Calibration for nuPRISM
– some points to inspire discussion

+ Smaller than SK:
  reflection more important than water scatt.
+ Moving detector:
  stability against movement
+ Higher rate
  variation in position

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Key points in calibration

- Reduce variations: reduce the need for calib.
  - Time: stable system
  - Noise: suppress background effects
- Control the environment (monitoring/feedback)
  - Identify the key environment parameters
  - Implement enviroment monitors: temperature, B–field, position/angle, etc.
- Calibration design
  - Model sources of variations
  - Develop calibration strategy and devices
  - Model and characterize (Monte Carlo) the calibration devices
  - Redundancy important for unexpected effects
- Physics process to test the calibration (systematics)

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Reduce variations

- Time variation reduction
  - Environmental control: temperature/B-field shielding
  - Stabilize positions: (γ telescope uses moving PMT arrays)
    - **anchoring, damping vibration, flat blacksheet surface**
  - Stable power supply and water system
- Noise/background reduction
  - High rate capability for pile-ups: **wave form digitizer**
  - PMT/electronics noise reduction, e.g grounding
  - Light scattering:
    - Water: purification (less important for nuPRISM)
    - PMT, Cover, Blacksheet: **index matching**
      - high QE PMT has less reflection (BeO layer)
      - Teflon black sheet (n~1.34)
      - n~1.4 material between water and plastic/glass

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PMT and Black sheet reflection at SK

