plastic scintillator is of order 10 s of percent based on the geometric area of the detector used (\(\sim 60\%\) for the 15 cm \(\times\) 15 cm \(\times\) 15 cm EJ-309 cube) in the fast neutron regime. The acquisition system sampling rate was well equipped to handle the high rate and still able to discriminate incident stimuli based on pulse shape. For data sets...
where the total event rate exceeded 50 kHz, the number of pile up events and falsely identified PSD events increased. However, given that the edge of the recoil proton spectrum was the main interest for this work and was clearly identified in the analysis procedure, the number of piled up events were acceptable because the main "n/γ" bands were cleanly separated.

4.2. Analysis

The main focus of the characterization was to test the response of the EJ-299-33 light output vs. recoil proton energy. Based on the spectra shown (Fig. 7), to compare our results with the widely accepted non-linear recoil proton light output vs. energy curves, we follow the method outlined by Verbinski et al. [25] where the half height of the abrupt edge near the maximum pulse height corresponds to the maximum hydrogen recoil energy (n-p scatter). The enhancement (bump) prior to the edge in each curve in Fig. 7 is the result of neutrons produced from the first excited state of $^{7}$Be, which serves as an additional data calibration point. The first excited state sits on the lower energy continuum of down-scattered and background neutrons, leading to the observed broadening.

Spectra from each detector were used to construct a curve of the recoil proton light output vs. energy (response function). To correct for differing gain settings, the curves from each detector and the data from Verbinski et al. were normalized to the Compton edge of $^{60}$Co as measured by the 12.7-cm diameter EJ-301 cylinder. (The EJ-301 equivalent scintillator was used in the original work of Verbinski et al.). Shown in Fig. 8 are the results of the normalized Verbinski et al. response, the 10 cm × 10 cm × 10 cm EJ-309 cube, and the EJ-299-33 (cylinder and cube) data in comparison with the previously determined EJ-301 response [25].

Along with the γ-ray calibration data, the fit results allow us to obtain a relationship for the $E_{e.e.}$ vs. $E_{p.e.}$. The value for the proton recoil centroids were input to the γ-ray calibration curves, defining $E_{e.e.}; E_{p.e.}$ is the recoil proton energy imparted by the accelerator-produced neutrons. This relationship is shown in Fig. 9 for the 12.7-cm diameter EJ-301 cylinder and the associated FWHM error bars at each energy. These data are shown in comparison with Verbinski et al. – the functional form of one of the standard response curves quoted for EJ-301/NE-213 scintillator. The EJ-301 data acquired at the UML facility is in agreement to within error with Verbinski et al. Also shown in Fig. 9 are the common light decaying background. The user input curve parameters define a fit region from a point prior to the rollover in the spectrum to a point that precedes the high-energy background continuum; the region associated with neutrons arising from the first excited state were fit in the same manner. A background region extending past the endpoint of beam-related neutrons is also defined. The output from the fitting procedure is the centroid of the $\text{erfc}(x)$ and the associated FWHM.

For a more quantitative measure of the maximum recoil proton energy and associated error, the spectra accumulated from each detector were fit using the curve fit procedure in ScientificPython (SciPy) [26]. The functional form used for the fitting procedure was the complementary error function, $\text{erfc}(x) \equiv 1 - \text{erf}(x)$, where $\text{erf}(x)$ is the standard error function [27] on an exponentially broadened.

![Fig. 7. Neutron energy spectra obtained from the 10 cm × 10 cm × 10 cm cube of EJ-299-33 plastic scintillation detector.](image1)

![Fig. 8. Response functions for PSD-capable plastic (EJ-299-33) and liquid (EJ-301 and EJ-309) scintillation detectors shown with the previously determined EJ-301 response [25].](image2)

![Fig. 9. The relationship between the electron equivalent energy ($E_{e.e.}$) vs. the proton equivalent energy ($E_{p.e.}$) for the data set obtained with the EJ-301. The data (with error bars) are shown for comparison with the functional forms of: Verbinski et al. [25], Cecil et al. [28], and Aksoy et al. [29].](image3)
response functions for EJ-301 (and its equivalent) provided by the Eljen Technology data sheet [28][29]. The results from Cecil et al. [28] extend over the range of 1–300 MeV, yielding a higher light output compared to Verbinski et al. Conversely, the functional form for $E_{e.e.}$ vs. $E_{p.e.}$ provided by Aksoy et al. [29] dramatically underestimates the response. Although it is noted that the Aksoy et al. results are valid in the 5–17 MeV energy range, the curve is shown here to demonstrate the inaccuracies of extrapolation to lower energies.

Fig. 10 shows the EJ-299-33 data, displaying that the overall light output is reduced compared to the EJ-301 standard. The curve associated with the EJ-299-33 is fit with the function of the form given by Eq. (2):

$$E_{e.e.} = aE_{p.e.}^b \ln(E_{p.e.}) + c \ln(E_{p.e.})$$

where the coefficients were determined to be: $a=0.114$, $b=1.382$, and $c=0.297$ (EJ-299-33 cube); $a=0.112$, $b=1.214$, and $c=0.316$ (EJ-299-33 cylinder).

