Measurement of the Air Fluorescence Yield with the AirLight Experiment

T. Waldenmaier[1], J. Blümer[1,2], H. Klages[1], S. Klepser[3]

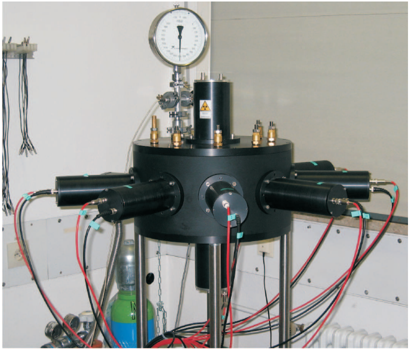
[1]Forschungszentrum Karlsruhe,

[2]Universität Karlsruhe,

[3]DESY Zeuthen

4th Air Fluorescence Workshop, Prague, May 2006

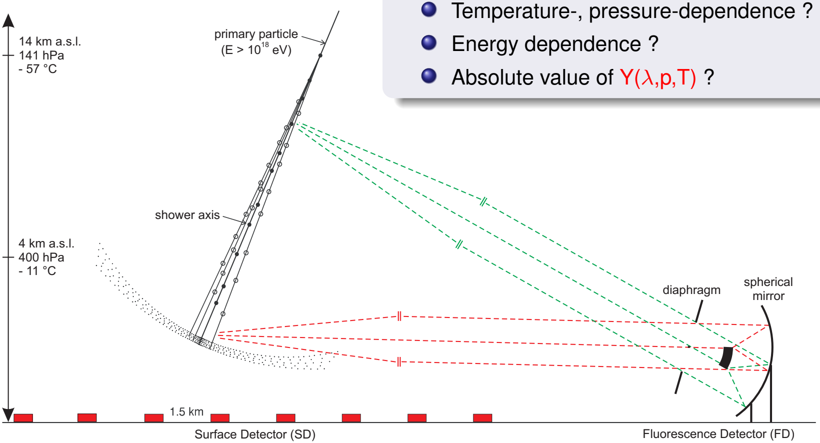
Outline



Motivation

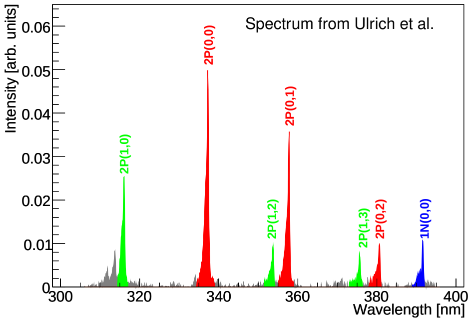
Questions to answer

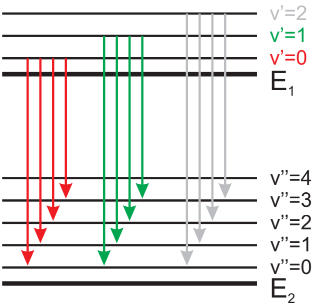
- Temperature-, pressure-dependence ?
- Energy dependence ?
- Absolute value of $Y(\lambda,p,T)$?



$$\frac{dN_{\gamma}^{obs}}{dX} = \frac{dE_{dep}}{dX} \cdot \int Y(\lambda, T, p) \cdot T_{atm}(\lambda) \cdot \varepsilon_{det}(\lambda)\, d\lambda$$

Nitrogen Fluorescence Spectrum





Properties

- Rotational-vibrational spectrum.
- Mainly three electronic-vibrational band systems between 300 nm and 400 nm: $2P(v' = 0, v'')$, $2P(v' = 1, v'')$, $1N(v' = 0, v'')$
- (Radiative) transition rate: $\frac{1}{\tau_{v'}} = \sum_{v''} \frac{1}{\tau_{v' \to v''}} = \frac{1}{\tau_{0\,v'}}$
- Constant intensity ratios between transitions within a vibrational band system.

Collisional Quenching

Additional radiationless deactivation channels via collisional energy transfer

- Total transition rate: $\frac{1}{\tau_{v'}} = \frac{1}{\tau_{0\,v'}} + \frac{1}{\tau_{c\,v'}}$
- Quenching rate: $\frac{1}{\tau_{c\,v'}} = \sum_x Q^x_{v'}(T) \cdot n_x \quad , x = N_2, O_2, Ar, H_2O, ...$
- Quenching rate "constant": $Q^x_{v'}(T) \propto \sqrt{T}$ $(\rightarrow$ kinetic gas theory)
- Number density: $n_x = \frac{p_x}{kT} = \frac{f_x}{kT} \cdot p$

$$\Downarrow$$

Total transition rate

$$\frac{1}{\tau_{v'}} = \frac{1}{\tau_{0\,v'}} \cdot \left(1 + p \cdot \underbrace{\frac{\tau_{0\,v'}}{kT} \sum_x f_x \cdot Q^x_{v'}(T)}_{1/p'_{v'}}\right)$$

$\rightarrow$ linear pressure-dependence for constant mixing ratios and temperatures.

Fluorescence Yield

Fluorescence yield for any transition $v' \rightarrow v''$ from same electronic-vibrational level

$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

Fluorescence Yield

Fluorescence yield for any transition $v' \longrightarrow v''$ from same electronic-vibrational level

$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

Fluorescence Yield

Fluorescence yield for any transition $v' \rightarrow v''$ from same electronic-vibrational level

$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

Fluorescence Yield

Fluorescence yield for any transition $v' \rightarrow v''$ from same electronic-vibrational level

$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

Fluorescence Yield

Fluorescence yield for any transition $v' \rightarrow v''$ from same electronic-vibrational level

$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

Advantages of this representation

- Consistent description.
- Clear meaning of parameters.
- Does not depend on energy loss function (Bethe-Bloch or similar).

Fluorescence Yield

Fluorescence yield for any transition $v' \rightarrow v''$ from same electronic-vibrational level

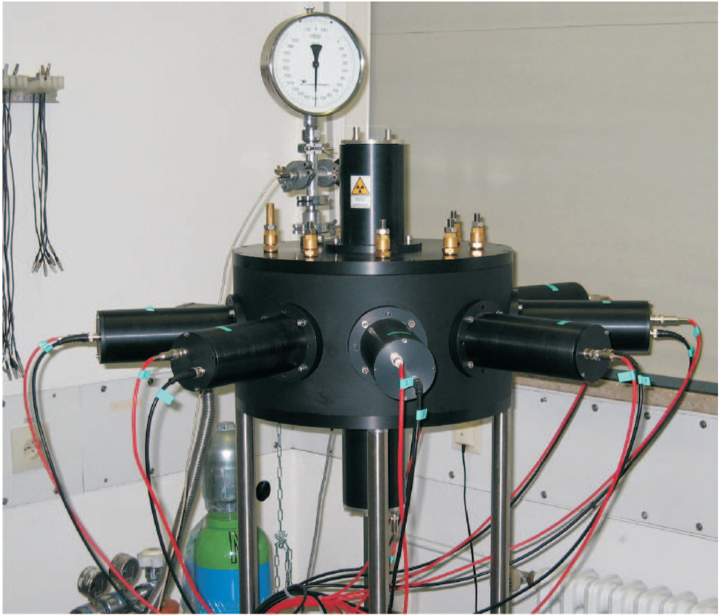
$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} \qquad \left[\frac{photons}{dep.\ energy}\right]$$