430 S. Fukuda et al. / Nuclear Instruments and Methods in Physics Research A 501 (2003) 418–462

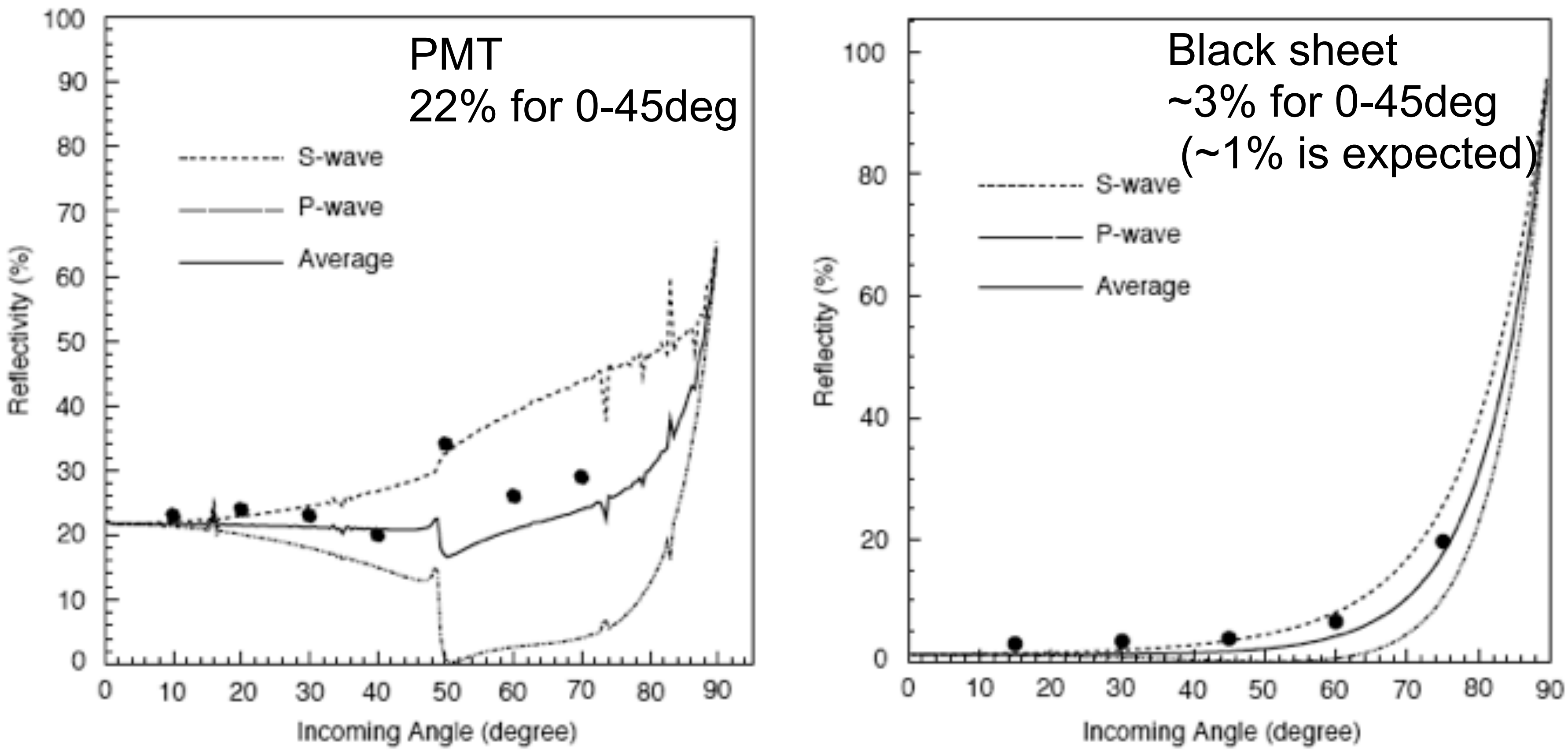


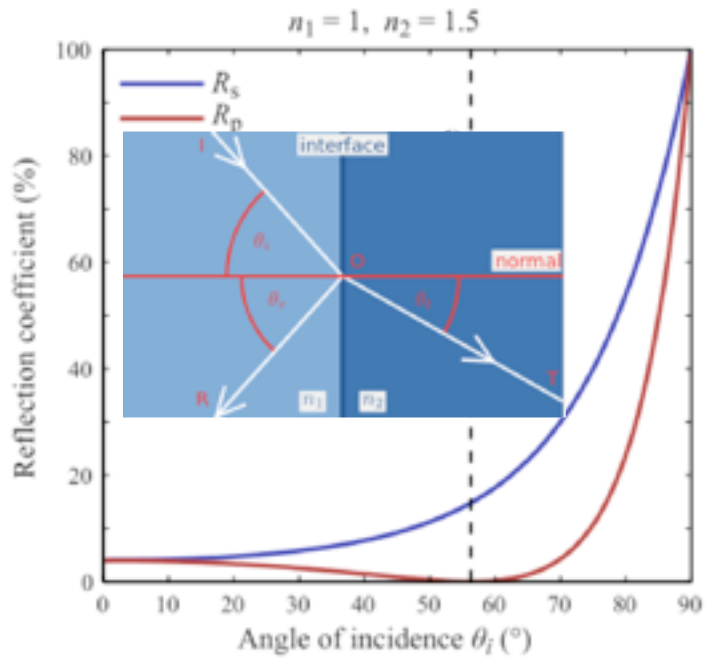
Fig. 12. Reflectivity of PMT surface (left panel) and the opaque sheets used to fill gaps between PMTs (right panel). Points show the results of measurements, and lines show calculated values: the dashed line shows the S-wave, the dotted line shows P-wave and the solid line shows the averaged value.

Important in particular for fiTQun analysis

Fresnel refletion

$$R_s = \left|\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right|^2 = \left|\frac{n_1\cos\theta_i - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1\cos\theta_i + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}\right|^2$$

$$R_p = \left|\frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2\cos\theta_i}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2\cos\theta_i}\right|^2$$



Refrectance R=(Rs+Rp)/2

- Large reflection near 90 deg. (grazing angle)
- Reflection can be suppressed by matching the index of refraction.

Rs in water (n=1.33)

n	0 deg.	45deg.	80deg.	90deg.
1.4	0.07%	0.25%	9.5%	100%
1.5	0.36%	1.35%	25%	100%
1.6	0.85%	2.5%	35%	100%
1.7	1.5%	4.5%	41%	100%

Reflection can be reduced by a more gradual transition of the index of refraction between different media.

B: 1.33, 1.517
water glass

C: 1.33, 1.41, 1.517
water, Sylgard 184, glass

D: 1.33 1.35 1.41 1.4914 1.517
water, Dupont PFA, Sylgard 184, acrylic, glass

E: 1.33 1.35 1.41 1.475 1.4914 1.517
water, Dupont PFA, Sylgard 184, glycerol, acrylic, glass

F: 1.33 1.335 1.340 1.345 1.35 1.41 1.4914 1.517
water, X, Y, Z, Dupont PFA, Sylgard 184, acrylic, glass

gradual transition at surface

Environmental control (monitoring)

- PMT gain/efficiency
  - Voltage/current (power supply) monitoring
  - Temperature, B-field sensors
- Light scattering
  - Water quality monitoring: sampling
  - Surface condition of PMT/sheets: ccd camera?
- Geometry
  - PMT position/tilt: laser tracker, ccd camera
- Accidental rate monitoring for pile ups
  - light leaks, electric noise monitoring
  - event rate monitoring

