Deuterated-xylene (xylene-d₁₀; EJ301D): a new, improved deuterated liquid scintillator for neutron energy measurements without time-of-flight

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Abstract

In conjunction with Eljen Technology, Inc. (Sweetwater,TX) we have designed, constructed, and evaluated a 3 in. x 3 in. deuterated-xylene organic liquid scintillator (C₈D₁₀; EJ301D) as a fast neutron detector. Similar to deuterated benzene (C₆D₆; NE230, BC537, and EJ315) this scintillator can provide good pulse-shape discrimination between neutrons and gamma rays, has good timing characteristics, and can provide a light spectrum with peaks corresponding to discrete neutron energy groups up to ca. 20 MeV. Unlike benzene-based detectors, deuterated xylene is less volatile, less toxic, is not known to be carcinogenic, has a higher flashpoint, and hence is much safer for many applications. In addition EJ301D can provide slightly more light output and better PSD than deuterated-benzene scintillators. We show that, as with deuterated-benzene scintillators, the

light-response spectra can be unfolded to provide useable neutron energy spectra without need for time-of-flight (ToF). An array of these detectors arranged at many angles close to a reaction target can be much more effective (x10 to x100 or more) than an array of long-path ToF detectors which must utilize a narrowly-bunched and pulse-selected beam. As we demonstrate using a small Van de Graaff accelerator, measurements can thus be performed when a bunched and pulse-selected beam (as needed for time-of-flight) is not available.

1. Introduction

The detection of high-energy neutrons (i.e. a few MeV and beyond) as first done originally by James Chadwick [1], typically requires detection of a secondary, recoiling charged particle. The latter usually is a proton recoil from n+p elastic scattering although other neutron-induced reactions can occur in the detector medium. For example ^3He also may be used, especially if energy information of the neutron or fast timing is not needed [2,3]. In contrast to the latter, ^1H -based organic plastic or liquid scintillators can in principle provide information on the energy of the incident neutron either directly from the scintillation light or using a neutron time-of-flight (n-ToF) measurement given the fast nsec-level timing capability for such detectors [2,3]. In addition ^1H -based liquid organic scintillators such as NE213, BC501, EJ 301, EJ 309 and others as well as some new ^1H -based organic plastic scintillators such as EJ 299-33 [4-6] can provide pulse-shape discrimination (PSD) to separate gamma rays from neutrons incident on the detector [2,3,7-9].

Good PSD is essential for optimal use of scintillators in certain nuclear-reaction measurements and especially for applications in nuclear non-proliferation where fission neutrons 0.1 to several MeV must be detected and characterized in the presence of many gamma rays. Unfortunately as they are iso-spin states of the same basic nucleon, there is fore-back symmetry in n+p elastic scattering. This produces a rather

featureless recoil-proton scintillation light spectrum (L) up to some maximum related to the maximum proton recoil energy and hence the energy of the incident neutron [2,3,9]. While it is possible in some cases to unfold the light spectrum to obtain the energy spectrum of the incident neutrons, this is often problematic. One then typically must use n-ToF for neutron energy measurements, often requiring a long flight path e.g. several meters for MeV-energy neutrons [2,3,9]. This becomes less feasible when low-intensity, secondary, short-lived radioactive ion beams are being studied as is now often the case at many nuclear-research accelerators e.g. at the University of Michigan (UM) -University of Notre Dame (UND) low-energy radioactive ion-beam facility *TwinSol* at UND [10]. At the *TwinSol* facility, we have used deuterated-benzene detectors (benzene-d₆; EJ315) for neutron measurements with both stable and short-lived, low-intensity secondary beams such as ⁶He and ⁷Be [11]. Likewise n-ToF experiments are more complex when the accelerator beam cannot be narrowly bunched in time and pulse selected. In such a situation, a secondary reaction particle [12] must be used to initiate the n-ToF signal, with often a significant sacrifice in overall detection efficiency.

