Comparison of Parasitic Scattering from Window Materials used for Small-Angle X-ray Scattering: a Better Beryllium Window

BY S. J. HENDERSON*

Biology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

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Abstract

The parasitic scattering of several materials used as windows in small-angle scattering experiments, including IF-1 beryllium, Kapton, Mylar, mica and glass has been measured over the q range 0.05–2.0 nm−1 with Cu Kα radiation ($q = 4\pi \sin \theta / \lambda$, 2θ = scattering angle). Based on the criteria of high strength, high transmission and low parasitic scattering, the best material was found to be IF-1 beryllium.

1. Introduction

The optimization of windows for X-ray cells and instruments is a little studied area of technology. The reduction of transmission is usually the main focus of such developments, although several other factors are also important. These include chemical compatibility, rigidity, mechanical strength, opacity, permeability and parasitic (usually small-angle) scattering. Many of these window properties are known from tables or simple inspection, with the notable exception of parasitic scattering, which is the major theme of this paper. The functions and requirements of windows are diverse: they are used from the exit port of the X-ray generator, at the entry and exit ports for evacuated beam paths, as liquid or powder sample containers and as the entry port for X-ray detectors. Historically, X-ray window materials used for these places have included mica, glasses, beryllium, polymer films (Mylar, Kapton etc.), carbon and carbon fiber materials.

The ideal choice of sample cell window material depends on the characteristics of the experiment and the sample. Solid samples such as polymers can usually be studied with no windows around the sample, as well as no windows between the optics and the detector, which is ideal. For transmission and parasitic scattering reasons, the best window is always no window, if possible. The emphasis in this paper on parasitic scattering focuses the attention on window materials used at or near the sample position in small-angle X-ray scattering (SAXS) cameras, such as those in liquid sample cells, and on instrument windows. Usually, the only windows in the SAXS camera used between the optics and the detector are such windows (evacuated flight paths usually require secondary windows around liquid sample cells). Reduction of the parasitic scattering from window materials will enable weakly scattering samples (such as dilute protein solutions) to be resolved better [i.e. with a better signal-to-noise (s/n) ratio]. Window scattering can be greater than sample scattering for weak X-ray scatterers, although the s/n ratio at the lowest angles is usually limited by the instrumental parasitic scattering from optics rather than that from windows.

2. Experiment and materials

The three beryllium samples used were of IF-1-grade beryllium, which is the highest purity beryllium sold by Brush Wellman Electrofusion Products (BW), CA, USA. IF-1 is also the highest purity beryllium commercially available to my knowledge. The specific treatment differences between the beryllium samples are given in Table 1. Our samples were 99.93% beryllium from BW analysis. The mass-absorption coefficient for the beryllium supplied was 1.06 cm² g⁻¹ from its given composition, which is close to the known value for pure beryllium (1.01 cm² g⁻¹; Handbook of Chemistry and Physics, 1991). The manufacturing history of IF-1 is unusual. It used to be made by a special extraction process at Kawecki Berylco Industries, which closed in the 1970s. The IF-1 beryllium stock was then purchased by BW and is now being consumed without replacement.

The Mylar and Kapton film were supplied by Fralock, CA, USA, and are registered names of DuPont. The Fralock designation for the Mylar was TMA (DuPont calls this EL film) and its designation for the Kapton was TKH (DuPont calls this HN film).

Perhaps the oldest window material is glass in the form of glass capillaries. These were supplied by Charles Supper Company (CSC), MA, USA. These were formerly available in only quartz glass or special glass, but they have recently become available in borosilicate (BS) glass. The BS glass was used for this experiment, because it has lower absorption than the other two types owing to its boron content. The nominal single-wall thickness of glass capillaries is given by CSC as $t = 0.01$ mm, but the sample we used had $t = 0.041$ mm (for two walls), calculated from the linear attenuation.
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Table 1. The treatment history of the beryllium samples studied