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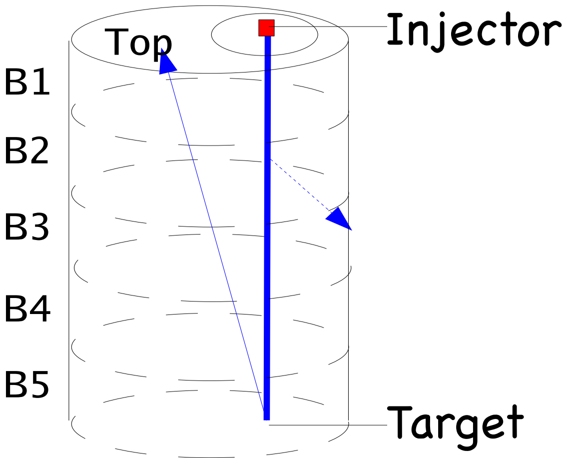
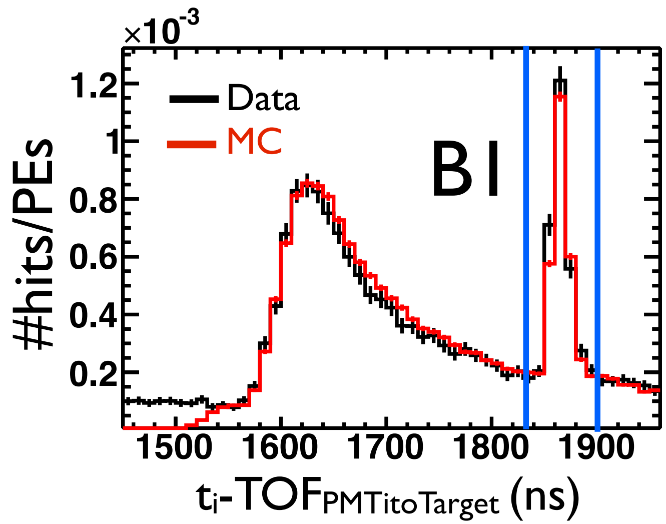
Calibrations

- PMT gain/efficiency and timing
  - Ni ball, Xe-scint. ball
  - Manipulation system to deploy at different positions:
    - attached to the nuPRISM-lite and automatic deployment
  - ex-situ characterization of PMT response
    - angular response
    - HV/temperature/B-field dependence
- Reflection: water/surface quality changes
  - laser/LED calibration, Rayleigh scattering device
  - ex-situ characterization of water, blacksheet, etc.
- Geometry (change due to movement)
  - laser tracker, ccd camera
- Electronics calibration

