The Light Reflection Simulation in Geant4

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12th Geant4 Collaboration Workshop, Hebden House,

Hebden Bridge (UK), 13-19 September 2007

Introduction

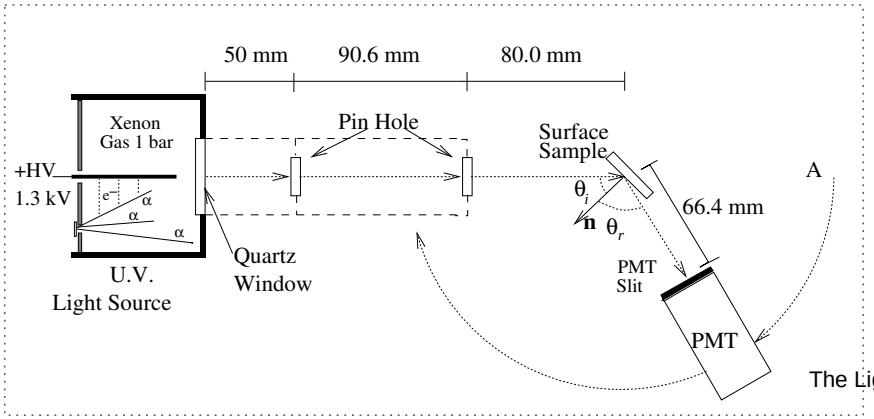
- The correct simulation of the reflectivity of the detector's inner surfaces is important to describe the observed phenomena
- Some materials exhibit a reflection profile involving different types of reflection (specular, diffuse, backscattering)
- The reflection profile for each material depends of the surface finish and the λ of the incident light

Overview

- Measurements of the reflected VUV light for PTFE, Copper and Glass
- Simulation of the experimental results using Geant4
- Modeling the specular and diffuse reflection
- The Fit to the experimental results
- The proposed model to the Geant4 simulation

The Experiment

- The incident light is from the xenon scintillation light ($\lambda = 175nm$)
- The measurements are performed in a controlled environment (argon atmosphere)
- Measurements were made for copper, glass and PTFE
- Data was taken changing the angles θ_i, θ_r and ϕ_r.



The Geant4 optical simulation

- Geant4 has two different models `Glisur` and `Unified`
- The Glisur model has two parameters (polishment and reflectance)
- The Unified Model depends of the interface
  - `Dielectric - Dielectric`
  - `Dielectric - Metal`

The Dielectric - Metal Interface

- The user introduces two parameter the reflectance of the surface and the surface roughness