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial thickness (mm)</th>
<th>Chemical treatment</th>
<th>Final thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be(1)</td>
<td>0.026</td>
<td>None</td>
<td>0.026</td>
</tr>
<tr>
<td>Be(2)</td>
<td>0.268</td>
<td>Etched</td>
<td>0.094</td>
</tr>
<tr>
<td>Be(3)</td>
<td>Identical to Be(2)</td>
<td>None</td>
<td>0.268</td>
</tr>
<tr>
<td>Be(4)</td>
<td>Identical to Be(2)</td>
<td>Etched + DuraCoat®</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Table 2. Relative whole detector parasitic count rates [equation (1)]

<table>
<thead>
<tr>
<th>Window material</th>
<th>( t ) (mm)</th>
<th>( T ) (relative)</th>
<th>2 m rate (relative)</th>
<th>5 m rate (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be(1)</td>
<td>0.026</td>
<td>0.995</td>
<td>5.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Be(2)</td>
<td>0.094</td>
<td>0.982</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Be(3)</td>
<td>0.268</td>
<td>0.949</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Be(4)</td>
<td>0.092</td>
<td>0.982</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>BS glass</td>
<td>0.041</td>
<td>0.749</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Mylar</td>
<td>0.025</td>
<td>0.979</td>
<td>6.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Kapton</td>
<td>0.026</td>
<td>0.979</td>
<td>6.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Mica(1)</td>
<td>0.013</td>
<td>0.839</td>
<td>18.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Mica(2)</td>
<td>0.031</td>
<td>0.722</td>
<td>4.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Another potential window product is chemical vapour deposition (CVD) diamond film. This was investigated briefly in its unpolished form, but it showed very high parasitic scattering, so it was not studied further. The whole detector count rate was about a factor of ten higher than that for Mylar.

Recently, a beryllium coating called DuraCoat® from Moxtek Inc., UT, USA was announced. A duplicate window to Be(2) (Table 1) was made and coated on both sides with 1.0 mm of DuraCoat®. This sample was designated Be(4). The Be(4) substrate was fabricated at the same time as Be(2), from the same parent beryllium lot, so they are assumed to be identical.

Two samples of mica were studied. Mica(1) was from Asheville Mica Inc., VA, USA and mica(2) was from Goodfellow Corporation, PA, USA. The former is used at Oak Ridge National Laboratory (ORNL) and the latter is used at Stanford Synchrotron Radiation Laboratory (SSRL) for SAXS.

All small-angle X-ray measurements were performed on the 10 m SAXS camera at ORNL, which has been described in detail elsewhere (Hendricks, 1978; Wignall, Lin & Spooner, 1990), although the instrument has been improved further since these publications. Briefly, the X-ray beam from a Rigaku RU-200 rotating-anode generator is monochromatized by a flat pyrolytic graphite monochromator and is then collimated by two pinholes (usually 1 mm in diameter) 1.5 m apart. The X-ray flight path between the first pinhole and the detector window is in vacuum, so it has no windows (the detector window is the seal for the end of the flight path). The detector is an MWPC type (model 2200X from Ordela Inc., TN, USA), which has an active window area of about 200 × 200 mm.

Data were recorded for periods of up to 5 h per sample at sample-to-detector distances of 2 and 5 m. All samples measured were mounted in the vacuum about 3.3 m from the generator. The detector image with no sample (the empty beam) was subtracted from each sample image. The data were reduced with SPECTOR software (John Hayter, ORNL), where counts are normalized by sample transmission, sample thickness, beam monitor and detector efficiency. The reduced data are converted to absolute intensity units (cm⁻¹) by comparison to secondary standards. The angle is expressed in units of momentum transfer \( q \), where \( q = 4\pi \sin \theta / \lambda \), \( \theta \) is the scattering angle and \( \lambda \) is the wavelength of the radiation used (0.154 nm for Cu Kα).

The measurements were made at two sample–detector distances and are normalized to sample transmission \( T \) and thickness \( t \). The 2 m distance corresponds approximately to a \( q \) domain of 0.2 to 2.7 nm⁻¹ and the 5 m distance to one of 0.1 to 1.1 nm⁻¹.

3. SAXS results

The relative window performance for parasitic scattering is defined as the net total detector count rate, normalized for transmission and thickness. This is:

\[
\text{relative net rate} = \left( k / \rho \right) \left[ \left( \text{sample rate} - dc \right) / T \right] - \left( \text{empty beam rate} - dc \right),
\]

where \( dc \) is the whole detector count rate with no X-rays, \( T \) is the sample transmission, \( t \) is the sample thickness and \( k \) is an arbitrary constant (\( k = 0.025 \) in Table 2). These rates are tabulated in Table 2.