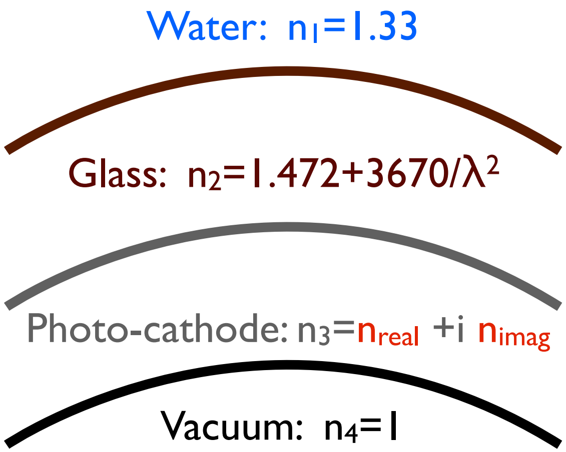
PMT reflection tuning

Calibration laser data on 07/07/2009



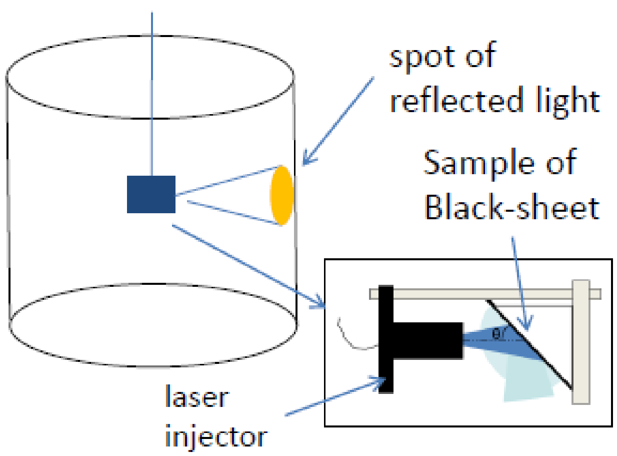


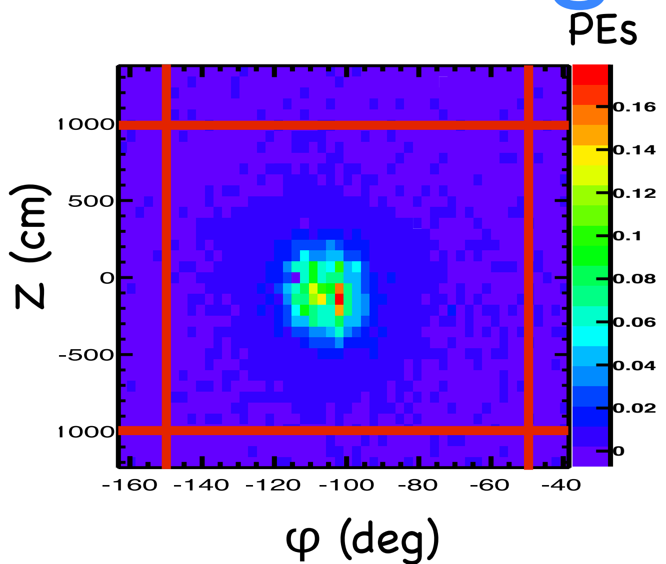
PMT model



Black sheet reflection tuning

Kameda-san's 2009 laser data



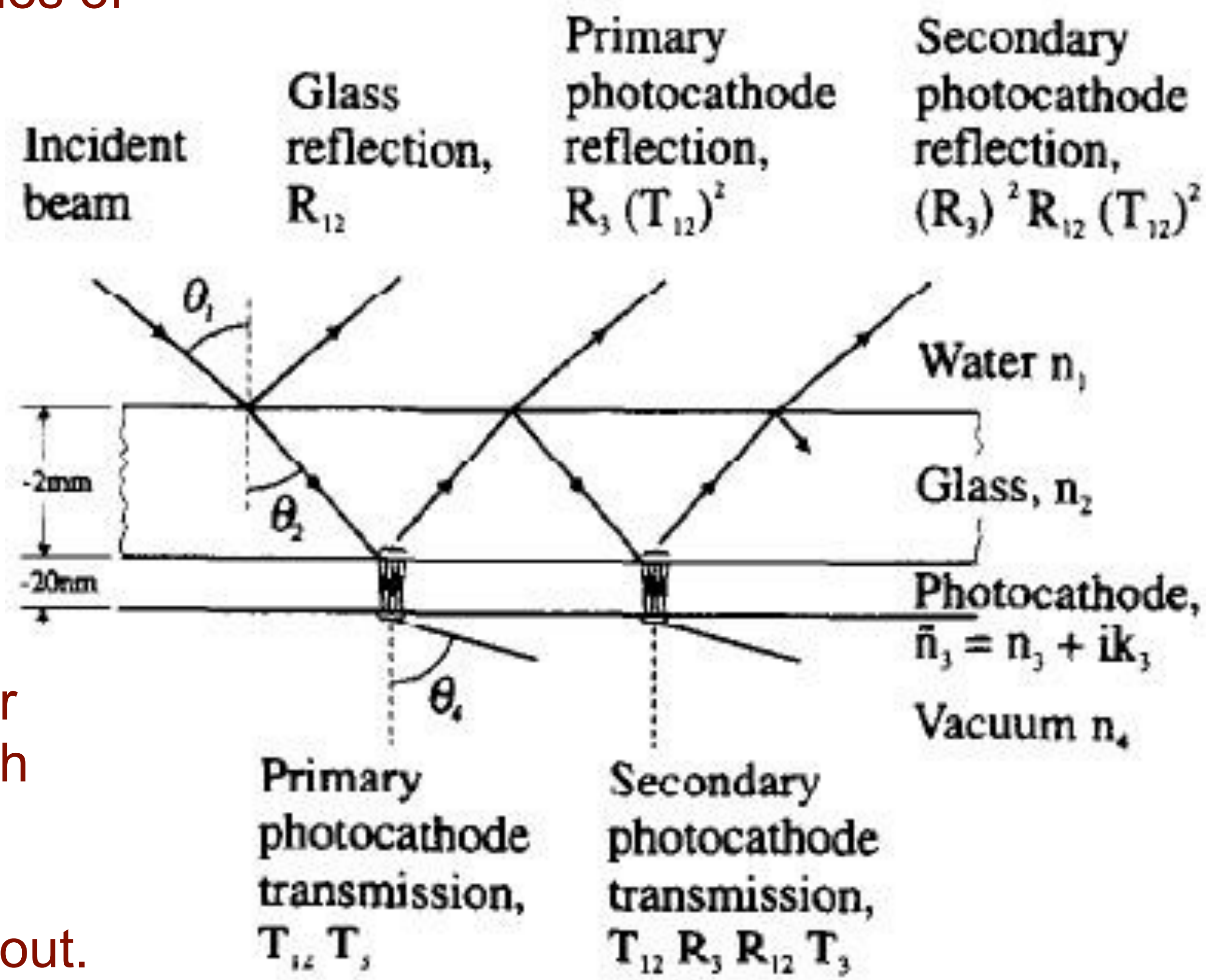


Reflection mechanism on PMT

Reflections at boundaries of
- water-glass
- glass-cathode
- cathode-vacuum

Photocathode has high refractive index: n~3+i (lots of reflection)

Photocathode is thinner than optical wave length (20nm) to suppress reflection and to allow photoelectron to come out.