Brooks, et al. pioneered the concept of using ²H-based scintillators to remove the limitations of ¹H-based scintillators and in particular the limitations on unfolding the scintillation light spectra to extract the incident neutron energy spectra [13,14]. It was realized that in contrast to n+p scattering at MeV energies, the large asymmetry in the corresponding n+d elastic scattering for incident neutrons at these energies produces distinct peaks in the light spectrum. In addition to the creation of distinct peaks, these detectors provide somewhat better PSD, in principle at least, due to the larger density of ionization and hence larger pulse-height defect associated with recoiling deuterons in the scintillator relative to recoiling protons. These features *greatly* facilitate the identification of discrete neutron energy peaks and the subsequent spectral unfolding to obtain usable neutron energy spectra.

Brooks et al. originally demonstrated this effect using small

deuterated-anthracene detectors [13] and later with deuterated benzene (benzene-d₆, C₆D₆), specifically NE230 [14]. Subsequently other groups including our group at UM, have exploited deuterated-benzene detectors (BC-537,NE-230), now marketed as EJ315, in a number of nuclear reaction studies using both stable and short-lived nuclear beams, as well as demonstrating applications of such detectors in nuclear security and nuclear non-proliferation [11,15-21]. However, benzene-based liquid scintillators have potential safety issues e.g. for field applications, and in particular the low flashpoint (Table 1) and its carcinogenic properties. Likewise as noted their PSD and light output are somewhat poorer than other organic scintillators such as xylene-based NE213 and EJ301. Better PSD for low-energy fission neutrons (E less than 1 MeV), and for neutron energies > 10 MeV where n+d breakup can start to produce a significant number of recoil protons is important [11,18]. Breakup protons must be separated using PSD from the recoil deuterons in order to preserve the neutron peaks in the recoil-deuteron spectrum. As noted in the abstract, this generally limits the useful neutron energy region to < 20 MeV. This limits the use of deuterated benzene and other deuterated detectors in some applications unless specific dopants are employed to enhance the PSD, such as in the special EJ315M detector we have previously evaluated [11,18].

Working with C. Hurlbut and colleagues at Eljen Technologies, Inc.. (Sweetwater TX) we have designed, constructed and evaluated a prototype 3 in. dia. x 3 in. (ca. 75 mm dia. x 75 mm) xylene-d₁₀ liquid scintillator (denoted here as 3x3 EJ301D; Fig.1). While presently about twice as expensive as a similar deuterated-benzene based scintillator the improved performance and added safety may justify the increased cost in many applications. (The formulation of deuterated scintillators requires that all solvents and additives, where possible, also be highly-enriched deuterated compounds and this is an expensive process relative to producing normal ¹H-based scintillators). The custom EJ301D detector cell, PMT (a 3 inch dia., ETEL 9821KEB), and PMT base are similar to the

other Eljen detectors (EJ315 in particular) we have designed and have in active use. The design includes an SMA fiber optic port at the cell-PMT interface (Fig.1) for insertion of a stabilized LED light pulser signal.

In parallel with the evaluation of the EJ301D detector we also have for comparison data obtained for several xylene ^1H -based EJ301 detectors of similar design (including the PMT and base) as well as several EJ315 and EJ315H (^1H -based version of EJ315) detectors of similar size and design. This includes a 3 in. dia. x 2 in. EJ315 detector from Scionix, Inc. (which we will denote as 3x2 EJ315) that will be used here to compare with many of the 3x3 EJ301D detector measurements.

The characteristics of the EJ301D and EJ315 deuterated scintillator liquids are shown in Table 1. In addition to the different flashpoints, the xylene-based scintillator has slightly more light output and more ^2H content relative to carbon than a benzene-based scintillator which should yield a somewhat better PSD and intrinsic neutron detection efficiency for a given detector volume. However this can be impacted by the efficiency and intrinsic resolution of the light collection for a specific detector+PMT combination (see below).

2. PSD and neutron scintillation spectrum from ^{252}Cf fission neutron sources

Initial PSD and spectrum measurements were performed using various commercial ^{252}Cf fission sources that were previously available, or ones recently purchased specifically for scintillator evaluations having accurately-known activity. This included a very intense ^{252}Cf fission source (5.63 mCi). Owing to the gas-filled expansion volume inside the cell (about 3 % of the volume), the Eljen detector is operated horizontally. This minimizes interference of the gas expansion volume (Fig.1) with the light collection if the detector were operated vertically, e.g. face down with the gas volume at the PMT face [11].