Reflectance

Independent of θ_i

Absorption

Reflection

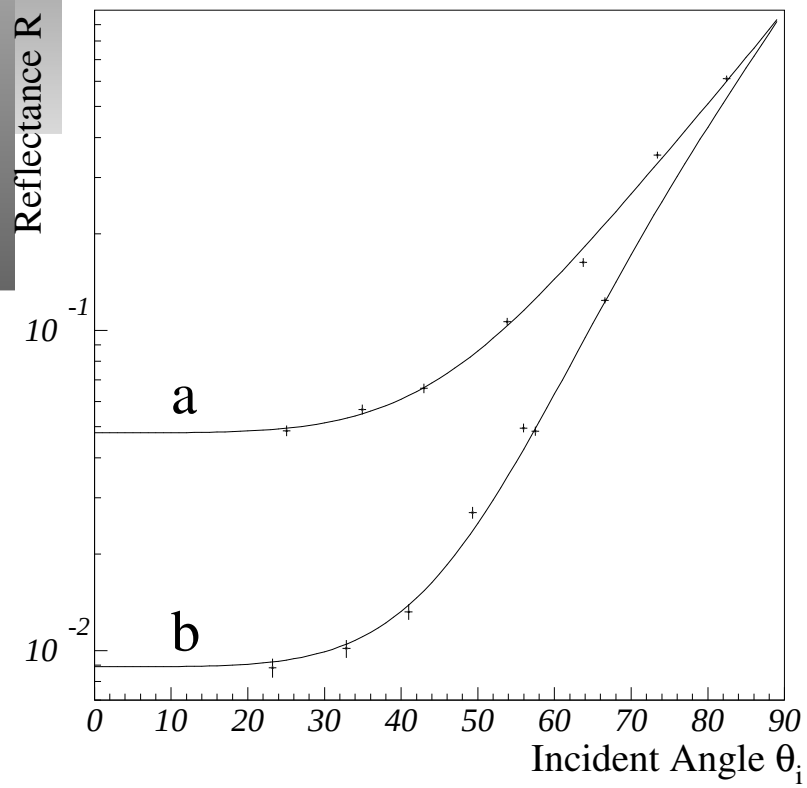
Polished

$\theta_i = \theta_r$

Rough

$D(\sigma_\alpha)$

The Dielectric - Metal Interface



- The copper measurements show a reflectance highly dependent of θ_i
- Geant4 assumes a constant reflectance
- Fresnel equations $F(\theta, n, \kappa)$ are required

$$a: \quad n = 1.04 \pm 0.02 \qquad \kappa = 0.439 \pm 0.004$$

$$b: \quad n = 0.972 \pm 0.004 \qquad \kappa = 0.193 \pm 0.003$$

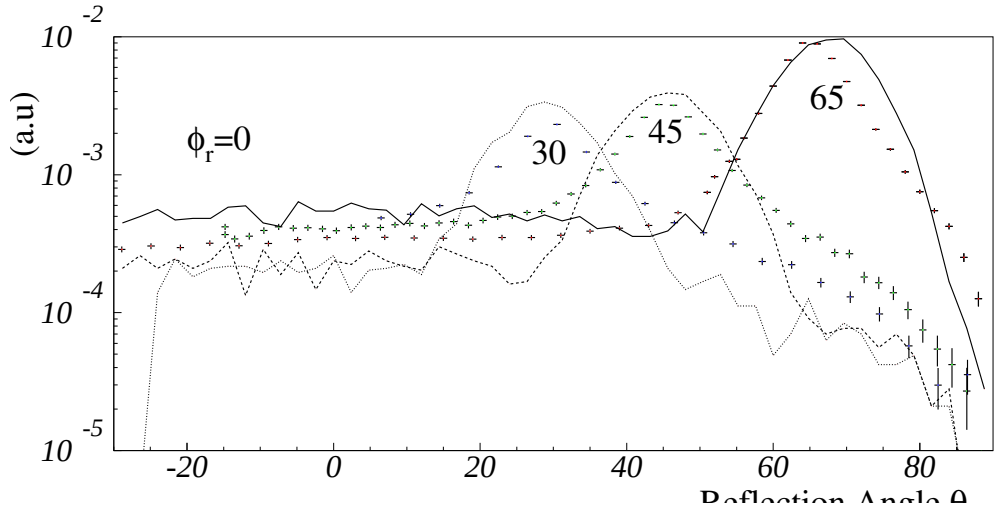
a and b are for two different oxidations of the copper sample

The Dielectric - Dielectric Interface

- The Geant4 simulation uses three parameters $n, W_D/W_L, \sigma$
- The values of the parameters were tunned so that the Geant4 simulation approaches our measurements
- The predicted reflectance is given by the number of reflected photons over to the number of incident photons

The Dielectric - Dielectric Interface

PTFE Measurements



but the reflectance obtained from the Geant 4 simulation is not realistic:

θ_i	$30°$	$45°$	$65°$
R	8%	10%	25%

PTFE is considered a very good reflector

The Dielectric - Dielectric Interface

MICROFACET NORMAL

$$n_1 \sin\theta_r = n_2 \sin\theta_t$$

$\sin\theta_t > 1$

Total Internal Reflection

$\sin\theta_t < 1$

Amplitude $F\left(\theta_r^{'}, n\right)$

Reflection

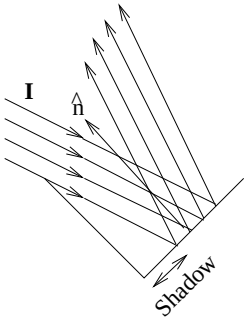
Refraction

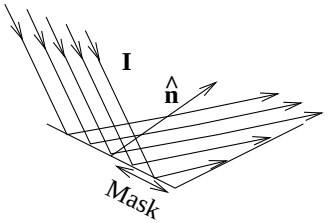
lobular

spike

lamb

The Dielectric - Dielectric Interface

- Geant4 looks at $\vec{I} \cdot \hat{n} < 0$ to test 

but fails to verify effects such 

- In general $R = R\left[F\left(\theta, n, \kappa\right)\right]$
- The lambertian component is proportional to the specular reflection