The SAXS scattering curves of the three non-coated beryllium samples (1, 2, 3) are shown in Fig. 1. Fig. 2 shows the SAXS scattering curves for the best beryllium sample (2), the glass, the polymer films and the two mica samples. Fig. 3 shows the SAXS scattering curves for the Moxtek coating test, i.e. beryllium samples (2) and (4).
4. Discussion

Preliminary investigation of other beryllium grades (unetched) showed that the IF-1 grade was clearly superior to the three other grades looked at. No comprehensive survey of all beryllium grades available was attempted. It is assumed that etched IF-1 would be similarly superior to the other beryllium grades if they were also etched. Table 3 shows the large variation observed in total detector count rate for various pieces of unetched beryllium. The count rates from the first and fourth samples in Table 3 are probably systematically low compared to the others because their ratios of surface thickness to bulk thickness are lower. This paper shows that beryllium foils are not isotropic perpendicular to the surface: the surface layers scatter much more than the inner core beryllium. The variation shown in Table 3 is therefore affected by the number of surfaces per sample.

IF-1 is a single-rolled foil (rolling to achieve the desired thickness is carried out in one direction only), while most lower purity grades from BW are cross-rolled. The use of a two-dimensional detector enables isotropic and anisotropic scatterers to be distinguished if anisotropy lies in the sample plane perpendicular to the beam direction. No anisotropy was seen in the beryllium SAXS images due to single rolling, so the two-dimensional data exhibited circular symmetry about the beam center. All other samples showed similar isotropic two-dimensional scattering patterns (except for the polymer films), which enables the two-dimensional information content to be reduced to one-dimensional information content \([q, l(q)]\) by integration of concentric
rings (azimuthal averaging). The uncoated-beryllium sample intensities show a decay with a slope of around −3.4 on the log–log plots, which is close to Porod behavior (slope = 4).

4.1. Parasitic scattering

From Tables 2 and 3 and Figs. 1 and 2, it is clear that etched IF-1 beryllium [Be(2)] is the superior window material (for the lowest parasitic scattering) amongst those studied in this paper. This superiority is greater at higher q values, where typical SAXS samples give their weakest scattering \[I(q) \sim q^{-4}\]. At lower q values, BS glass has a similar performance to the etched beryllium. The marked improvement on etching means that the structures of the surface layers are different from the ‘bulk’ beryllium away from the surface. The thickness reduction by etching was from 0.0106 in (0.268 mm) down to 0.0037 in (0.094 mm), or 0.0034 in (0.086 mm) per face. This thickness was removed because it was known from Brush Wellman data to give an increase in window strength (discussed below). The actual thickness of this ‘skin’ is suggested by the count rates of Table 2. If Be(1) and Be(3) have surface layers of the same thickness on a core bulk beryllium and Be(2) is only bulk beryllium, the surface layers would be about 0.0005 in (0.012 mm) thick. This simple model is not exact as the linear equations set up from such a bulk + skin model are only approximately consistent between the three samples, presumably because the ‘skin’ thicknesses are different between samples.

The mica films differed by about a factor of 10 in scattering, although both looked optically clear and identical. Mica is usually mined and sold as is, where grading is done on optical clarity. These two samples suggest that a large variability in parasitic scattering exists between mica samples from different sources, even though a comprehensive study on micas was not intended. The difference is probably due to variation in the interlayer cation content of the samples, and in particular iron. Elemental analysis was not done on these samples.

Mylar and Kapton films are widely used as windows in both X-ray cells and instruments so they make an important comparison to the etched IF-1 beryllium window measured. Their parasitic scattering was much higher, although the low cost and convenience of these materials will mean they continue to be preferred for many applications. These polymer films showed anisotropic scattering, which is usual in these materials. These both showed broad maxima in two diagonally opposite quadrants in the scattered image. The azimuthal averages plotted in Fig. 2 ignore the anisotropy and so represent averages only. If Mylar or Kapton windows are used in an experiment on sample cells, it is important to align all the windows in the same way to ensure correct subtractions.