The initial measurements of the PSD and ^{252}Cf fission-neutron

spectra were obtained using the digital signal processing (DSP) hardware and software developed previously for use with our EJ315 detector array [11,18] together with commercial, low-intensity ^{252}Cf sources (<100 uCi). The latter permitted measurements with the detector close (e.g. 1m or less) to the source without pulse pile up and negligible room-return scattered neutrons. Later measurements used the intense, commercial 5.63 mCi ^{252}Cf source set up for n-ToF, with DSP hardware and software developed specifically for detector evaluations [20,21].

In order to obtain ToF spectra, a fast timing plastic scintillator and PMT was set up near the sources to trigger on prompt fission gamma rays and provide a start signal. However the use of the intense source and long flight paths also required measurement and removal of the room-return scattered background neutrons using a long polyethylene shadow bar (see below).

In all our measurements the PSD signal was generated in DSP software from the fully digitized PMT anode signals, which were event-mode recorded as appropriate to a large-capacity computer disk. The DSP parameter was generated using user-specified short and long pulse-integration gates on the PMT anode signals. These gates could be optimized as needed using the stored event-mode data for a specific measurement. The PSD parameter for a particular set of gating parameters was then displayed vs. the long-gate integrated signal (total scintillation light) as shown in Fig.2. 2D gates set on the neutron and gamma groups were then used to project out their respective combined or individual scintillation light or ToF spectra (e.g.Fig.3).

In these and later measurements (below) the PMT HV was adjusted, typically between -1750 and -1850 volts, as needed to obtain a suitable scintillation signal for accurate digitizing. The light spectrum (i.e. integrated PMT anode light-pulse signal) was then calibrated in units of electron-equivalent units (MeVee) using the measured energies of the Compton edge (58% point in the measured spectrum) for one or more standard gamma ray sources and in particular ^{137}Cs (0.662 MeV gamma).

This corresponds to procedures previously developed and used to calibrate the 3x2 EJ315 and other scintillator detectors [11,18,20,21]. It is based on simulations of where the Compton edge will be located when a realistic detector resolution function is included in the Compton electron spectrum. The calibration procedure allows the PMT HV to be changed as needed for a specific measurement yet permits renormalization of the data back to the same MeVee light-output scale in a consistent manner.

One can define the quality of the PSD by defining a figure of merit (FOM) value given by $FOM = s/(\delta n + \delta \gamma)$, where "s" is the separation between the PSD neutron and gamma bands at a given light output (Fig.2) with δn and $\delta \gamma$ the full-width half-maximum (FWHM) of the neutron and gamma bands, respectively. The EJ301D scintillator liquid has a somewhat faster response than EJ315 (Table 1) and hence somewhat different pulse shape for the light signal detected by the PMT. Hence the PSD parameters used in the DSP software were varied to optimize the 3x3 EJ301D PSD FOM. A 40 nsec delay between the start of the total pulse integration and the start of the shorter, pulse-tail gate was deemed optimal for most purposes.

A comparison between the FOM obtained for the 3 x 3 EJ301D detector and the 3 x 2 EJ315 detector is shown in Fig. 4. As expected the 3x3 EJ301D exhibits somewhat better PSD over the neutron energies shown. One can see effective n- γ separation down to about 0.05 MeVee or about 0.35 MeV equivalent neutron energy (see below) that is comparable to that obtained with other EJ315 detectors [11,16-21]. Further improvements in the low-energy FOM and n- γ separation for EJ301D should be possible with the use of a lower noise, higher efficiency, albeit more expensive PMT, or by utilizing a smaller detector cell with better light collection [16-18].

Gating on the 2D PSD spectrum to generate a neutron light spectrum yields the ^{252}Cf fission-neutron spectrum for one of the low intensity sources is shown in Fig.5. As expected, this is comparable to that observed using EJ315 detectors [11,18,20,21]. It was shown for the

latter detectors that owing to the special properties of deuterated scintillators, if the response matrix $L(E_n)$ is known, the light spectra can be accurately unfolded without use of n-ToF to obtain the intrinsic fission-neutron energy spectrum down to the detector PSD threshold [8]. Hence it was demonstrated that such detectors can be used to identify the specific fission source material [20,21]. This can have important applications in the detection of weapons-grade materials for national security and nuclear non-proliferation. However such unfolding requires a good knowledge of the light spectrum vs. incident neutron-energy response transfer matrix [8,11,18, 20,21].