$$I_L = L \cdot F\left(\theta_r^{'}, n\right)$$

Reflection Models in the Literature

- **Oren Nayar:** diffuse reflection - caused by the surface roughness
- **Wolf:** diffuse reflection - caused by internal scattering
- **Torrance-Sparrow:** specular reflection
- **Combined Model:** diffuse plus specular reflection

The Oran-Nayar Model

- Is intended to describe the diffuse lobe
- Models the surface as a set of V-shaped cavities
- The width of each facet is small compared to its length
- The roughness of the surface is specified using a probability distribution function for the facet slopes
- The facet area is large enough compared with the λ of the incident light
- Reflection in each facet is purely lambertian

The Oran-Nayar Model

$$
\begin{aligned}
L_r\left(\theta_i, \theta_r, \phi_r - \phi_i, \sigma\right) &= L_i \frac{W_D}{\pi} \\
&\quad \times \left(A + B \cdot \max\left\{0, \cos\left(\phi_r - \phi_i\right)\right\}\right. \\
&\quad \left. \times \sin\left(\gamma\right) \tan\left(\beta\right)\right)
\end{aligned}
$$

$$
\begin{aligned}
A &= 1.0 - 0.5 \frac{\sigma^2}{(\sigma^2 + 0.33)} \\
B &= \frac{0.45\sigma^2}{(\sigma^2 + 0.009)} \\
\gamma &= \max\left\{\theta_i, \theta_r\right\} \\
\beta &= \min\left\{\theta_i, \theta_r\right\}
\end{aligned}
$$

Combined Model for Diffuse Reflection

- Both models are complementary in their applicability to surfaces with different roughness properties
- Surfaces with a intermediated roughness exhibits a combination of effects produced by both internal scattering and external roughness
- The two models can be joined together making the assumption that each V-groove micro-facet reflects according the Wolf model replacing the factor A by

$$C = A\left[1 - F\left(\theta_i, n, \kappa\right)\right] \times \left\{1 - F(\sin^{-1}[(\sin\theta_r)/n'], 1/n')\right\}$$

The Torrance Sparrow Model

- Planar micro-facets oriented according a distribution $D\left(\alpha_r, \sigma_r\right)$
- The reflection in each micro-facet is specular
- The Fresnel Factor $F(\theta_r^{'}, n, \kappa)$ introduces polarization dependence
- The shadowing and masking effects are accounted for by the geometrical attenuation factor, G

The Torrance Sparrow Model

$$L_r = W_s \frac{F(\theta^{'}, n, \kappa) G\left(\theta_i, \theta_r, \phi_r\right) D\left(\alpha_r, \sigma\right)}{4 \cos \theta'}$$

- W_s is the weight factor for the specular lobe
- $F(\theta^{'}, n, \kappa)$ are the Fresnel equations for the absorbing media
- $G\left(\theta_i, \theta_r, \phi_r\right)$ is the geometrical attenuation factor
- $D\left(\alpha_r, \sigma_r\right)$ is the micro-facet distribution function

The Combined Model

$$L_r \quad \frac{W_D}{\pi} \times \left(C + B \cdot \max\left\{0, \cos\left(\phi_r - \phi_i\right)\right\} \times \sin\left(\gamma\right) \tan\left(\beta\right)\right)$$
$$+W_s \frac{F(\theta^{'},n,\kappa)G(\theta_i,\theta_r,\phi_r)D(\alpha,\sigma_r)}{4\cos\theta'}$$

where C is:

$$C = A\left[1 - F\left(\theta_i, n, \kappa\right)\right] \times \left\{1 - F(\sin^{-1}[(\sin\theta_r)/n'], 1/n')\right\}$$

the reflection distribution function depends of 5 parameters $L_r = L_r\left(\theta_i, \theta_r, \phi_r, \kappa, n, W_D, W_S, \sigma_r\right)$