5. Window coatings

The Moxtek beryllium coating, DuraCoat® was designed for corrosion protection for beryllium in harsh chemical environments. The coating composition is proprietary, so it is not given by Moxtek. It was studied in this series of tests because it also had potential to be a convenient aqueous barrier (water slowly reacts with beryllium) for use in a new, low parasitic scattering, beryllium sample cell being developed here. The results are shown in Fig. 3. While DuraCoat® still has useful and possibly unique anticorrosive properties, and would be satisfactory with medium to strongly scattering samples, the parasitic scattering increase from it is not acceptable for weakly scattering samples. At synchrotron facilities, oxidation protection is required for beryllium windows owing to the high thermal loading from the beams, so this coating would be useful here and possibly superior to others used for this purpose (8).

One of the problems for scattering from solution samples using cells with polymer-film windows (Kapton or Mylar) is that they are permeable to solvents. For synchrotron SAXS experiments, which may take only a few minutes, this is not important. For rotating-anode SAXS experiments, the measurement time can be many hours for weakly scattering samples. If water loss is calculated from the water-vapor permeability, then Kapton windows would lose 8% (0.0054 g H₂O in 2 d⁻¹ mm⁻¹) of their contents for a 1 mm path length and a 12 h experiment. Mylar’s permeability is one third of that for Kapton. Many different materials are commercially laminated to or vapor-deposited on Mylar and Kapton to augment their physical/chemical characteristics. The most common material used to lower water permeability is aluminium, where the reduction is usually an order of magnitude. The aluminium coating itself is also often coated with a third material to preserve its integrity. These coated polymer films have higher parasitic count rates in this q domain and a detailed study of these is not attempted here. In the authors’ experience, the rates vary from almost the same as the uncoated polymer to an order of magnitude higher.

5.1. Mechanical strength of beryllium

Large beryllium windows are often used at the ends of flight tubes and on area detectors, while sample position windows (if present) are much smaller. The reduction of parasitic scattering is important for windows at or near the sample position, although this factor can be ignored for windows at or near the detector. Large windows often need to support a pressure difference of 0.1 MPa or more, so maximization of strength with minimization of thickness (for better transmission) is usually the primary design factor for these. Fortuitously, both a marked reduction of parasitic scatter as well as a marked increase in rupture strength is achieved by chemical etching of
beryllium. BW has done beryllium-window strength tests by pressurizing a series of windows until fracture occurred. These are listed in Table 4. For brittle materials, failure occurs when the maximum stress reaches the ultimate tensile stress of the material involved. The maximum stress occurs in the surface of the plate, so failure would occur at surface imperfections, which are removed/reduced by etching. Stress theory (Roark, 1989) for circular plates with fixed edges gives

\[ \sigma = \frac{0.08884}{(D/t)^{2}}, \]  

(2)

where \( \sigma \) is the pressure difference on the plate required to collapse the plate, \( D \) is the plate diameter, \( t \) is the plate thickness and \( \sigma \) is the yield point of the material. The 'small deflection' condition is usually quoted as one that is not more than half the plate thickness. This is exceeded well before rupture for beryllium, so the values in Table 4 all exceed quoted values for \( \sigma \). For large deflections, the plate is stiffer than ordinary theory predicts and the load-stress and load-deflections equations are nonlinear. The values given for the maximum stress in beryllium for a cross-rolled sheet vary – a typical value is 320 MPa (BW). The trend from (2) still applies; the strongest window in Table 4 is the etched sample (line 3), stronger by a factor of nearly two over the similar unetched sample on line 4 of Table 4.

The importance of chemical etching of beryllium for mechanical strength has been known for some time (Dow Chemical Company, 1972), but the benefits of this for SAXS have been ignored. Generally, for brittle materials, etching removes surface flaws from which fracture cracks propagate, so such materials become stronger. The increase of strength in glass etched with hydrofluoric acid (Henderson & Speedy, 1990) is enormous (several orders of magnitude). For example, 50 μm-outiameter glass tubes with wall thickness 5 μm will withstand 200 MPa internal pressure (actual breaking pressure is higher and unknown).