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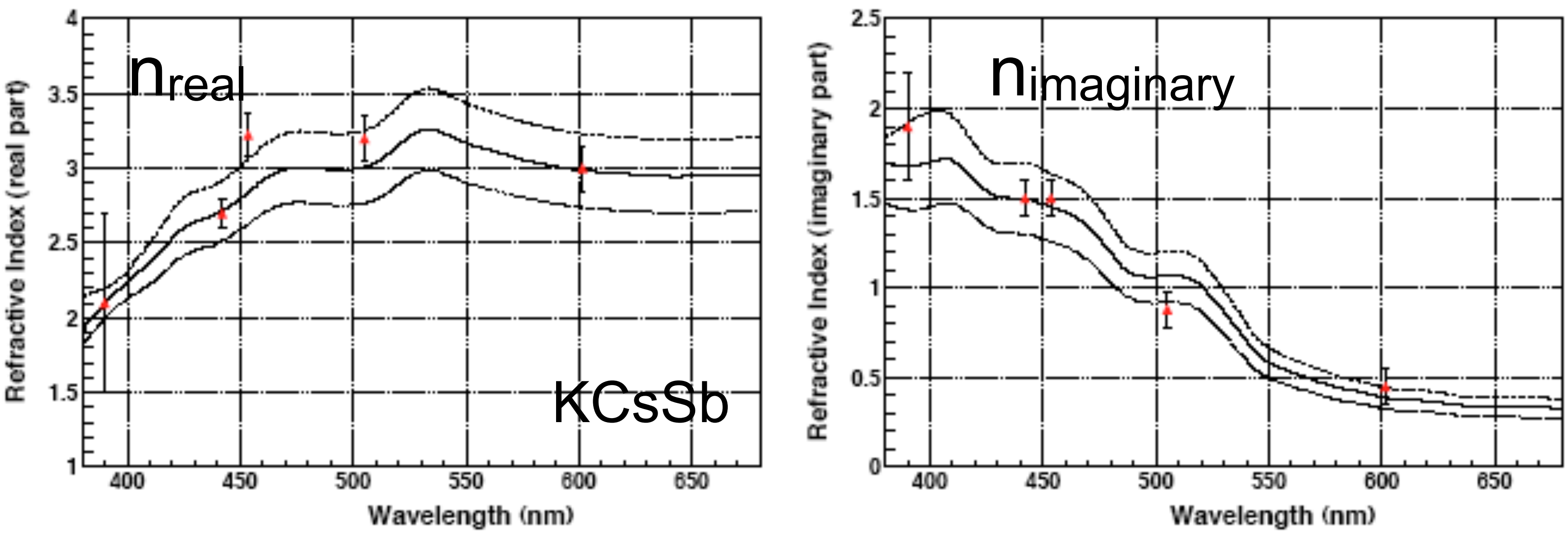
Refractive index of photocathode

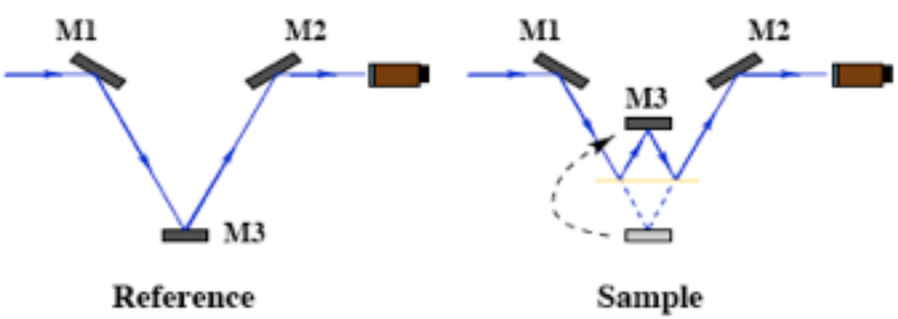
D. Motta, S. Schönert / Nuclear Instruments and Methods in Physics Research A 539 (2005) 217–235