The Fit

$$\mathbf{x} = [\theta_i, \theta_r, \phi_r]$$

$$\mathbf{p} = [W_D, W_S, n, \kappa, \sigma]$$

$$\min \sum_{\mathbf{x}} \frac{\left(I\left(\mathbf{x}\right) - L_r\left(\mathbf{x}, \mathbf{p}\right)\right)^2}{\sigma^2_{I(\mathbf{x})}}$$

- The results were fitted with this model
- We used a genetic algorithm to find the minimum

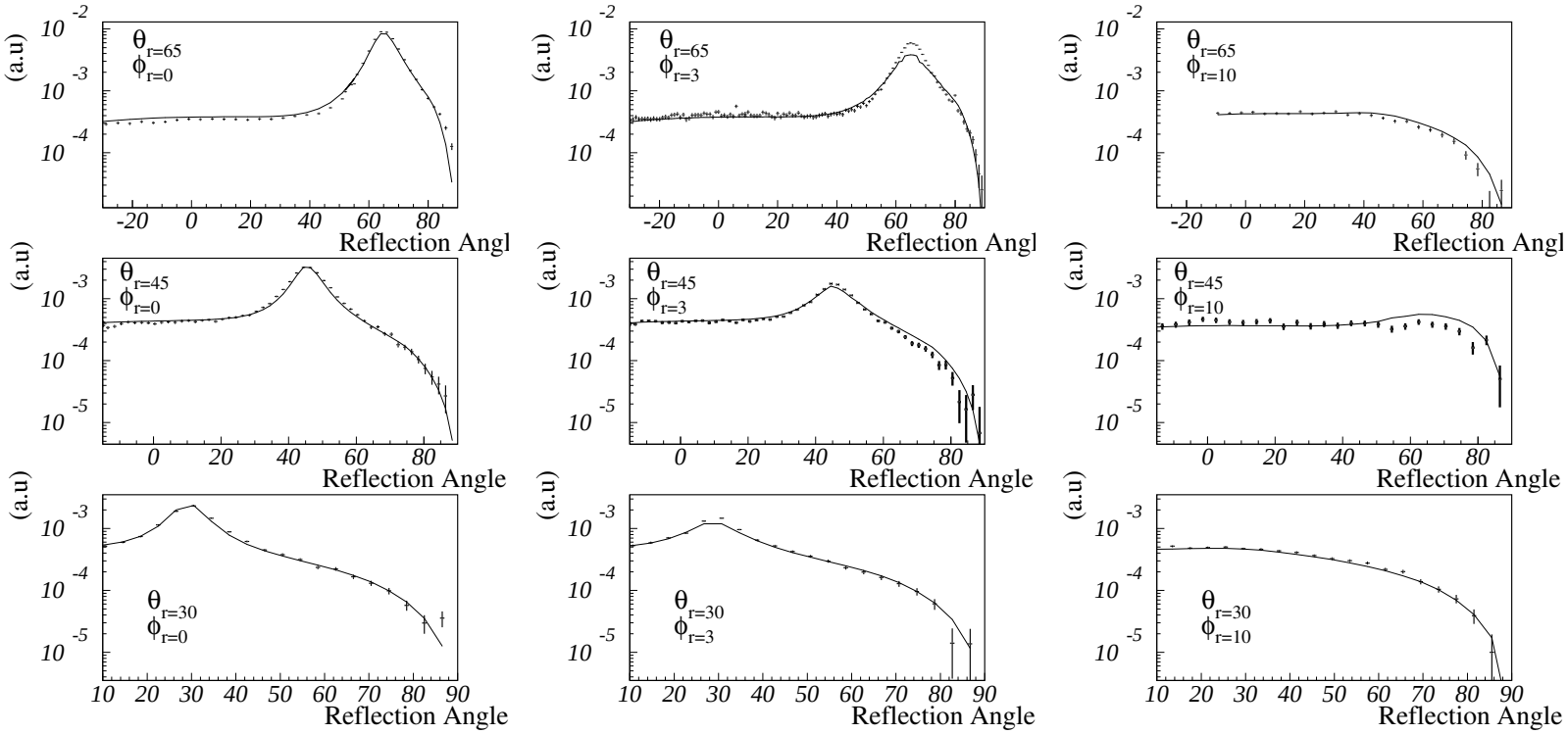
The Fit

- A global fit was performed
- Number of data points used: 2439 $\mathbf{x} = \{\theta_i, \theta_r, \phi_r\}$
- Number of fitted parameters: 5
  $\mathbf{p} = \{W_D, W_S, n, \kappa, \sigma\}$
- The micro-facet distribution $D(\alpha, \sigma_r)$ was considered Lorentzian