SAXS instruments using large MWPCs have historically had two options for separation of the vacuum of the flight path from the detector gas:

(A) A single thick beryllium window could be used on the detector (Hayashi, Hamada, Suehiro, Masaki, Ogawa Miyaji, 1988), where the thickness was calculated from the classical theory above (with an added safety margin included) to support a 0.1 MPa pressure difference (usually) between the detector gas and the external vacuum.

(B) Two thin beryllium windows could be used (Hendricks, 1978). One seals the end of the evacuated flight tube and is reinforced with a metal grid to support a 0.1 MPa pressure difference; a second forms the detector window, which now has no pressure differential across it.

Option B used to be used at the SAXS lab at ORNL, until it was replaced by a third, better method, which is:

(C) use a single window as in method (A), but etch this to enhance its strength, so that its thickness is reduced by a factor of 2–3 from that otherwise used.

For a square window, edges fixed, with a uniformly distributed load and small deflections, we have (Roark, 1989):

\[ \sigma = \frac{0.308}{(L/t)^{2}}, \]  

(3)

and

\[ d = \frac{0.0138}{L^{4}/E^{3}}, \]  

(4)

where \( L \) is the length of a side, \( E \) is the modulus of elasticity (2.9 \( \times 10^{5} \)) and \( d \) is the maximum deflection of the plate. The window on the Ordela MWPC 2200X is 20.8 × 20.8 cm square. The standard window is BW PS-200E-grade beryllium, \( t = 0.64 \) (8) mm and no etch is done. The detector is designed to be used at ambient 1 MPa pressure, so there is no pressure differential across the window. The window recommended for vacuum is identical, except \( t = 2 \) mm. The transmission of these windows varies significantly with thickness as expected but is also a strong function of the beryllium grade used (see Table 5). An 80% increase in detector count rate is achieved by changing of the standard vacuum-prepared detector window for the unconventional thinner-etched window of higher grade. It should be noted that IF-1 beryllium is much more expensive than PS-200E beryllium when in large pieces such as large-area detector windows, sufficiently so to make such a substitution justifiable in special circumstances only.

During a detector rewire by Ordela, an attempt to measure the fracture pressure for a standard window (\( t =

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**Table 4. BW beryllium window fracture data**

<table>
<thead>
<tr>
<th>Beryllium grade</th>
<th>( p ) (MPa)</th>
<th>( D ) (in)*</th>
<th>( t ) (in)*</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF-1</td>
<td>0.95</td>
<td>1.50 (38.1)</td>
<td>0.010 (0.25)</td>
<td>( \sigma = 0.95 \times 10^{3} )</td>
</tr>
<tr>
<td>IF-1</td>
<td>0.22</td>
<td>1.50 (38.1)</td>
<td>0.006 (0.15)</td>
<td>( \sigma = 1.21 \times 10^{3} )</td>
</tr>
<tr>
<td>PS-200E</td>
<td>0.83</td>
<td>5.50 (139.7)</td>
<td>0.016 (0.41)</td>
<td>( \sigma = 0.87 \times 10^{3} )</td>
</tr>
</tbody>
</table>

\* Values in mm are given in parentheses.

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**Table 5. Transmission \( T \) of beryllium windows as a function of thickness \( t \) and beryllium grade, for Cu Kα (8.04 keV)**

<table>
<thead>
<tr>
<th>( t ) (mm)</th>
<th>( T ) (IF-1)</th>
<th>( T ) (PS-200E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.64</td>
<td>0.89</td>
<td>0.080</td>
</tr>
<tr>
<td>1.00</td>
<td>0.82</td>
<td>0.71</td>
</tr>
<tr>
<td>2.00</td>
<td>0.68</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Table 6. Uranium content of selected beryllium samples (as stated by supplier)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Beryllium grade</th>
<th>Beryllium (%)</th>
<th>Uranium content (parts in $10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Wellman</td>
<td>IF-1</td>
<td>99.9</td>
<td>0-2</td>
</tr>
<tr>
<td>Brush Wellman</td>
<td>PF-60</td>
<td>99.0</td>
<td>25-140</td>
</tr>
<tr>
<td>Brush Wellman</td>
<td>PS-2-E</td>
<td>98.0</td>
<td>50-150</td>
</tr>
<tr>
<td>Manufacturing Sciences</td>
<td></td>
<td>99.5</td>
<td>&lt;250</td>
</tr>
</tbody>
</table>