The response curves for the EJ-309 scintillator are shown in comparison to the standard EJ-301 curve (Fig. 11). One can see that there is excellent agreement for the 10 cm × 10 cm × 10 cm cube; there is also good agreement for the 15 cm × 15 cm × 15 cm cube up to 2.5 MeV$p.e.$, where our measured data diverges from the EJ-301 standard curve, indicating higher light output.

### 4.3. Monte Carlo simulations

Monte Carlo numerical modeling was carried out using the NRL-developed SWORD (SoftWare for Optimization of Radiation Detection) radiation transport package [30]. The SWORD package provides a graphical CAD system for constructing the simulated scenario with built-in defined detector materials, geometries, and neutron/γ-ray emission spectra. The SWORD framework supports the transport engines of GEANT4 [31] and MCNPX [32].

#### 4.3.1. Neutron beam environment

Using SWORD to simply model the detector response to a monoenergetic neutron beam, results show a single, broadened peak (based on detector energy resolution) centered at the given energy. However, as shown by the measured data in Fig. 12 (solid curve), the results show a low-energy continuum preceding the recoil proton edge energy, followed by a background continuum. To properly assess the scenario, a mass model of the representative 15 cm × 15 cm × 15 cm EJ-309 cube was constructed inside the UML facility (volume: 10 m$^3$, wall material: concrete) situated behind the neutron spectrometer on axis with respect to the target. The full reaction of the Li target undergoing bombardment by 4.7 MeV protons was simulated by isotropic point source emission of 3.03 MeV (from the ground state) and 2.579 MeV (from the first excited state) neutrons from the location of the target with respect to the detector. The angular dependence of the reaction was not simulated. Events that triggered a hit were then convolved with an energy resolution function of the form: $1/\sqrt{\delta E/E}$, with 32% $\delta E/E$ at 662 keV. The first excited state reaction was scaled by 6% given the relative reaction rate [16]. Summing the simulated events show the low-energy continuum ($< 2.0$ MeV) produced by the down-scattered accelerator neutrons (Fig. 12, dashed curve). However, there is a discrepancy between the counts in the low-energy continuum in the sum of the simulated data, compared to the measured data. This discrepancy is also present in the region between the edges corresponding to

![Fig. 10](image1.png)

![Fig. 11](image2.png)

![Fig. 12](image3.png)
neutrons from the ground and first excited state. (To normalize the first excited state neutron events riding on the low-energy continuum, we matched the relative heights of ground state and first excited state in the observed data. The first excited state reaction was increased by a factor of 2.5 relative to the ground state). The sum of the simulated data is lower by a factor of ~2–4. This result could be attributed to piled-up events contaminating the neutron-PSD selected events in the measured data, leading to the increase in counts. The likelihood for the false identification of neutron-PSD selected events, especially at lower energy (pulse height), increased due to the high flux encountered during the experiment.

To assist in fully understanding the resulting distribution, we must consider other competing reactions that can occur within the organic scintillator, such as elastic scattering between neutrons and constituent carbon nuclei (n-C scatters). Experimentally there is no reliable way to account or correct for these events in the fast neutron energy range. For n-C scatters, the neutron can transfer up to 28% of its incident energy to the recoil carbon, whereas in the case of the n-p scatter the neutron can deposit up to 100% of its incident energy to the recoil proton [33]. On average, a n-C scatter occurring prior to a n-p scatter results in a 14% lower energy deposit to the recoil proton (assuming the neutron deposits its full energy in the reaction), which could additionally contribute to the low-energy continuum. For a n-C scatter occurring after the n-p scatter, recoil carbon produces an undetectable amount of scintillation light in the few MeV neutron range and thus would not contribute to the overall measured pulse height. Moreover, the cross section for elastic n-p scattering in the few MeV range is greater than that for elastic n-C scattering by a factor of ~2, aside from the resonance reactions in the 3–6 MeV range. The inelastic n-C scattering cross section, which has a comparable cross section to the elastic n-C reaction above 7 MeV, was not considered in this work.

4.3.2. Background data + neutron beam simulation

For the background, a five minute data set at the UML facility did not show what was observed above 4 MeV in Fig. 12 (solid curve). The high-energy background component is thus a combination of contaminated events within the neutron PSD selection with some contribution from high-energy background neutrons. A data set with either: the beam stop in or with the detector situated elsewhere (not in the beam path) with the beam on could have with either: the beam stop in or with the detector situated elsewhere (not in the beam path) with the beam on could have with either: the beam stop in or with the detector situated elsewhere (not in the beam path) with the beam on could have with either: the beam stop in or with the detector situated elsewhere (not in the beam path) with the beam on could have.
[32] Monte Carlo N-Particle (MCNP), MCNPX-5 Monte Carlo Team, LA-UR-03-1987, Los Alamos National Laboratory, Los Alamos, NM.