Ingredients

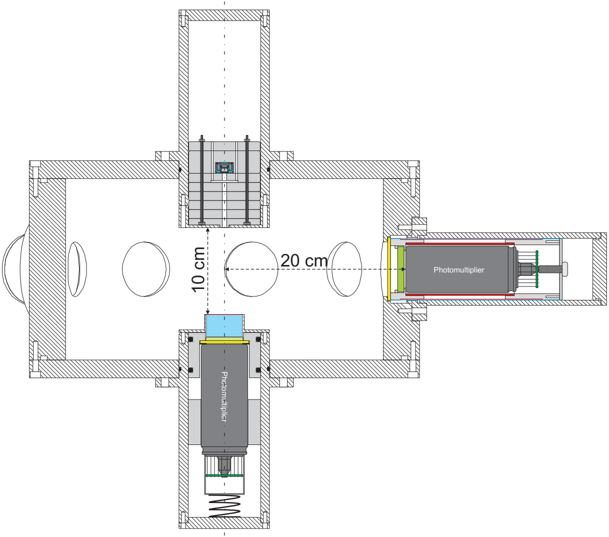
- Intrinsic fluorescence yield of most intensive transition: $Y^0_{v'}(E)$ $\left[\frac{photons}{dep.\ energy}\right]$
- Constant intensity ratios $R_{v',v''}$ relative to most intensive transition.
- Fraction of radiative transitions: $\frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{1/\tau_{0\,v'}}{1/\tau_{v'}(p,T)} = \frac{radiative\ rate}{total\ rate}$

⇒ All these parameters have been measured with the AirLight-Experiment ...

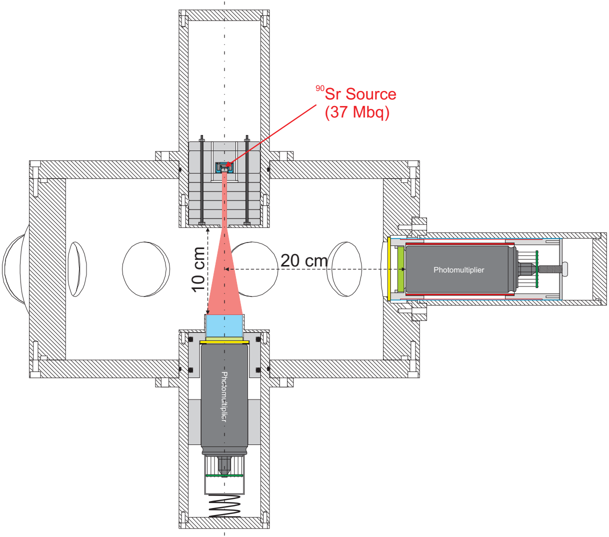
Setup of the AirLight Experiment



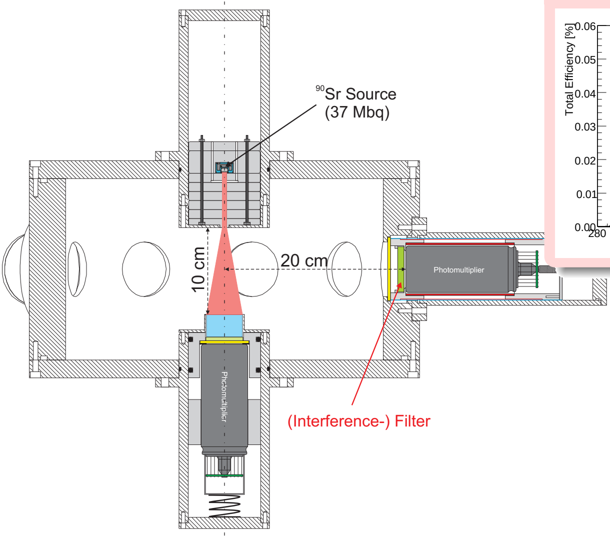
Setup of the AirLight Experiment



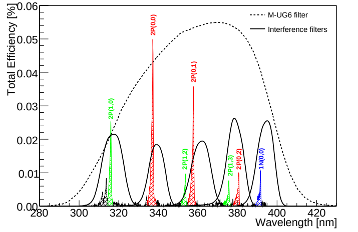
Setup of the AirLight Experiment



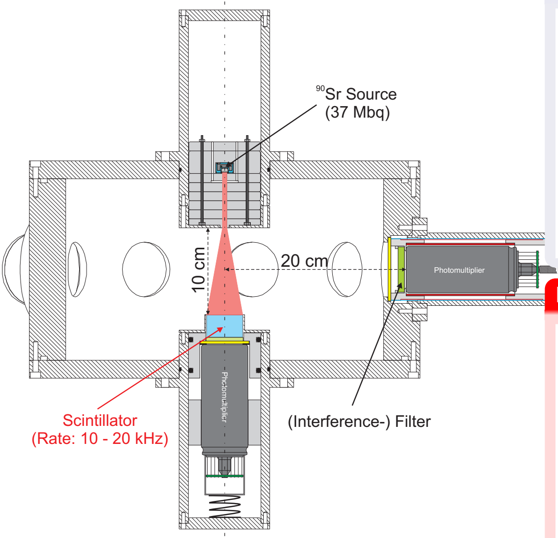
Setup of the AirLight Experiment



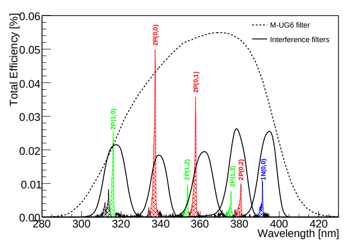
Filter Efficiencies



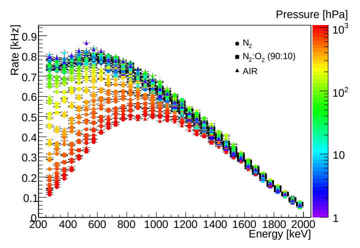
Setup of the AirLight Experiment



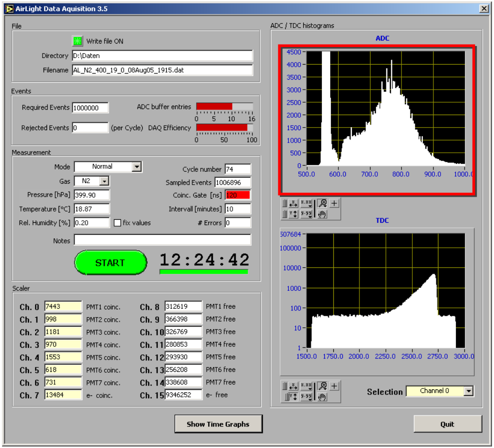
Filter Efficiencies



Energy Spectra @ Scintillator



Data Acquisition



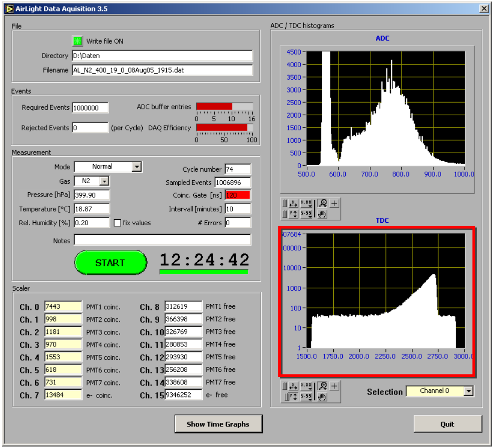
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