0.64 mm was made, with the window mounted and vacuum sealed in the normal way. Only $\Delta p = 0.08$ MPa was reached before technical problems halted the experiment prior to any window failure. The window deflection in the center was 33 mm MPa$^{-1}$. From this measurement, it is concluded that a similar window that has been etched down to 0.64 mm thickness would also suffice for use in vacuum, without window rupture. A more cautious approach was actually adopted: a thicker window (final $t = 1.0$ mm, after removal of 0.15 mm per side by etching) was fitted that has since been pressure-cycled hundreds of times without failure. The window deflection in the center was now 25 mm MPa$^{-1}$, which gave no image distortion. Comparisons of the maximum stress in these two windows from (3) to those in Table 4 suggest that the Ordela window could be as thin as 0.4 mm for vacuum service.

Rigaku Corporation built a MWPC (Hayashi, Hama-da, Suehiro, Masaki, Ogawa & Miyaji, 1988) to operate in vacuum, and made their 127 $\times$ 127 mm detector window 2 mm thick. On the basis of the above observations, this thickness could be reduced by up to a factor of 9 without rupture; a thickness of 0.5 mm would have given a good safety margin and better detector performance.

5.2. Radioactive elements in beryllium

Large beryllium windows are often used at the ends of flight tubes, and on area detectors, while sample position windows (if present) are much smaller. Natural beryllium consists of only the stable $^9$Be isotope. The major radioactive contaminant of beryllium is probably uranium (i.e. $^{238}$U), which makes up 99.3% of the natural element. The uranium content varies widely between beryllium grades, and is shown by the manufacturer-quoted values in Table 6. For weakly scattering systems, low detector background is useful, and this can be reduced by selection of beryllium with a lower uranium concentration (as well as the choice of a thinner window). When circular beryllium samples from Manufacturing Sciences were placed on the Ordela area-detector window (which uses grade BW PS-200E), their shapes were visible on the data display after 5 min counting time. Presumably, the spontaneous fission (SF) component (half life = 4.51 $\times$ 109 years, SF = 23%, 48 keV) of $^{238}$U decay is being counted. The energy window in the detector electronics does not reject these events so their detection may be via some secondary interaction that produces a lower-energy X-ray.

With the assumption that the $\alpha$ decay makes no contribution and that the detector counts half the low energy $\gamma$-rays emitted ($2\pi$ solid angle) with 100% efficiency, the background count rate from the existing window (208 $\times$ 208 $\times$ 1 mm, 92 parts in $10^6$ U) should be about 15.2 Hz, which is just a little more than that that measured at 13 Hz. The additional correlation with the increase in count rate from the study of Manufacturing Sciences beryllium leads the author to believe that most of the background counts in MWPCs probably come from uranium in the beryllium. A systematic study of uranium in beryllium is not attempted here, but the numbers uncovered through the above studies promote inclusion. Comparison with detectors having thicker beryllium windows (2 mm) or carbon fiber windows will establish these observations in the future. For now, they suggest that an IF-1 detector window (very low uranium) would give almost no background counts.

6. Concluding remarks

The benefits of using etched IF-1 beryllium have been shown. This material has excellent strength characteristics, high transmission and the lowest parasitic small-angle scattering of all materials investigated. When windows are being built into instruments near the sample position, it is usually worth optimizing these, because all sample images have the scattering images of these windows superposed. Similarly, the major strength enhancements of etching enable large windows to be built thinner, while still being able to withstand a typical pressure differential of 0.1 MPa.

Appreciation is given to Manfred and Danny Kopp from Ordela, Inc. for assistance in pressure testing two beryllium windows mounted in the area detector used in this study, D. Clark Turner of Moxtek, Inc for coating one of the windows discussed in this study, staff at Brush Wellman Electrofusion Products for discussion and the test fracture data, H. Hendershot of Manufacturing Sciences for supplying test samples, James Rice, South Dakota State University, for useful discussion, and Hiro Tsuruta, SSRL, for supplying and prompting the inclusion of mica in these studies. This research was sponsored by the Directors RD Fund, Oak Ridge National Laboratory, US Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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