$$D(\alpha, \sigma_r) = \frac{1}{\alpha^2 + \left(\frac{\sigma_r^2}{2}\right)^2}$$

- Fit results: $\mathbf{p} = \{W_D, W_S, n, \kappa, \sigma\} = \{0.00145, 0.032, 1.09, 0.41, 0.072\}$ $\chi^2 \simeq 10$

The Results


θr=65
φr=0
θr=65
φr=3
θr=65
φr=10
θr=45
φr=0
θr=45
φr=3
θr=45
φr=10
θr=30
φr=0
θr=30
φr=3
θr=30
φr=10
(a.u)
Reflection Angl
Reflection Angle

Proposed model for the Geant4 simulation

Mirror reflections

- For High Reflectances: R constant
- For $\kappa \lesssim \frac{1}{2\pi}$: $R\left[F(\theta^{'}, n)\right]$
- For $\kappa \gtrsim \frac{1}{2\pi}$: $R\left[F(\theta^{'}, n, k)\right]$

Proposed model for the Geant4 simulation

specular lobe plus diffuse lobe

The user has to provide five parameters

$$\mathbf{p} = \{W_D, W_S, n, \kappa, \sigma\}$$

the function L_r is sampled in the simulation,

$$\begin{aligned} L_r &= \frac{W_D}{\pi}(C + B \times \max\{0, \cos(\phi_r - \phi_i)\} \times \sin(\gamma)\tan(\beta) \\ &\quad + W_s \frac{F(\theta',n,\kappa)G(\theta_i,\theta_r,\phi_r)D(\alpha,\sigma_r)}{4\cos\theta'} \end{aligned}$$

Proposed model for the Geant4 simulation

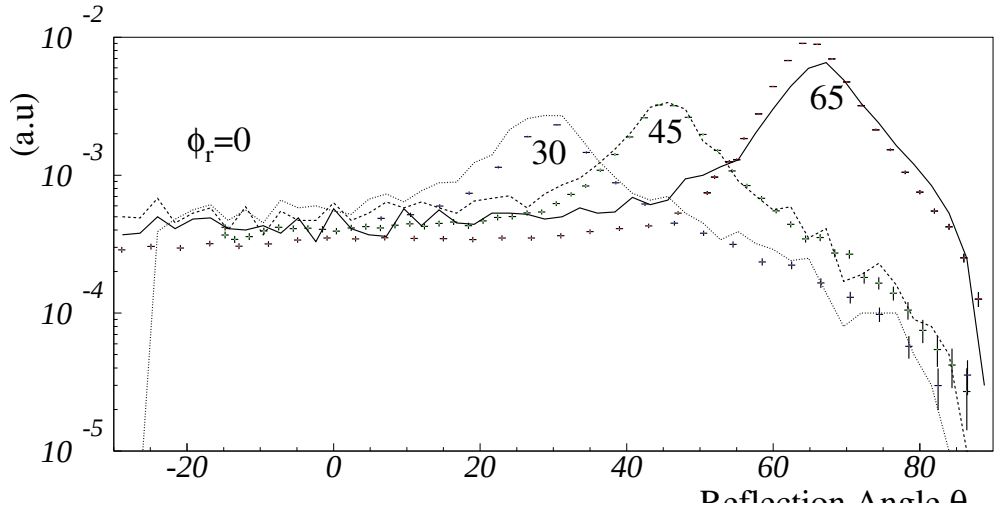
Radiance $L(\theta_i, \theta_r, \phi_r, \mathbf{p})$
Integration in (θ_r, ϕ_r)