3. ^{252}Cf n-ToF spectrum, light output, and preliminary response matrix

Preliminary measurements of the response matrix (L vs E_n) needed to permit spectrum unfolding for EJ301D scintillator was obtained using n-ToF data obtained with the 5.63 mCi ^{252}Cf source noted above. The detector was placed 2 m from the source with a fast start signal provided as noted above. Using the DSP system employing software-generated constant-fraction discrimination (CFD) fast timing with about 1 ns timing resolution after CFD processing, n-ToF spectra (including corrections for room-return neutron background) similar to that shown in Fig 3 were obtained. ToF gates spanning small neutron energy windows centered on specific incident neutron energies up to ca. 6 MeV were then used to project out the light-response spectrum for a given incident neutron energy. This then provided a first set of response matrices $L(E_n)$ for EJ301D spectrum unfolding to obtain neutron energy spectra. Such spectra resemble those later obtained at ca. $E_n=2.5$ MeV using a dd neutron generator (see below).

As expected the preliminary response matrix elements and light output values deduced for 3x3 301D detector resemble those previously

measured for EJ315 detectors [11,18,20,21]. Improved measurements with lower statistical uncertainties are in progress using the above set up. Likewise, additional measurements to higher neutron energies are planned using the special long-path (14 m) n-ToF beam line constructed for this purpose at the UND FN tandem Van de Graaff accelerator (or a similar facility) [11,18,20].

The n-ToF measurements with the ^{252}Cf sources yield data for the EJ301D scintillator light output vs. E_n corresponding to the maximum energy ($8/9 E_n$) for the deuteron-recoil peaks observed in the energy-gated n-ToF light spectra. Using this and other data (see below) the response of EJ301D relative to EJ301/BC501 and EJ315 /NE230 scintillators was determined for fission and other neutrons, and is shown in Fig.6. Previously, liquid scintillator light-response data has been fit well with an appropriate equation by A. Enqvist et al. [23]. This approach is shown in the Fig.6 along with the response calculated with the same equation with parameters fitted to the present 3x3 301D data for $E_n > 1$ MeV.

4. Resolution measurements using coincident Compton scattering and LED pulser

The light-spectrum resolution for recoil electrons inside specific detectors was measured using coincident Compton-electron gamma-ray scattering. The Compton-scattering set up used at the UM Advanced Physics Teaching Laboratory is shown in Fig. 7. In this measurement, the liquid scintillator cell serves as an active target to detect Compton-recoil electrons from an incident, intense (mCi-level), collimated MeV gamma source (^{137}Cs ; 0.662 MeV). A coincidence between the electrons detected in the liquid scintillator with the scattered gamma rays detected in a well-collimated NaI(Tl) detector situated at a specific angle relative to the active-target scintillator produced electrons with known energies. The latter had a FWHM of about 1% due to the collimation and associated

angular acceptance for the liquid scintillator under study. The recoil electron energy could then be altered by changing the Compton gamma-ray scattering angle (Fig.7). The detector cells have relatively thin aluminum shells that only slightly attenuate and further scatter the gamma rays. The PMT anode signals from the 3x3 EJ3901D detector for various PMT HV settings overlapping those used in other measurements were processed using conventional NIM electronics together with a NIM coincident unit. The resulting electron signals were then analyzed with an Amptek 8000A MCA and associated software.

Typical coincident-electron spectra for the 3x3 EJ301D detector are shown in Fig.8. The electron scintillation light signal resolution for 0.2 to 0.5 MeV electrons ranges from 25 % to 16 % FWHM respectively. The resolution in the companion 3x2 EJ315 detector is expected to be similar [8]. The intrinsic resolution for the EJ301D detector due to the light collection and PMT was then estimated using a fast, pulsed, stable (<1% variation in light output) blue LED light source [24] inserted via a fiber optic (FO) cable to the SMA FO fitting at the detector cell-PMT interface (Fig.1) to simulate a detector scintillation signal. A typical LED pulser spectrum in the 3x3 EJ301D detector, with the LED intensity matched to a similar Compton electron signal, is shown in Fig.8. This and similar measurements indicate an intrinsic light-collection+PMT resolution in the detector of 20% to 12% FWHM over the equivalent light output generated by 0.2 to 0.5 MeV electrons respectively. (The LED port was not available on the particular 3x2 EJ315 detector used).