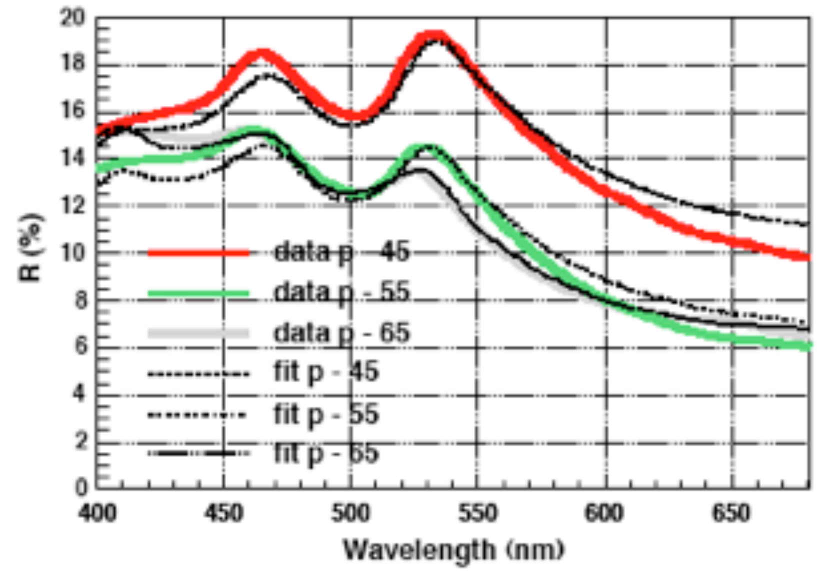


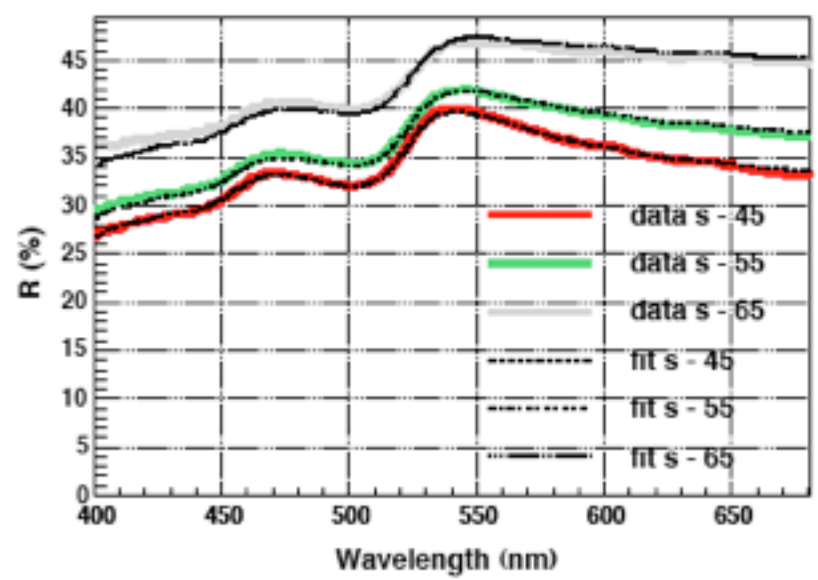
- n_{real} is smaller (less refrection) and $n_{imaginary}$ is larger (more photoelectric absorption) at shorter wave length: Higher QE

Ellipsometry

- Study of thin film using reflection of polarized light at different angles.
- Detailed study of PMT photocathode by Motta and Shonert NIMA539(2005)217







Physics process to test calibrations

- Michel electrons from stopping cosmic rays
  - scintillator box (miniBooNE)
- Through-going muons (beam, cosmic rays)
- π^0 mass
- Characteristic neutrino interaction processes
- Beam tests of small scale detector:
  - e.g. TRIUMF M11 beam
  - tagged neutron beam at RCNP