Data Acquisition



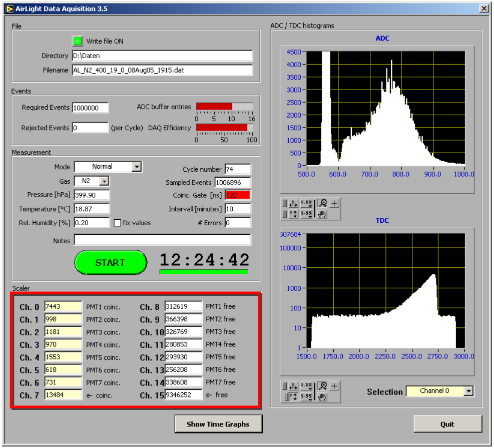
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

Data Acquisition



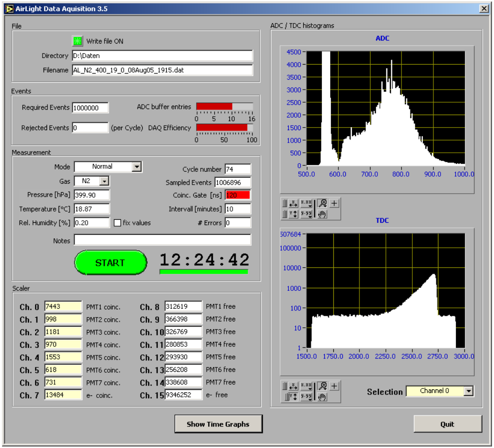
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

Data Acquisition



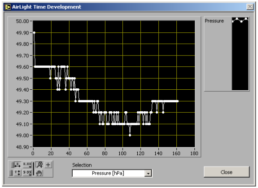
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

Data Acquisition



Pressure

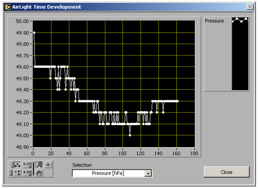
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

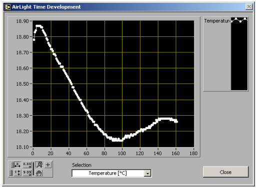
Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

Data Acquisition



Pressure



Temperature

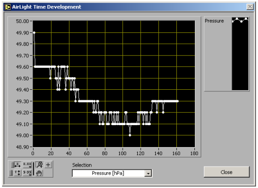
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

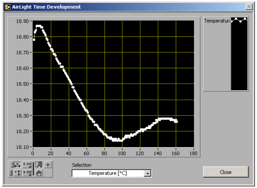
Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

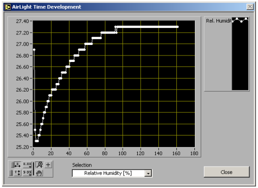
Data Acquisition



Pressure



Temperature



Relative Humdity

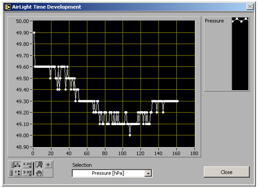
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

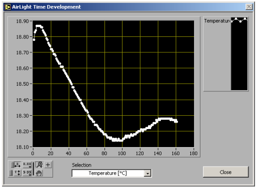
Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

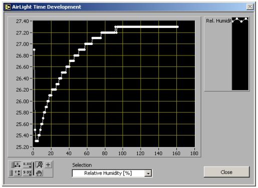
Data Acquisition



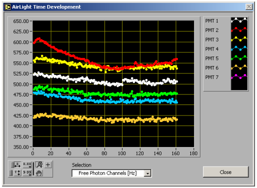
Pressure



Temperature



Relative Humdity



Free PMT rates

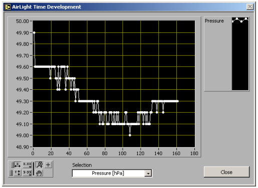
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

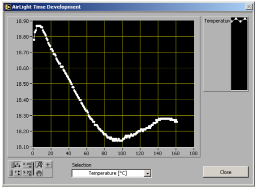
Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

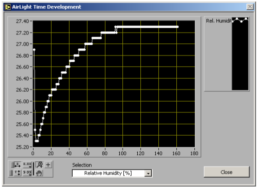
Data Acquisition



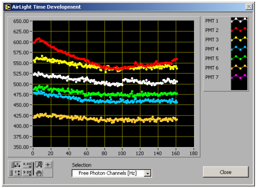
Pressure



Temperature



Relative Humdity



Free PMT rates

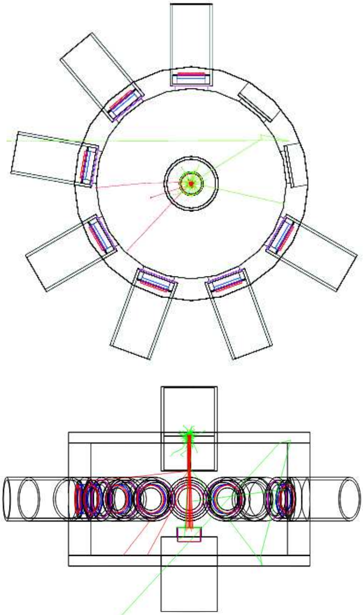
Measurement of coincidences between electron- and photon-detectors:

- Pulse height distributions.
- Difference-time spectra.
- Absolute scaler values.
- Coincident/free electron energy spectra.

Monitoring of environmental conditions:

- Pressure.
- Temperature.
- Relative Humidity.
- Free/Coincident event rates.
- High Voltage/Current.

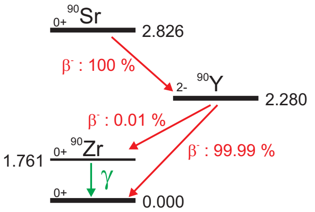
Simulation



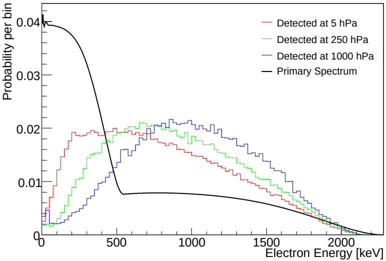
GEANT4 Simulation (version 7.1) to determine:

- Electron energy spectra.
- Energy deposit in chamber.
- Photon angle distribution.
- Acceptance of photomultipliers.