A fast electronic pulser signal inserted at the PMT anode output signal verified that the intrinsic PMT electronic and dark noise in the system was negligible at the keVee signal level. Hence as expected much of the detector resolution is primarily the result of the photon light-collection statistics for the particular cell+PMT combination used and is similar to that observed for like-size EJ315 cells [8,18] including the 3x2 EJ315 detector. The scintillator resolution and PSD improves [8,11] with better light collection (e.g. smaller cell size) and increased PMT efficiency

(e.g. as noted by use of a low-noise, high efficiency, more costly PMT [11]).

5. In-beam measurements

In addition to the ^{252}Cf fission-source measurements, a series of measurements was made using 1) a dd 2.5 MeV neutron generator and 2) neutrons from (d,n) reactions on various targets at $E_d = 6$ MeV.

5.1 dd- generator measurements

Mono-energetic neutrons at 2.46 MeV (spread 0.13 MeV FWHM) were generated with a Model MP320 Thermo Scientifictm dd neutron generator [23]. The 3x3 EJ301D and companion 3x2 EJ315 detectors were located 82.6 cm from the generator in a well-shielded concrete-walled accelerator room with the intensity adjusted to minimize pulse pile up (80 kV tube voltage, 60 μA current, 100% duty cycle). Also, 5 cm of lead to reduce the gamma-ray flux and a 61 cm polyethylene shadow bar to measure and remove room-return scattered neutrons were utilized. Spectra obtained are shown in Fig. 9 where we compare the response for the 3x3 EJ301D and 3x2 EJ315 detectors normalized by their respective scintillator volumes. Again the light outputs (using the light-pulse integral) were matched with Compton electrons using a ^{137}Cs gamma source and calibrated in units of MeVee. As expected both exhibit similar spectra and pulse resolution with slightly more light output observed for the 3x3 EJ301D scintillator. The light output data obtained are included in Fig. 6.

A comparison of the measured and simulated response (see below) for the EJ301D detector is shown in Fig. 10. The simulations appear to be quite satisfactory for most applications.

5.2 In-beam (d,n) spectra, $E_d = 6$ MeV

A set of (d,n) spectra measurements was obtained using a special beam line (Fig. 11) set up at the University of Michigan Ion-Beam Laboratory (MIBL). A beam of deuterons at $E = 6.000$ MeV with an energy

spread of only a few keV was focused to a small beam spot (area $<1 \text{ mm}^2$) on a variety of thin-foil targets. These were located on a moveable target ladder inside a small ISO-50 (i.e. 50 cm dia.) stainless-steel tee that served as a small, thin-wall scattering chamber (Fig.11). The beam was stopped in a tantalum-backed faraday cup located 1 meter downstream and shielded with lead blocks from the target chamber. The tantalum beam stop produced very little background as the incident 6 MeV deuteron beam was below the energy needed for nuclear reactions to occur in the tantalum.

The 3x3 EJ301D detector was placed on a tripod at 25 degrees (lab), 50 cm away from the targets with provisions for inserting up to 40 cm of polyethylene blocks to act as a shadow bar. As expected, there was very little room or beam-stop background which made for acquisition of very accurate target-induced neutron light spectra from the (d,n) reactions studied. The latter included the $d(d,n)^3\text{He}$ reaction ($Q= 3.269 \text{ MeV}$) using a 0.7 mg/cm^2 CD_2 target, the $^{13}\text{C}(d,n)^{14}\text{N}$ reaction ($Q= 5.326 \text{ MeV}$) using a 2.5 mg/cm^2 enriched $^{13}\text{CH}_2$ target, and $^{27}\text{Al}(d,n)^{28}\text{Si}$ ($Q= 9.361 \text{ MeV}$) using a 3.1 mg/cm^2 pure aluminum foil. The foils were thin enough to produce negligible spread in the outgoing neutron energy compared to the detector resolution. Likewise the $<0.1 \text{ MeV}$ kinematic spread ($<1\%$) in the outgoing neutron energy due to the angular acceptance (FWHM ca. 2.5 deg.) of the 3x3 EJ301D detector also was small compared with the detector resolution (Sect. 4).