- These will serve for systematics evaluation

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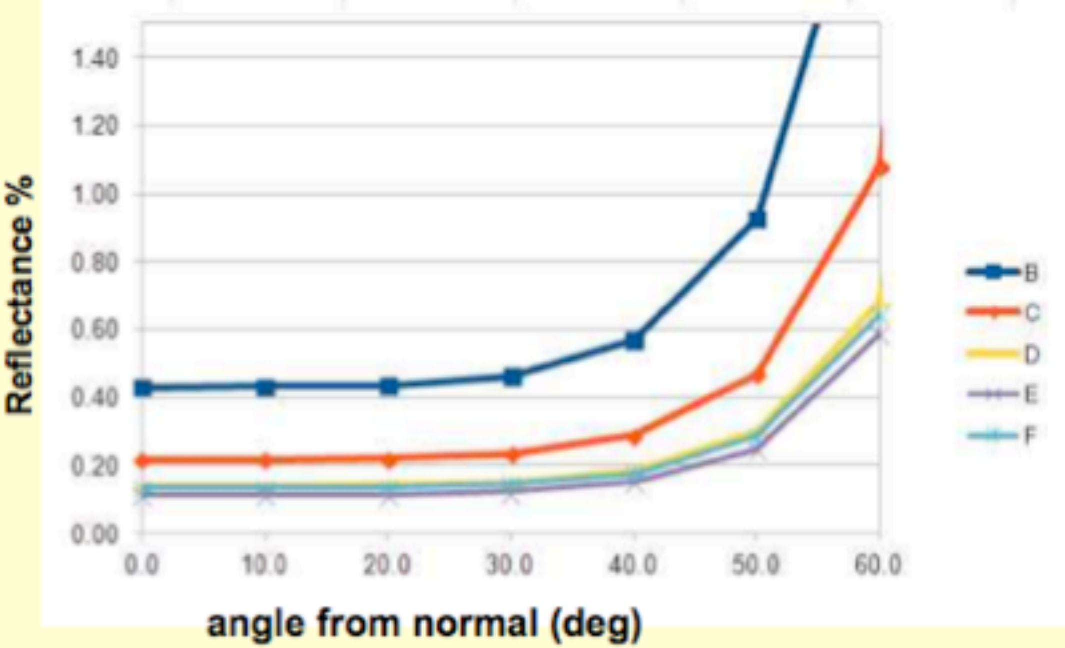
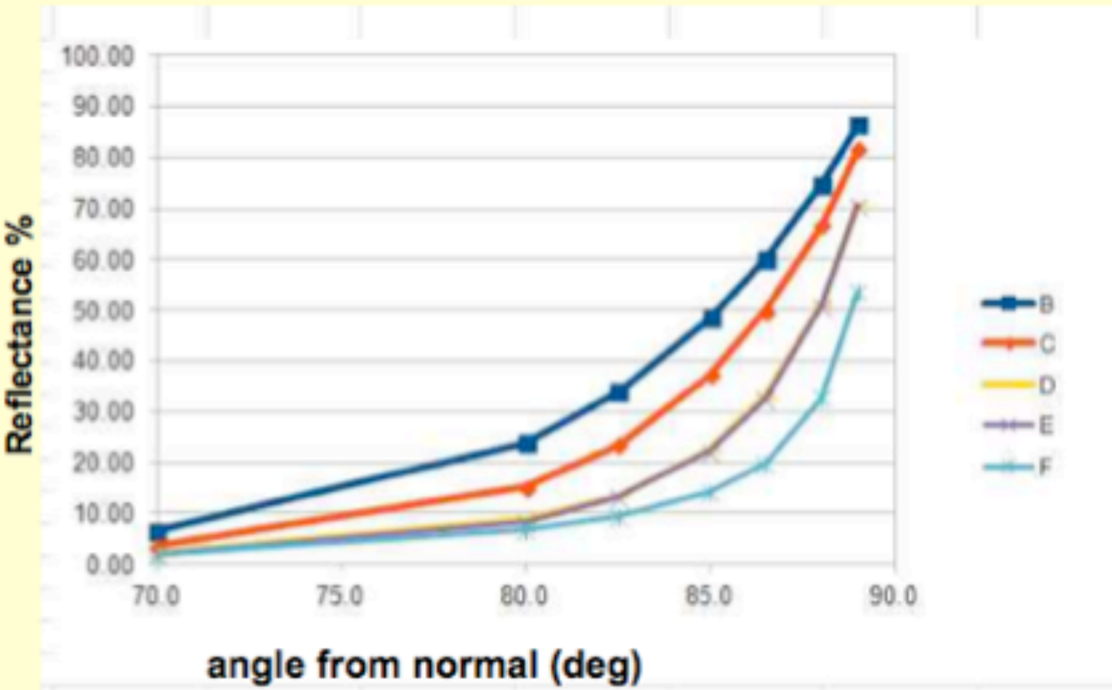
Backup slides

How can we suppress PMT reflection?

- PMT reflection is 22% at 0degree and very large at grazing (large) angle.
- Fresnel reflection at water(1.33)-glass(1.5):
  Add transition sheet in front of glass
  - A sheet with n~1.4 (e.g. Dupond ETFE n=1.407)
  - Multi-layer graded index (1.33-1.5)?
- Reflection at the photocathode:
  High QE PMT (less reflectance, more transmittance)
  - Anti-reflective layer between glass and cathode:
    BeO based layer with intermediate refractive index
  - Photocathode thickness is increased to reduce transmittance (into vacuum) and thus more QE.
- Very interesting test at the PMT test facility!
- NIMA539(2005)217 provides simulation/analysis



For near-normal angles adding a single additional layer (1.33 1.41 1.517) reduces reflectance by 50%, adding more layers does not help much.



For near-grazing angles, adding more layers reduces the reflectance, many finely-graded layers for a gradual transition at the surface greatly reduces the reflectance, from 86% to 54% at 89 degrees.