^{90}Sr Energy Spectrum

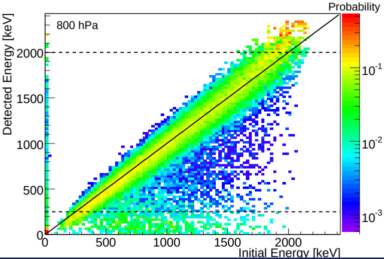


$$^{90}_{38}\mathrm{Sr} \xrightarrow{t_{1/2}\,=\,29\ \mathrm{a}} {}^{90}_{39}\mathrm{Y} \xrightarrow{t_{1/2}\,=\,64\ \mathrm{h}} {}^{90}_{40}\mathrm{Zr}$$

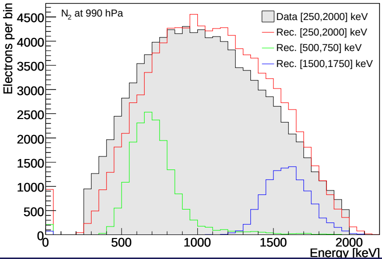


$$\frac{dN}{d\varepsilon} \propto \eta \cdot \varepsilon \cdot (\varepsilon_0 - \varepsilon)^2 \cdot F(Z,\eta) \cdot C(Z,\eta)$$

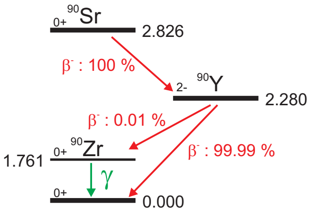
Migration Matrix



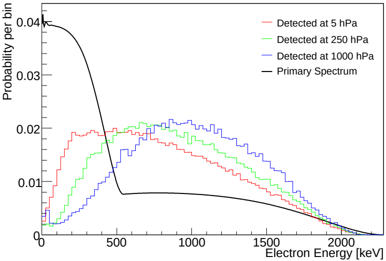
Initial Energy Spectra



^{90}Sr Energy Spectrum

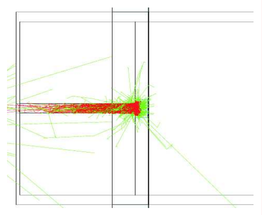


$$^{90}_{38}\mathrm{Sr} \xrightarrow{t_{1/2} = 29\ \mathrm{a}} {}^{90}_{39}\mathrm{Y} \xrightarrow{t_{1/2} = 64\ \mathrm{h}} {}^{90}_{40}\mathrm{Zr}$$



$$\frac{dN}{d\varepsilon} \propto \eta \cdot \varepsilon \cdot (\varepsilon_0 - \varepsilon)^2 \cdot F(Z, \eta) \cdot C(Z, \eta)$$

Important note

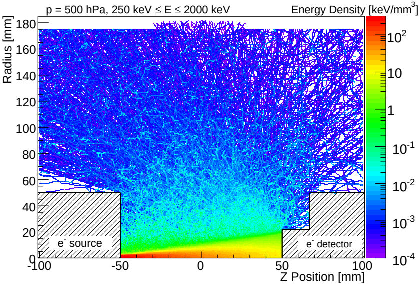


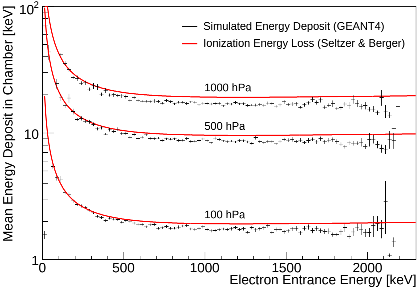
Measured energy spectrum is very much affected by multiple- or back-scattering effects in the collimator and in the gas!

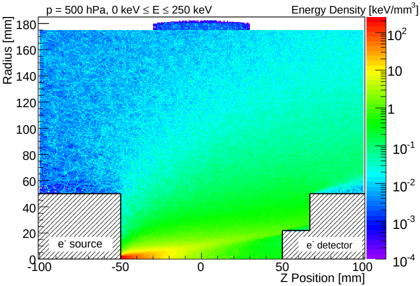
⇒ To obtain reasonable results the *facrange* parameter of the multiple scattering model has to be lowered to 0.01!

0 500 1000 1500 2000 Initial Energy [keV] 0 500 1000 1500 2000 Energy [keV]

Energy deposit in chamber

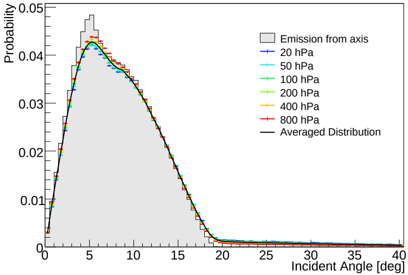


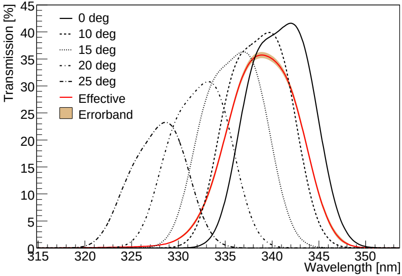


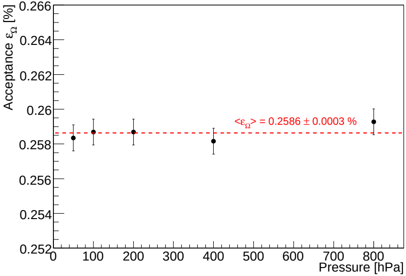


- Generation of Energy deposit maps for all pressures applied for the measurements.
- $\langle E_{dep} \rangle \leq \langle E_{loss} \rangle$ due to limited chamber volume.
- Influence of delta electrons is correctly treated.

Angle Distribution & Acceptance







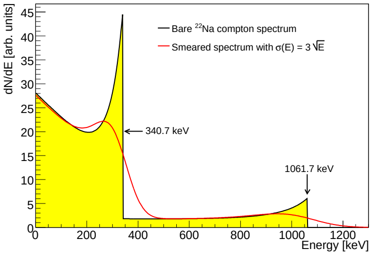
- Assumption: $\#Photons \propto E_{dep}$.

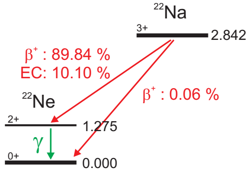
→ Generation of optical photons according to energy deposit maps.

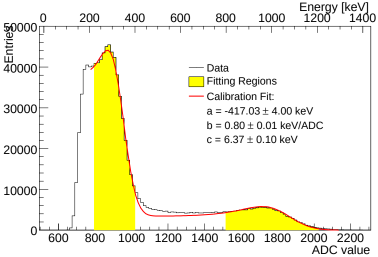
- Slight pressure dependence of angular distributions (→ averaging).