The beam current, which was a DC beam i.e. one having no time bunching or pulse selection, was adjusted for beam currents in the range 5 to 20 nA. This was done to minimize damage to the targets and also keep the data rates low (few k/s) to minimize pulse pile up in the DSP data acquisition system. The latter included the same DSP hardware, event-mode recording and data analysis software that was used in many of the other measurements described earlier. Likewise the PSD was optimized as needed to provide clean neutron scintillation spectra over the range of energies of interest.

Several of the neutron scintillation spectra (taken over 0.5 to 1.5 hours each), again using the total DSP light-pulse integral for the light output, are shown in Fig. 12. Well defined peaks are observed in most cases, corresponding to the known, discrete neutron energy groups expected for the various (d,n) reactions. The (d,n) data for the ^{27}Al target, which produces neutrons up to 15 MeV, have peaks which are not as prominent due to the lower (d,n) cross sections and the background in the neutron PSD from break-up protons in the scintillator [11,18]. Such spectra usually can be improved by further optimization of the PSD to remove more protons in the high energy regions of the PSD spectra or as noted use of a detector with special additives and a higher efficiency PMT to enhance the PSD (e.g. EJ315M [11,18]).

5.3 Unfolded neutron energy spectra

As noted, the preliminary 3x3 EJ3091D response matrix elements deduced using ^{252}Cf n-ToF spectra appeared to be similar to that measured in more detail and over a larger energy range for several EJ315 detectors [11,18,20,21], and likewise the response data observed for 2.46 MeV neutrons were similar (Fig.9). We therefore performed initial spectral unfolding for several of the EJ301D (d,n) spectra using the EJ315 response matrix and methods used previously to unfold similar EJ315 light spectra [11,18,20,21]. Given the low statistical uncertainty and minimal background present in the light spectrum for the $^{13}\text{CH}_2$ and other targets, the unfolding can be performed quite accurately. This yields neutron energy spectra with surprisingly good energy resolution (ca. 0.2 MeV i.e. 2-3 % FWHM in many cases).

Results are shown in Fig. 13 for $^{13}\text{C}(\text{d},\text{n})^{14}\text{N}$ observed with the $^{13}\text{CH}_2$ target and shows separation of many of the ^{14}N final states. This was also found true with our EJ315 deuterated-benzene detectors [11,18]. The peaks seen correspond with known levels in ^{14}N (Fig.13) and in particular with levels seen prominently in n-ToF measurements [25], yet were obtained in our case without any n-ToF. This illustrates the

417 advantage of deuterated-liquid organic scintillators including now
418 deuterated xylene in many types of neutron-energy measurements.

419 The unfolded neutron energy spectra obtained for the CD_2 and ^{27}Al
420 targets are shown in Fig. 14. Neutron groups corresponding to the
421 $\text{d(d,n)}^3\text{He}$ and $^{12}\text{C(d,n)}^{13}\text{N}$ g.s. reactions are clearly identified for the CD_2
422 target and provide additional data for the 301D response data (Fig. 6). As
423 noted, the situation for the $^{27}\text{Al(d,n)}^{28}\text{Si}$ data is complicated by the
424 presence of break-up protons in the deuteron-recoil portion of the PSD
425 spectrum due to the high-energy (ca. 15 MeV) neutrons incident on the
426 detector. This background makes the unfolding less precise, as indicated
427 in the figure [11,18].

428 429 430 431 432 6. Measured and simulated 3x3 EJ301D neutron detection efficiency

433
434 Using the known cell geometry, scintillator information (Table 1),
435 the parameterized light-output function (Fig. 6), and the known, tabulated
436 n+d elastic recoil cross sections as a function of energy, the light spectra
437 and intrinsic neutron detection efficiency were calculated using the MCNP-
438 PoliMi Monte-Carlo code [28]. This included the over-all efficiency for
439 detection of ^{252}Cf fission neutrons down to the detector threshold used to
440 generate a specific spectrum. The results could then be compared with the
441 efficiency calculated using the known 5.63 mCi ^{252}Cf source intensity and
442 geometry used for the associated n-ToF measurement.