Reflectance $R(\theta_i)$
$R(\theta_i, \mathbf{p}) + A(\theta_i, \mathbf{p}) + T(\theta_i, \mathbf{p}) = 1$

Refraction or Absorption

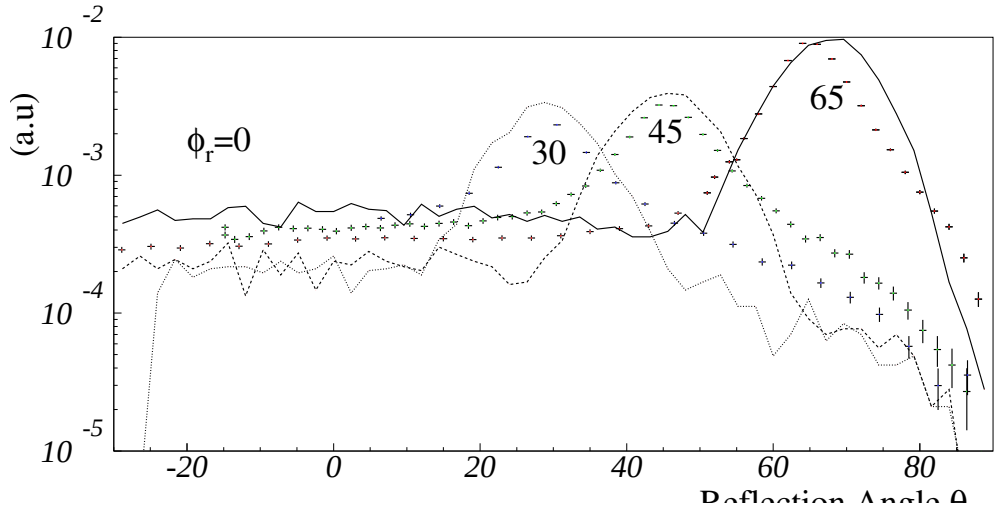
Reflection
$L(\theta_i, \theta_r, \phi_r, \mathbf{p})$
Choose θ_r and θ_i

Preliminary results obtained with the proposed model



Conclusions

- Geant4 simulation was compared with our light measurements.
- A new model for reflection by rough surfaces was considered.
- The new model was added to the Geant4 simulation. It seems to describe closely our measurements.
- This work is still going on.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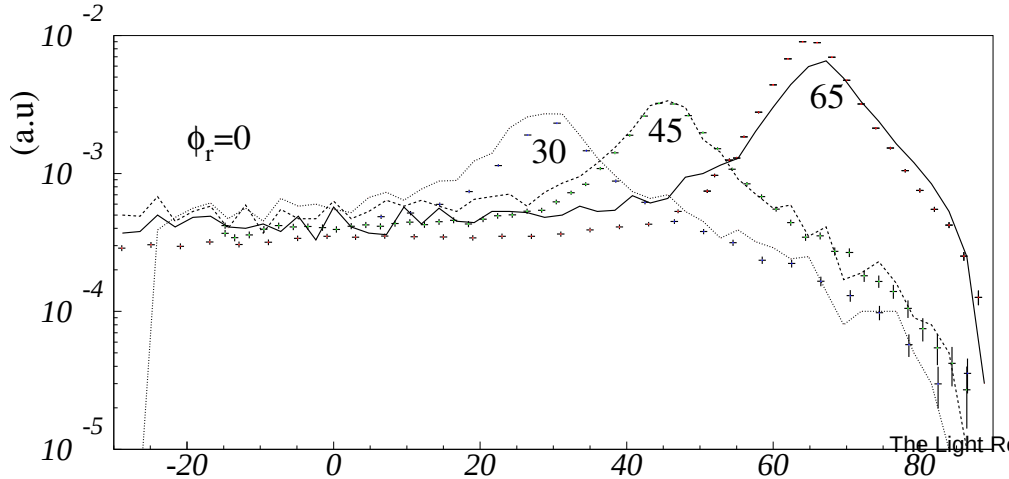
10^{-2}
10^{-3}
10^{-4}
10^{-5}
ϕ_r=0
30
45
65
-20
0
20
40
60
80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