- Acceptance $\varepsilon_\Omega = \frac{\#detected\ photons}{\#generated\ photons}$

Energy Calibration (1. ^{22}Na Method)







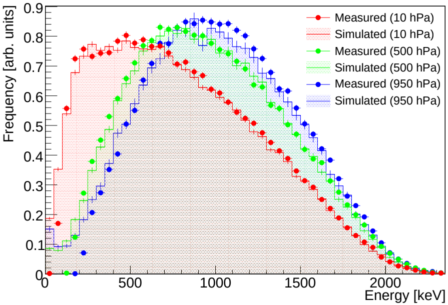
- Measurement of ^{22}Na Compton-spectrum $\frac{dN}{dE}(E)$.
- Convolution: $\frac{dN}{dE}(E) = \frac{dN_{bare}}{dE}(E) \otimes G(E, \sigma_E(E))$
- $E = a + b \cdot ADC\ , \quad \sigma_E(E) = \sqrt{\sigma_{ped}^2 + c \cdot E}$
- Calibration constants a, b, c from fit to measured spectrum.
- Typical energy resolution: $\frac{\sigma_E}{E} \sim 10\ \% \cdot \sqrt{\frac{1000\ \text{keV}}{E}}$

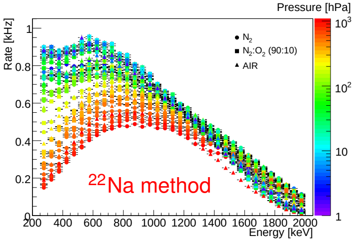
Energy Calibration (2. Monte Carlo Method)

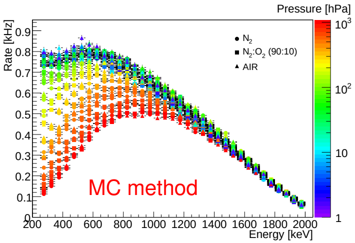
Idea: Why not use the ^{90}Sr-energy spectrum as reference spectrum?

Problem: Spectral shape at scintillator unknown due to scattering/energy loss in the chamber.

Solution: Simulate energy spectra at scintillator for different pressures (with *facrange* $\leq$ 0.01).



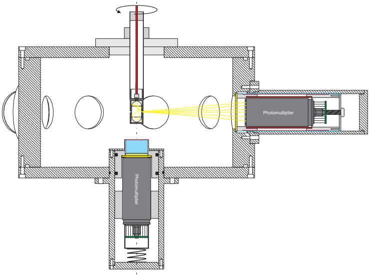


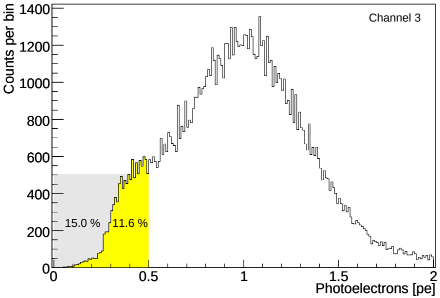


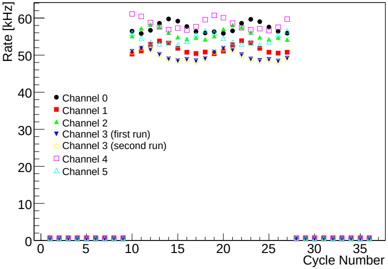
Advantages:

- Covering the whole energy range.
- Individual calibration of each run.
- Minimizing run-to-run fluctuations.

Relative Calibration of the Photomultipliers

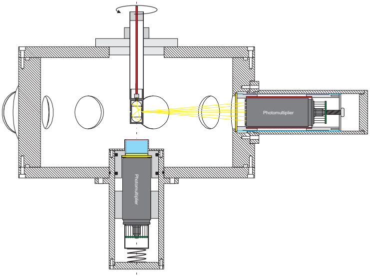


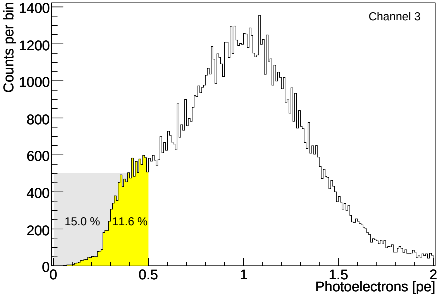


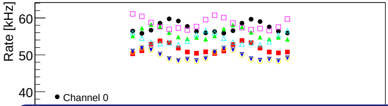


- Detected photons: $N_{det} = \varepsilon_{\Omega} \cdot \varepsilon_{s} \cdot f_{cal} \cdot N_0$
- $\varepsilon_s = \int_\lambda \varepsilon^0_{QE}(\lambda) \cdot T(\lambda) \cdot \frac{dN}{d\lambda}\, d\lambda = \mathit{const}.$
- Photoelectron cut: $0.5 \leq$ p.e. ≤ 2.0 (for calibration and measurement)
- Calibration relative to channel 3 ($f_{cal} \equiv 1$)

Relative Calibration of the Photomultipliers







- Detected photons: $N_{det} = \varepsilon_\Omega \cdot \varepsilon_s \cdot f_{cal} \cdot N_0$
- $\varepsilon_s = \int_\lambda \varepsilon^0_{QE}(\lambda) \cdot T(\lambda) \cdot \frac{dN}{d\lambda}\, d\lambda = \mathit{const}.$

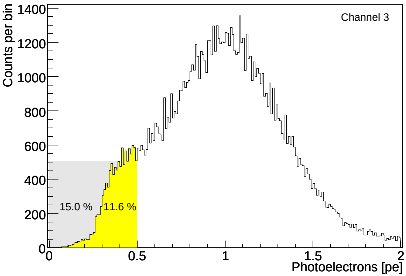
Resulting calibration constants f_{cal}

Date	Channel 0	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5
08/01	1.13 ± 0.03	0.97 ± 0.03	1.10 ± 0.03	1.00 ± 0.00	1.17 ± 0.04	1.08 ± 0.03
08/24	1.14 ± 0.03	0.97 ± 0.03	1.12 ± 0.03	1.00 ± 0.00	1.16 ± 0.04	1.07 ± 0.03
09/23	1.13 ± 0.03	0.97 ± 0.03	1.12 ± 0.03	1.00 ± 0.00	1.17 ± 0.04	1.07 ± 0.03
10/27	1.14 ± 0.03	0.97 ± 0.03	1.12 ± 0.03	1.00 ± 0.00	1.16 ± 0.04	1.08 ± 0.03

Systematic Errors

Relative Uncertainty

Relative calibration f_{cal}:	~ 3 %
Photoelectron cut ε_{cut}:	~ 2 %
Spectral efficiency ε_S:	$4 - 8\%$
Acceptance ε_Ω:	~ 0.4 %
Total:	$5.4 - 8.8$ %



Estimation of absolute uncertainty:

- Discriminator threshold assumed to be stable.
- Events above 2 pe are mostly background.
- $\sim$ 12 % of the events are between discr. threshold and 0.5 pe.
- Less than 15 % of the events are below discr. threshold.

$\Rightarrow$ $N_{abs} = (1 + 12\,\% + 7.5\,\% \pm 7.5\,\%) \cdot N_{rel} = (1.195 \pm 0.075) \cdot N_{rel}$

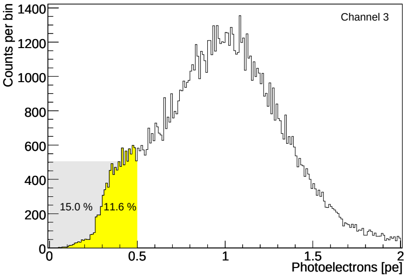
Normalization error of QE-curve assumed to be $\sim 10\%$:

$\Rightarrow$ Calibration constant: $C_{\text{abs}} = (1 \pm 0.1) \cdot \frac{N_{abs}}{N_{rel}} = 1.195 \pm 0.141 \quad , \quad \frac{\Delta C_{\text{abs}}}{C_{\text{abs}}} = 12\%$

Systematic Errors

Relative Uncertainty

Relative calibration f_{cal}:	~ 3 %
Photoelectron cut ε_{cut}:	~ 2 %
Spectral efficiency ε_S:	$4 - 8$%
Acceptance ε_Ω:	~ 0.4 %
Total:	$5.4 - 8.8$ %



Estimation of absolute uncertainty:

- Discriminator threshold assumed to be stable

Final absolute accuracies

$\Rightarrow$ Absolute accuracy of single bands $\lesssim 15$ %

- Reduction to $\lesssim 10$ % in future possible with calibration by Rayleigh scattering.