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Black sheet

- Black sheet: plastic+carbon black powder
- Carbon black is the burnt residue (soot)
  - Size is 20–300nm
- Refractive index of black sheet:
  - Since carbon black is smaller than optical wave length, average of carbon black and plastic
- Refractive index of carbon black:
  - n=1.95+0.7i mixed with air n=1.0+0i
  - typical one used is n~1.8+0.5i??
- Refractive index of plastic:
  - Teflon: n=1.31–1.4
  - PET (used by SK): n=1.575

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Sizes of cabon black

Types of carbon black used in tires

Name	Abbrev.	ASTM desig.	Particle Size nm	Tensile strength MPa	Relative laboratory abrasion	Relative roadwear abrasion
Super Abrasion Furnace	SAF	N110	20–25	25.2	1.35	1.25
Intermediate SAF	ISAF	N220	24–33	23.1	1.25	1.15
High Abrasion Furnace	HAF	N330	28–36	22.4	1.00	1.00
Easy Processing Channel	EPC	N300	30–35	21.7	0.80	0.90
Fast Extruding Furnace	FEF	N550	39–55	18.2	0.64	0.72
High Modulus Furnace	HMF	N683	49–73	16.1	0.56	0.66
Semi-Reinforcing Furnace	SRF	N770	70–96	14.7	0.48	0.60
Fine Thermal	FT	N880	180–200	12.6	0.22	--
Medium Thermal	MT	N990	250–350	9.8	0.18	--

- Smaller than the optical wave length
  - Averaged with medium for optical properties

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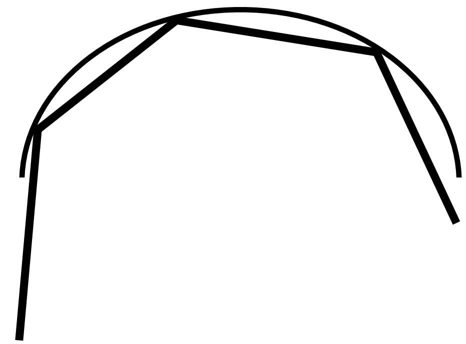
Index of refraction of carbon black

Reference	Cited by	Real (n)	Imag. (k)	Material
Measurements				
Coal				
McCartney et al. 1965	TW	1.7–2.0	0.25–0.5	Coal of various ranks
Gilbert 1962		1.8–2.05	0–0.8	Coal from specific mines
Carbon particles				
1 Batten 1985	H	1.20–1.35	0.1–0.22	Kerosene soot
2 Chang and Charalampopoulos 1990		1.77	0.63	Premixed propane-oxygen, $\phi = 1.8$
3 Chippett and Gray 1978		1.9	0.35	Smoke generator
4 Dalzell and Sarofim 1969	H	1.56	0.47	Average of coal and propane soots
5 Erickson et al. 1964		1.4	1.0	Benzene-air flame
6 Habib and Vervisch 1988		1.3	0.3	Premixed flames, various fuels
7 Janzen 1979	FMK	2.0	1.0	Carbon black
8 Lee and Tien 1981	CHH	1.95	0.48	Polystyrene and plexiglas flames
9 Mullins and Williams 1987		1.88–1.93	0.39–0.45	Toluene, propane, n-heptane
10 Marley et al. 2001		1.87	0.56	Soot from candle flame
11 Marley et al. 2001		1.68	0.56	Diesel soot
12 Pluchino et al. 1980	H, CHH	1.7–1.8	0.6–0.8	Carbon black, single particle
13 Powell and Zinn 1983	CHH	1.108	0.075	Flaming polymeric materials
14 Senftleben and Benedict 1918	TW	1.9	0.65	Arc-lamp soot
15 Stagg and Charalampopoulos 1993		1.52	0.36	Propane flame
16 Wu et al. 1997		1.58	0.51	Turbulent diffusion flames

T.C.Bond and R.W.Bergstorm Aerosol Science and Technology 40(2006)27

How can we suppress black sheet reflection?



- It is Fresnel reflection:
  - Match the refractive index!
  - Serious problem near the wall
  - Wavy structure should be avoided: multiple Fresnel reflection makes reflection back
- Match the refractive index with water:
  - Teflon: Dupond FEP (n=1.34), PTFE/PFA(n=1.35)
  - Use lower index carbon black, or use lower concentration of carbon black (instead of 25%)
- Test of black teflon sheet in the water at the PMT test facility will be very interesting!
  - black teflon (n=1.35) and black PET(n=1.575) used for SK
  - measurement at grazing angle is important.
  - why more forward and less backward scattering compared to Fresnel reflection? Angular smearing effect?

PMT Reflection: NIMA539(2005)217

- Large angle:
  Fresnel reflection at glass
- 42deg.
  total internal refl. at cathode
- 43% loss in transmittance
  and reflectance
  ⇒ high QE PMT by BeO layer