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Measurement of the Aerosol Differential Scattering Cross Section Using HiRes Fluorescence Detectors

Tracey Tessier[1], Byron Dieterle[1], John A.J. Matthews[1], Richard Gray[2], Lawrence R. Wiencke[2], Roger Clay[3] for the HiRes Collaboration.
[1]*New Mexico Center for Particle Physics, University of New Mexico, Albuquerque, NM 87131, USA*
[2]*Physics Department, University of Utah, Salt Lake City, UT 84112, USA*
[3]*Physics Department, University of Adelaide, South Australia, 5005*

Abstract

The next generation of air fluorescence experiments studying cosmic rays with energies near 10^{20}eV require significantly better atmospheric monitoring than the original Fly's Eye experiment in order to reconstruct accurately the energy of the cosmic rays. In this paper we review one proposed method to measure the combined molecular (Rayleigh) and aerosol (Mie) normalized differential scattering cross section using the HiRes fluorescence detectors. While the primary goal is to measure/monitor the unknown aerosol differential scattering cross section, the results may also be used in conjunction with the known Rayleigh scattering cross section to determine the absolute fluorescence detector efficiency (photons to ADC readout).

1 Introduction:

The atmospheric corrections applied to the High Resolution Fly's Eye (HiRes) experimental data (Sokolsky, 1999) are of two forms. The first takes into account the finite transmission of light from the extensive air shower to the fluorescence detectors; this is called the *transmission* correction (Matthews, 1999a). In practice, the observed signal includes both air fluorescence plus some scattered air Cherenkov light from the air shower. The latter must be subtracted as part of the shower reconstruction/analysis and, constitutes the second (*air Cherenkov*) correction to the fluorescence data.

The correction for air Cherenkov light scattered into the fluorescence detectors involves several elements. Furthermore, the magnitude of this correction varies significantly with shower geometry since showers directed toward a fluorescence detector will require the largest correction for scattered air Cherenkov light. Making these corrections requires knowledge of the density of scatterers as a function of height and, of the differential scattering cross sections for both molecular (Rayleigh) and aerosol (Mie) scattering. The Rayleigh scattering component depends on the vertical density profile of the atmosphere and, on the known molecular differential cross section. The vertical density profile is well modeled (Martin, 1999) and frequently measured (radiosonde data). The atmospheric density at the altitude of the fluorescence detectors, $z = 0$, is simply related to the local air temperature and pressure. The Mie scattering component, on the other hand, requires the measurement of several parameters: the vertical normalized density profile of aerosols, $\tilde{\rho}^a(z)$ (Matthews, 1999a), the horizontal attenuation length due to aerosols as a function of wavelength, $\Lambda^a(\lambda)$, and the Mie differential scattering cross section for scattering angles in the range: $20^\circ \sim 160^\circ$. We note that the aerosol differential scattering cross section in the angular range $20^\circ \sim 90^\circ$ is most relevant to the scattering of air Cherenkov light into the fluorescence detectors, while knowledge of the cross section in the angular range $\leq 160^\circ$ is useful for analyzing the scattering of laser light (used for atmospheric monitoring) into the HiRes fluorescence detectors.

The aerosol differential cross section must be known at the height, z, where the scattering of air Cherenkov light occurs. Studies are in progress by the HiRes collaboration (Dieterle, 1999) to determine how well this cross section can be measured using the fluorescence detectors to observe light scattered from upward going laser pulses (at 355nm). A detailed measurement of the aerosol differential cross section at the height of the fluorescence detectors provides an essential input to the $z > 0$ analysis as well as a determination of any wavelength dependence.

It is convenient to define the *aerosol phase function* as the normalized differential cross section: $\frac{\frac{d\sigma(cos(\beta),\lambda)}{d\Omega}}{\sigma}$, where β is the scattering angle from the initial light beam direction and λ is the wavelength of the light. Previously, the Fly's Eye and HiRes prototype experiments have used atmospheric simulation models (Kneizys, 1988), (Longtin, 1988) to predict the aerosol phase function for different desert conditions (Sokolsky, 1996). The remainder of this paper presents one method to measure the aerosol phase function in near real-time during actual HiRes runs. This technique will facilitate a more accurate analysis of the HiRes stereo data (Sokolsky, 1999) and, may assist in the absolute calibration of the fluorescence detectors.