$\Rightarrow$ $N_{abs} = (1 + 12\ \% + 7.5\ \% \pm 7.5\ \%) \cdot N_{rel} = (1.195 \pm 0.075) \cdot N_{rel}$

Normalization error of QE-curve assumed to be ~ 10%:

$\Rightarrow$ Calibration constant: $C_{\text{abs}} = (1 \pm 0.1) \cdot \frac{N_{abs}}{N_{rel}} = 1.195 \pm 0.141$, $\frac{\Delta C_{\text{abs}}}{C_{\text{abs}}} = 12\%$

Measurements & Data Analysis

The complete dataset used for the analysis consists of ∼ 50 runs with:

- Pure nitrogen
- Dry air (78% N_2, 21% O_2, 1% Ar)
- Mixture (90% N_2, 10% O_2)
- Nitrogen + water vapor
- Temperature: ∼ 20°C
- Pressure range: 2 hPa - 1000 hPa
- Duration: 12 h - 30 h (depending on gas and pressure)

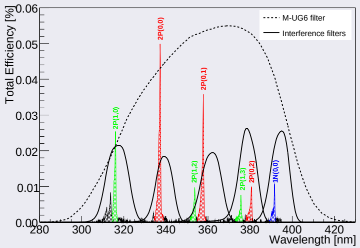
Analysis philosophy:

Step 1: Determination of quenching parameters and intensity ratios over whole energy range (→ max. statistics).

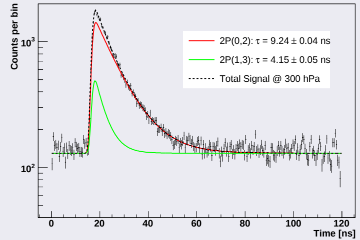
Step 2: Determination of intensities (intrinsic yields) with fixed parameters of step 1 for energy sub-ranges.

Step 1: Determination of Quenching Parameters and Intensity Ratios

Filter Channels



Time spectra in 380 nm filter channel



Problem

Overlapping bands within a single filter channel.

Solution

- Global analysis of all datasets ($\sim$ 50 runs).
- Constrained χ^2-minimization with minimal set of parameters.
- Physical constraints for transitions from same vibrational level v':

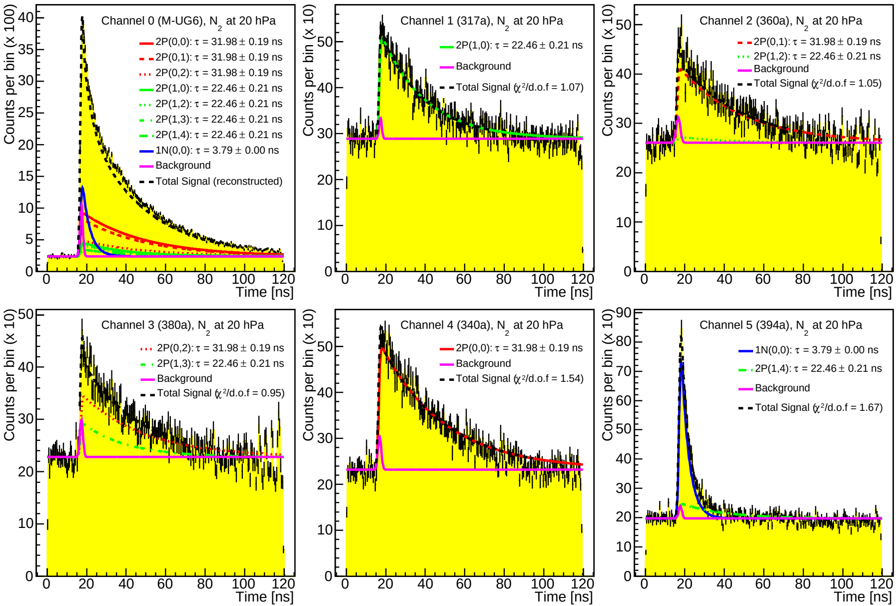
$\rightarrow$ Same intrinsic lifetime $\tau_{0\,v'}$.

$\rightarrow$ Same quenching rate constants $Q^x_{v'}$.

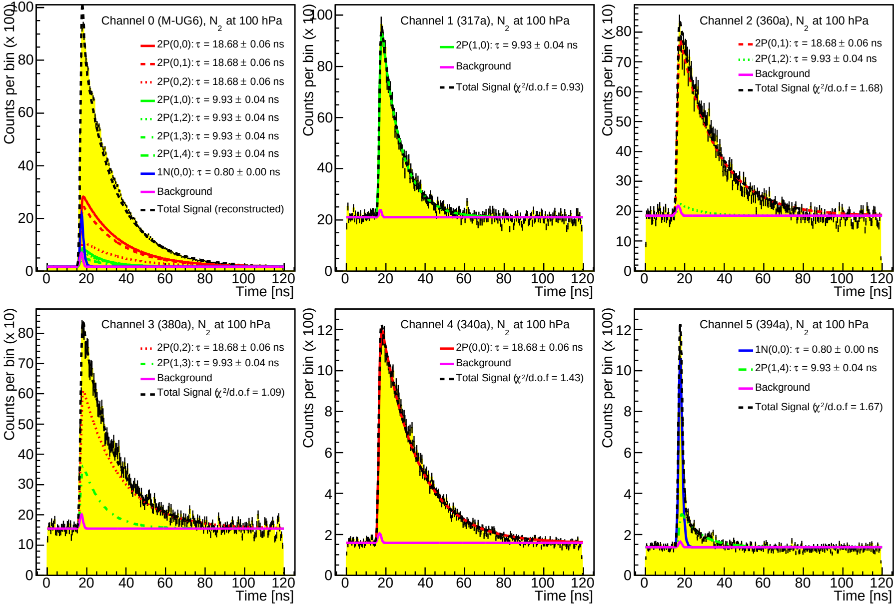
$\rightarrow$ Same intrinsic yield $Y^0_{v'}$.

$\rightarrow$ Constant Intensity ratios $R_{v',v''}$.