443 In the case of the dd-generator measurements (2.46 MeV neutrons),
444 the total efficiency using all events down to the detector threshold as well
445 as two methods for calculating the efficiency associated with the events in
446 the distinct deuteron recoil peak were determined. The latter minimizes the
447 dependence of the neutron detection efficiency on the detection threshold
448 setting, which is desirable. In one case a single exponential background

was subtracted before the peak summed, and in the second case a simple gaussian peak without any background subtraction was summed. The latter yields a higher apparent "peak" efficiency. The results are shown in Table 2. Owing to the slightly higher ^2H content in EJ301D compared to EJ315 scintillator (Table 1), the efficiency is slightly higher for a EJ301D detector than for a EJ315 detector of the same size. As indicated in Table 2, The efficiency of the neutron detection corresponding to peaks in the unfolded spectra (Figs.13 and 14) will depend on the type of unfolding procedure employed i.e. if all events down to the detector threshold are used, or if only events in the deuteron recoil peaks are summed [11,18].

In addition to calculations of the total efficiency, the related scintillation spectra measured were also compared with the MCNP-PoliMi simulations. This is displayed in Figs. 5 and 10 where it is seen that the simulations show good agreement with both the shape and magnitude of the EJ301D scintillator spectra,

7. Conclusions

We have evaluated a new, improved deuterated organic-liquid scintillator detector (EJ301D) which is less toxic, and has a higher, hence safer flashpoint than benzene- d_6 based detectors (EJ315, NE230, BC537). It also exhibits somewhat better PSD, light output, and neutron spectral response. Like deuterated-benzene scintillators, the new xylene- d_{10} -based scintillator produces distinct recoil-deuteron peaks in the resulting light spectra for incident neutrons having specific energies <20 MeV. These light spectra can then often be accurately unfolded using a suitable energy-to-light conversion matrix to yield a corresponding neutron energy spectrum without need for neutron ToF. The latter often requires use of long flight paths to the neutron detector in addition to use of a narrowly bunched and pulse-selected accelerator beam with a large reduction in data-collection efficiency compared to measurements using a DC beam. This severely limits the type of accelerator facilities that can

perform neutron reaction studies compared to one using deuterated scintillators, as we have also demonstrated with the newly-developed EJ 301D xylene-d₁₀ detector. The above limitations combined with the larger angular coverage possible with a deuterated scintillator array can yield a large improvement (x10 to x100 or more) in the overall data collection rates possible for many experiments involving the emission of neutrons, especially when using low-intensity exotic beams.

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Table1: Comparison of xylene-d₁₀ (EJ301D) and benzene-d₆ (EJ315,NE230,BC537)^{a)} scintillators

Scintillator:	EJ-301D ^{b)}	EJ-315 ^{c)}
Chemical Formula :	C ₈ D ₁₀	C ₆ D ₆
Light Output (% Anthracene):	78%	60%
L max	425 nm	425 nm
Blue Photons (per 1 MeVee) :	12,000	9,200
Ratio D to C :	1.20 ^{d)}	0.99 ^{d)}
Short Decay Component :	3.2 ns	3.5 ns
Index Refraction (n _D):	1.505	1.498
Flash Point:	26 °C (79 °F)	-11 °C (12 °F)
Mean free path of fission neutrons ^{e)}	4.94 cm	4.96 cm

a) Adopted from Eljen Technology, Inc. data sheets

b) Xylene based (custom fabricated by Eljen Technology, Inc.)

c) Benzene based

d) Includes carbon from the added (<5%) fluor compound

e) Mean free path averaged over ²⁵²Cf fission-neutron spectrum

Table 2 : 3x3 301D total and recoil-peak neutron detection efficiency for fission and 2.46 MeV neutrons (measured and calculated)

Neutron energies and criteria	Efficiency (+/- 1 SD) %	
	Measured ^a	Simulated ^b
²⁵² Cf fission-neutron spectrum down to to detector threshold of 0.05 KeVee	40.9 (2.2)	38.2 (0.5)
Total integrated light spectrum (2.46 MeV neutrons) down to detector threshold of 0.05 KeVee	42.1 (5.5)	39.5 (0.5)
Recoil-deuteron peak sum (2.46 MeV neutrons) with low-energy neutron subtraction (see text)	18.9 (2.5)	18.1(0.3)
Recoil-deuteron peak sum (2.46 MeV neutrons) fit with simple gaussian function, no corrections (see text)	35.5 (4.6)	34.9(0.5)

a) Measured with sources of known neutron fluence (5.63 mCi ²⁵²CF fission source and dd neutron generator. Uncertainty is given as +/- one standard deviation (+/- 1 SD)

b) Calculated with the Monte-Carlo detector response code MCNP-PoliMi (Ref. 28). Uncertainty is given as +/- one standard deviation (+/- 1 SD)