2 Local Aerosol Phase Function Measurement:

The procedure to measure the aerosol phase function at the height of the HiRes detectors will employ a xenon flash tube light source which will emit light pulses spanning a wide wavelength range. The duration of these pulses will be $\sim 1\mu$s, which is characteristic of distant showers. Individual wavelength intervals will be selected using optical filters and, a small telescope will be used to collimate the light. The light beam will then be directed horizontally past the fluorescence detectors from a nearby location. This geometry requires almost no attenuation correction for the light and allows the fluorescence detectors to measure the light scattered out of the beam over the desired range of scattering angles. (The HiRes detectors view with $1° \times 1°$ pixels over $360°$ in azimuth and from $4° \sim 30°$ in elevation.) Since the scattered light includes both aerosol and molecular contributions, the absolute intensity of each light pulse will be measured in order to subtract the Rayleigh background.

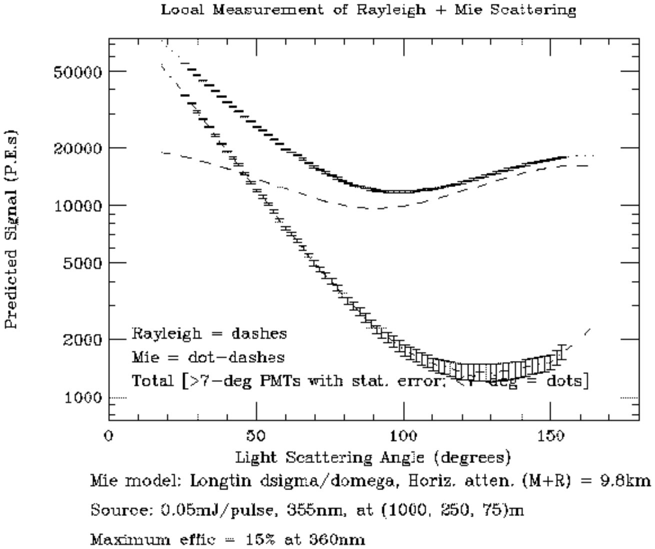

Figure 1: Simulated Rayleigh and Mie (Longtin, 1988) scattered light *versus* scattering angle, β.

The light scattered into a given HiRes phototube (PMT) depends on several factors, the first of which is the intensity of the light beam. This quantity decreases exponentially as the light moves away from the source with an attenuation length of $\sim$ 10km. The second main factor is the fraction, $f(\lambda)$, of light that undergoes aerosol or molecular scattering into the angular acceptance, $\Delta\Omega$, of the appropriate detector:

$$f(\lambda) \;=\; \{\, \frac{\tilde{\rho}^a(z)}{\Lambda^a(\lambda)} \cdot (\frac{\frac{d\sigma^a(cos(\beta),\lambda)}{d\Omega}}{\sigma^a}) \;+\; \frac{\tilde{\rho}^m(z)}{\Lambda^m(\lambda)} \cdot (\frac{\frac{d\sigma^m(cos(\beta),\lambda)}{d\Omega}}{\sigma^m})\,\} \;\cdot\; ds \;\cdot\; \Delta\Omega$$

where $\tilde{\rho}(z) \;=\; \frac{\rho(z)\sigma(z,\lambda)}{\rho(0)\sigma(0,\lambda)}$ is the normalized density of aerosols (superscript "a") or, of the molecular atmosphere (superscript "m") as a function of elevation, $\Lambda(\lambda) = \frac{1}{\rho(0)\sigma(0,\lambda)}$ is the appropriate horizontal attenuation length (*e.g.* in meters) at $z = 0$ as a function of wavelength, λ, and ds is the horizontal distance along the light beam viewed by a given PMT.

The simulated signal for a 0.05mJ light pulse at 355nm is shown in Fig. 1 as a function of scattering angle, β. The light pulse consists of a (simulated) laser shot fired horizontally past one of the detectors at an altitude 75m above the height of the detector. The beam comes within 250m of the fluorescence detector at closest approach. The modeled signal uncertainties include photo-electron statistics plus typical night sky backgrounds. Similarly, the planned measurement of the aerosol phase function at the HiRes site will occur at an altitude, $z \leq$ 100m, where $\tilde{\rho}^a(z) \approx 1$. Since the horizontal attenuation length, $\Lambda(\lambda)$, is measured as part of the HiRes atmospheric monitoring procedure, the necessary correction for light attenuation (from the source to the point of scattering and, from the point of scattering to the fluorescence detector) is straightforward.