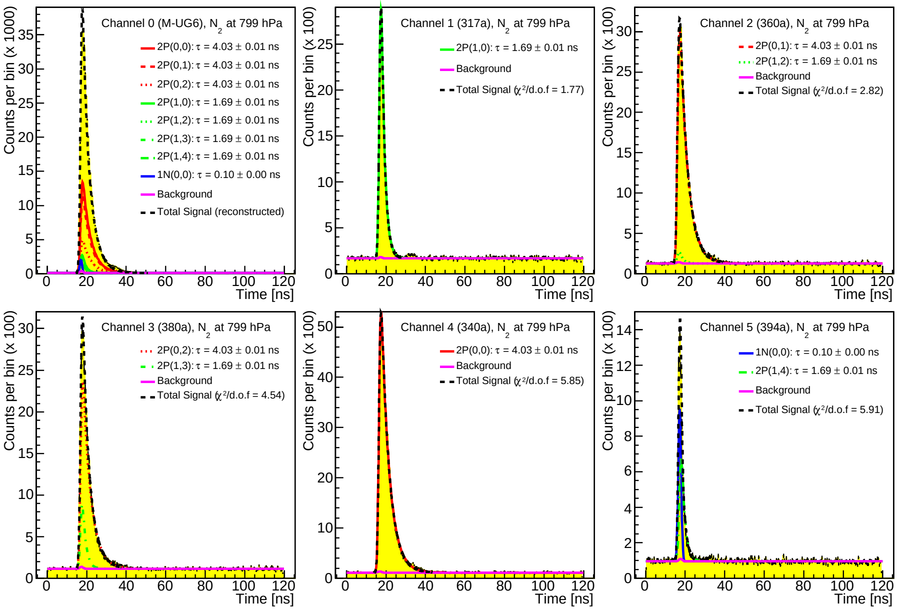
Time Spectra in Nitrogen at 20 hPa



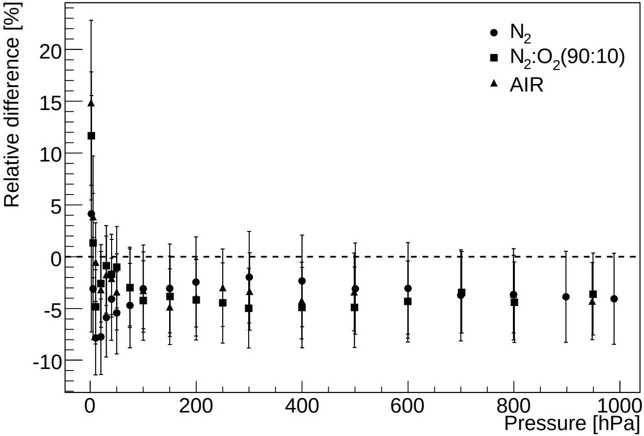
Time Spectra in Nitrogen at 100 hPa



Time Spectra in Nitrogen at 800 hPa



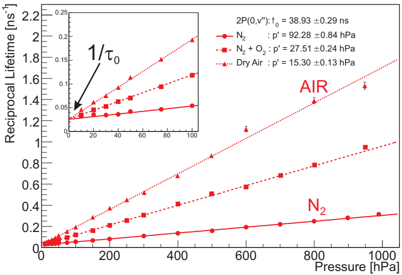
Reconstructed Signal in the M-UG6 channel:



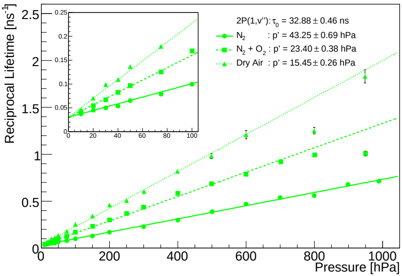
- Good relative description of the total fluorescence yield over whole pressure range within 4 %.

Nitrogen Quenching Results

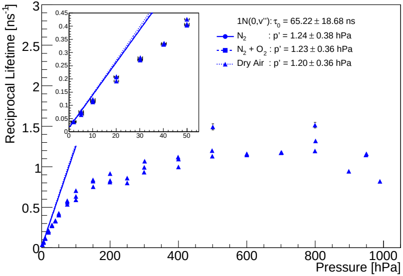
2P(0,v”)



2P(1,v”)



1N(0,0)



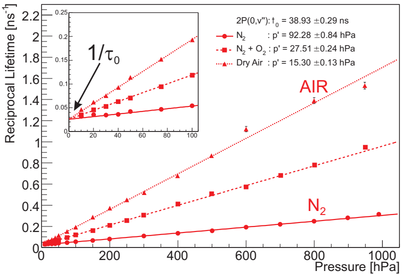
Additional constraint for lines:

$$\frac{1}{\tau_{v'}} = \frac{1}{\tau_{0\,v'}} \cdot \Bigg(1 + \underbrace{p \cdot \frac{\tau_{0\,v'}}{kT} \sum_x f_x \cdot Q^x_{v'}(T)}_{1/p'(T)}\Bigg)$$

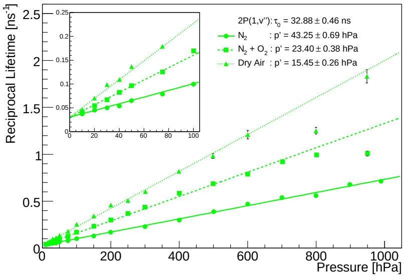
- Fit to 1N(0,0) data yields only reasonable results under this condition.

Nitrogen Quenching Results

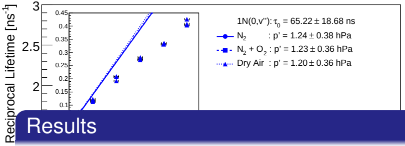
2P(0,v”)



2P(1,v”)



1N(0,0)



Additional constraint for lines:

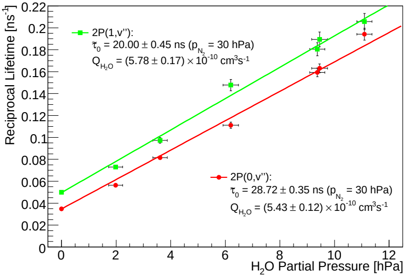
$$\frac{1}{\tau_{v'}} = \frac{1}{\tau_{0\,v'}} \cdot \left(1 + p \cdot \frac{\tau_{0\,v'}}{kT} \sum_x f_x \cdot Q^x_{v'}(T)\right)$$

Results

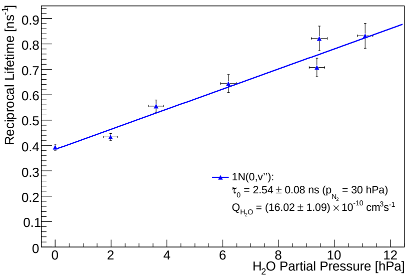
		2P(0,v”)	2P(1,v”)	1N(0,v’)
τ_0	$[ns]$	38.9 ± 0.30	32.9 ± 0.50	65.2 ± 18.7
Q_{N_2}	$[10^{-10} cm^3 s^{-1}]$	0.11 ± 0.00	0.29 ± 0.00	5.00 ± 0.17
Q_{O_2}	$[10^{-10} cm^3 s^{-1}]$	2.76 ± 0.01	2.70 ± 0.03	5.24 ± 0.79

The Effect of Water Vapor

2P(0,v”)



2P(1,v”)



Measurements with pure nitrogen at 30 hPa plus a variable amount of water vapor.