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691 Fig.1 Schematic of the Eljen 3x3 EJ301D (xylene-d₁₀) custom detector assembly.

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Fig. 2. 3x3 EJ301D PSD spectrum observed with a low intensity ^{252}Cf fission source ($< 100 \mu\text{Ci}$). Typical 2D gates used to project out neutron, gamma or combined spectra (as shown in Fig.3) are indicated.

Fig. 3. Total $n + \gamma$ and neutron ToF (1 meter flight path) gated on the groups as shown in the PSD spectrum of Fig. 2.

Fig. 4. PSD FOM as function of light output in electron-equivalent scintillation light-output units. The uncertainties are on the order of the size of the symbols.

Fig. 5. Comparison of measured and simulated [28] ^{252}CF fission neutron response for the 3x3 EJ301D detector.

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Fig. 6. Top: Light output of the 3x3 EJ301D detector compared with the EJ301 equivalent BC501 along with EJ315 and NE230 deuterated-benzene detectors of similar size. The curves are fitted with the light-output functional form also used by Enquist et al.[23] with the parameterization of the present 301D indicated. The deuteron-response data of Croft et al. [26] has been scaled to an equivalent incident neutron energy using $E_n=(8/9) E_d$ (see text). The BC501 (EJ301 equivalent) response data are from [27].

Bottom: Expanded low-energy portion of the light output data.

Fig.7. Coincident Compton-electron (3x3 EJ301D) - gamma (NaI) set up using a 0.662 MeV ¹³⁷Cs gamma source.

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Fig. 8. Top (A): 3x3 EJ301D detector response to Compton-scattered electrons (0.420 MeV) in coincident with ^{137}Cs gamma rays at 110 degs.

Bottom (B): Same as A for precision blue LED pulser signal [25] inserted at the PMT-scintillator optical interface (Fig.1).

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Fig. 9. Comparison of response of 3x3 EJ301D and 3x2 EJ315 detectors, normalized to same detector volume, to 2.46 MeV neutrons in terms of equivalent electron response (MeVee).

Fig. 10. Measured and simulated [28] EJ301D response spectra for dd-generator 2.46 MeV neutrons (room-return neutrons removed). Top: Linear scale; bottom: semi-log scale.

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Fig. 11. In-beam set up at UM MIBL tandem van de Graaff for (d,n) measurements with the 3x3 EJ301D detector (shown with polyethylene shadow bar in place) at 25 degs.(lab) and $E_d=6$ MeV.

Fig. 12. Relative light response data for the 3x3 EJ301D detector at 25 degs.(lab) for the foil targets indicated (room return neutrons negligible). Some of the counts seen at high light output are from pulse pileup or contamination due to proton recoils (see text).

Fig. 13. Top: Unfolded incident neutron energy spectrum (25 degs. lab) for $^{13}\text{C}(d,n)^{14}\text{N}$ at $E_d=6$ MeV using the 0.7 mg/cm^2 $^{13}\text{CH}_2$ target(see text). Levels in ^{14}N attributed to individual states or doublets seen in n-ToF measurements at similar excitation energies in ^{14}N are indicated [22].

Bottom: The 3x3 EJ301D scintillation light-spectrum data and the corresponding spectrum (solid line) generated by the spectral unfolding program developed in [11,18]. The neutron energy spectrum extracted is shown at the top.

Fig. 14. Top: Unfolded light spectrum for the CD_2 target (top) with $\text{d(d,n)}^3\text{He}$ and $^{12}\text{C(d,n)}^{13}\text{N g.s.}$ neutron groups indicated.

Bottom: Unfolded light spectrum for the ^{27}Al target with neutron groups attributed to ^{28}Si indicated (see Fig. 13 and text).