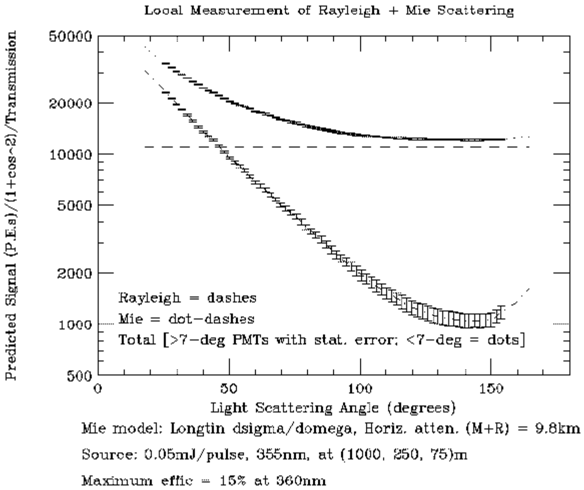

Figure 2: Corrected Rayleigh and Mie differential scattering cross sections plotted *versus* scattering angle, β; see text for the correction factor.

Fig. 2 shows the simulated signal (corrected for attenuation) divided by $1 + cos^2(\beta)$. This renders the Rayleigh scattering signal independent of scattering angle; see the dashed line in Fig. 2. The aerosol phase function is obtained by subtracting the predicted Rayleigh signal from the total corrected signal. This requires knowledge of the intensity of each light pulse (which will be measured), of the density of the air (which will be determined from the local temperature and pressure) and, of the overall efficiency of the fluorescence detectors. Since the corrected signal at scattering angles 120° $\sim$ 150° may be close to the pure Rayleigh contribution, see Fig. 2, the data provide some constraints on the subtraction.

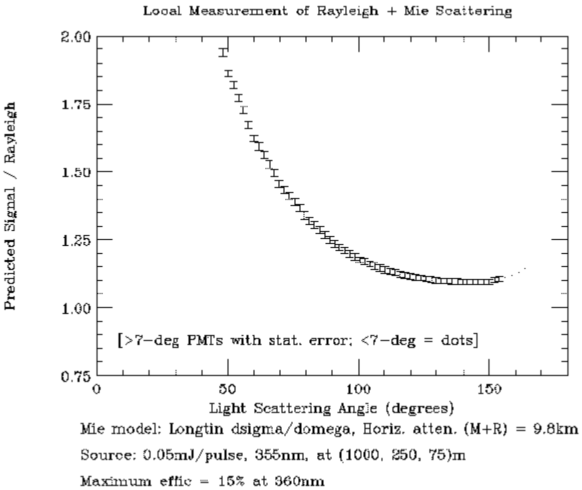

Figure 3: Ratio of Observed to Predicted Signals *versus* scattering angle, β. For nights with little aerosol scattering this ratio should approach the ratio: actual/input fluorescence efficiency; *e.g.*, in this simulation the ratio approaches $\sim$ 1.1 for $\beta \approx 140°$.

This argument can be inverted to use the observed signal at large scattering angles (*e.g.*, in the range 120° $\sim$ 150°) to measure the *end to end* (photons to ADC values) fluorescence detector efficiency. For example, on nights with low levels of aerosols in the atmosphere, *i.e.* large values for $\Lambda^a(\lambda)$, the ratio of the observed signal to the predicted signal at large scattering angles provides a cross check on the detector efficiency; see Fig. 3. In the limit of no aerosol scattering at these angles, the ratio in Fig. 3 gives the end to end fluorescence detector efficiency with respect to the efficiency as measured using other techniques (Matthews, 1999b).

The use of the scattered light signal at large angles to measure the fluorescence detector end to end efficiency may be improved in at least two ways:

1. The strong wavelength dependence ($\propto \lambda^4$) of the Rayleigh horizontal attenuation length, in comparison to the weak wavelength dependence predicted for aerosols (Longtin, 1988), provides one means to improve the separation of the molecular and aerosol signals.

2. An independent *table top* instrument designed to measure the scattered light intensity as a function of scattering angle is under development (Dieterle, 1999). This instrument has the potential to determine the absolute light scattering probability (*e.g.* per meter of air) as a function of angle. Use of this instrument at the HiRes site would provide knowledge of the light scattering probability in the local atmosphere at all angles, β, not just the angles where Rayleigh scattering dominates. It is then straightforward to predict the signal, in photons, expected from the local, pulsed, horizontal light source viewed by the fluorescence detector.

3 Conclusions:

This paper reviews the planned, on-site measurement of the aerosol (Mie) differential scattering cross section at the altitude of the HiRes fluorescence detectors. The measurement provides constraints on the aerosol differential scattering cross section at heights, z, above the fluorescence detectors as well as a determination of the wavelength dependence of the cross section. This will result in the ability to determine the energies of extensive air showers associated with high energy cosmic ray events to greater precision. Additionally, these results, combined with the known molecular (Rayleigh) scattering cross section, may provide a method to determine the absolute efficiency (photons to ADC readout) of the HiRes fluorescence detectors.

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