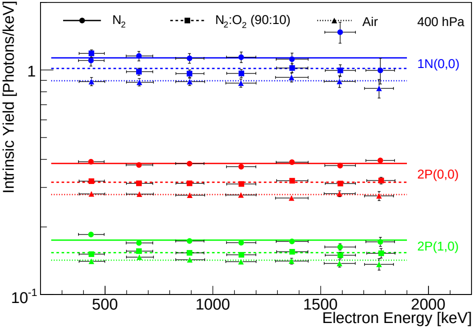
Results

	Q_{H_2O} $[10^{-10} cm^3 s^{-1}]$
2P(0,v”)	5.43 ± 0.12
2P(1,v”)	5.78 ± 0.17
1N(0,v”)	16.02 ± 1.09

Large quenching rate constant of 1N system due to polar character of ionized nitrogen?

Step 2: Energy Dependence of Intrinsic Yield

Re-analyzing sub-samples of 250 keV energy intervals with fixed quenching parameters and intensity ratios.

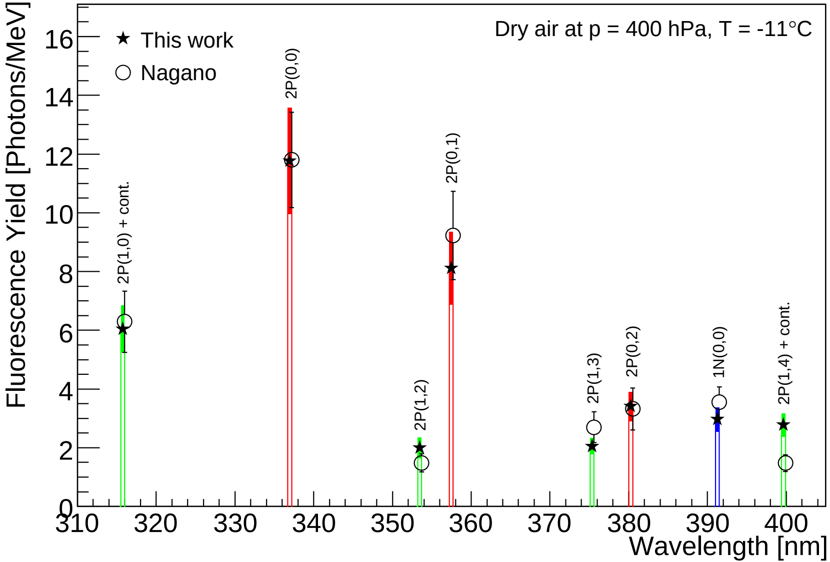


$$Y_{v',v''}(E,p,T) = Y^0_{v'}(E) \cdot R_{v',v''} \cdot \frac{\tau_{v'}(p,T)}{\tau_{0\,v'}} = \frac{N_\gamma}{E_{dep}}$$

- Determination of deposited energy from GEANT4 simulations.
- No energy dependence of $Y^0_{v'}(E)$ in investigated range.

⇒ Number of photons is proportional to ionization energy loss.

Fluorescence Spectrum in Air at 400 hPa and -11°C

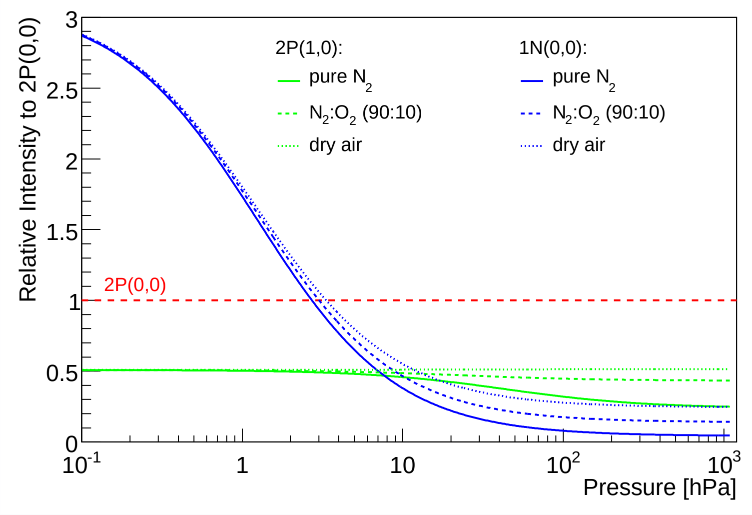


→ Good agreement with values of Nagano et al. [*Astroparticle Physics **22** (2004) pp. 235 - 248*]

Fluorescence Spectrum in Air at 400 hPa and -11°C

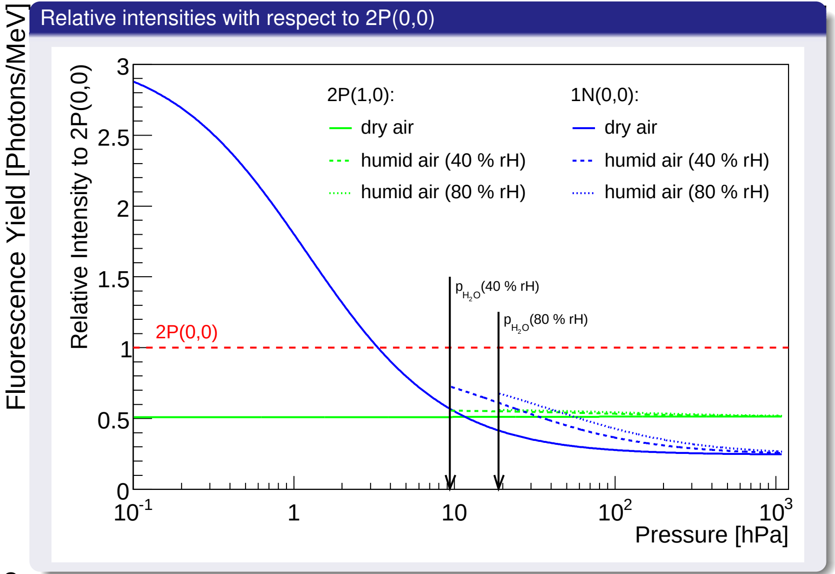
Fluorescence Yield [Photons/MeV]

Relative intensities with respect to 2P(0,0)



→ Good agreement with values of Nagano et al. [*Astroparticle Physics* **22** *(2004) pp. 235 - 248*]

Fluorescence Spectrum in Air at 400 hPa and -11°C



→ Good agreement with values of Nagano et al. [*Astroparticle Physics* **22** *(2004) pp. 235 - 248*]

Summary

Achieved so far ...

- Nitrogen fluorescence spectrum can be sub-divided into several (three) sub-spectra.
- Transitions of a sub-spectrum are connected by several relations.
- Fluorescence spectrum has been measured with the AirLight-Experiment and analyzed according to these relations.
- Global fit leads to consistent description of fluorescence yield with a minimal set of parameters.
- Fluorescence yield does not depend on energy.
- Absolute uncertainties of single nitrogen bands $\lesssim 15\,\%$.

Still to do ...

- Further reduction of absolute uncertainties down to $\sim 10\,\%$.
- Quantification of water vapor influence on shower reconstruction.

Ph.D. Thesis: http://www.auger.de/interna/docs/repository/FZKA7209_Report.pdf