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Rainbows as complex phenomena

N. Nešković[1] and M. Ćosić[2]

[1]World Academy of Art and Science and Serbian Chapter of the Club of Rome
[2]Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia

1. Introduction

The optical rainbow effect – scattering of light in the limiting case of small wavelengths.
Sunlight and water droplets in the atmosphere – **the meteorological rainbows**.
The first explanation of the effect – **Aristotle** in the middle of the fourth century BC.
A satisfactory quantitative theory of the effect – **Nussenzveig** in 1969.

The rainbows in scattering of atoms by atoms or molecules.
The rainbows in scattering of nuclei by nuclei, in scattering of atoms from crystal surfaces, and in ion transmission through crystal channels.

The meteorological rainbow effect.
The rainbow effect in ion transmission through crystal channels – **the crystal rainbow effect**.
The main aim – to demonstrate that the two phenomena are complex.

2. Meteorological rainbow effect

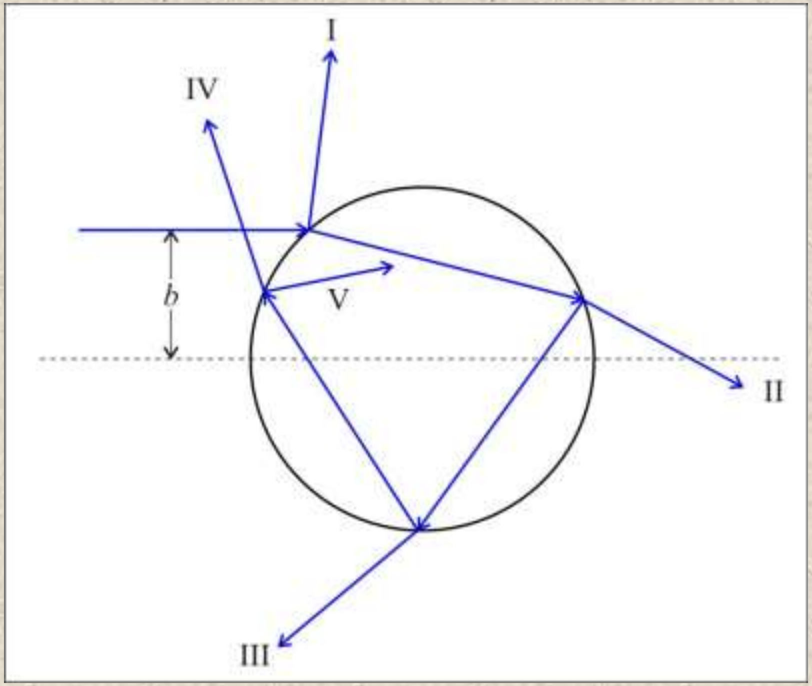
The meteorological rainbow effect: the primary, secondary and supernumerary rainbows.

The primary rainbow – a bright circular bow seen in the sky at an angle of about 42° relative to the horizon.

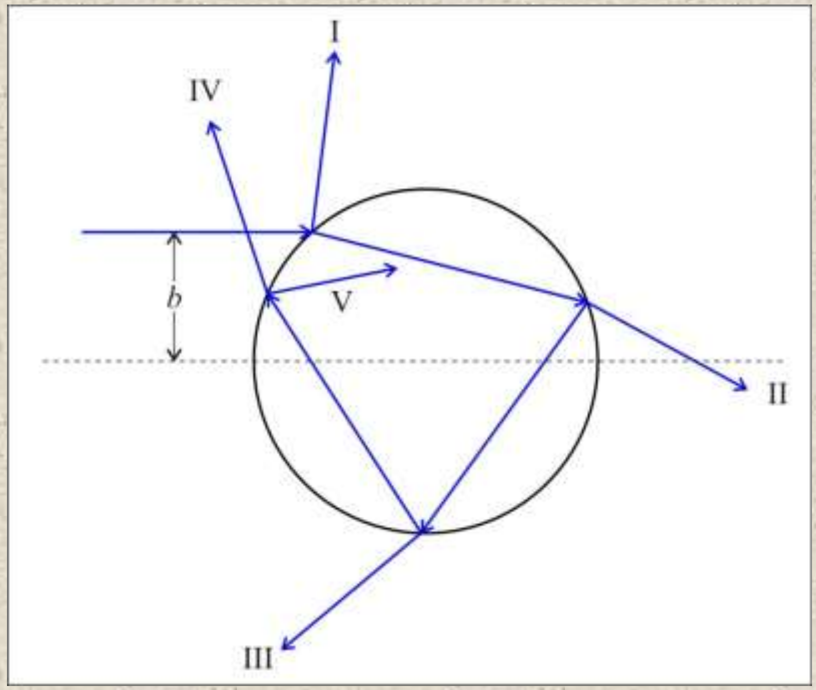
The secondary rainbow – a bright circular bow occurring in the sky on the outer side of the primary rainbow at an angle of about 50° relative to the horizon.

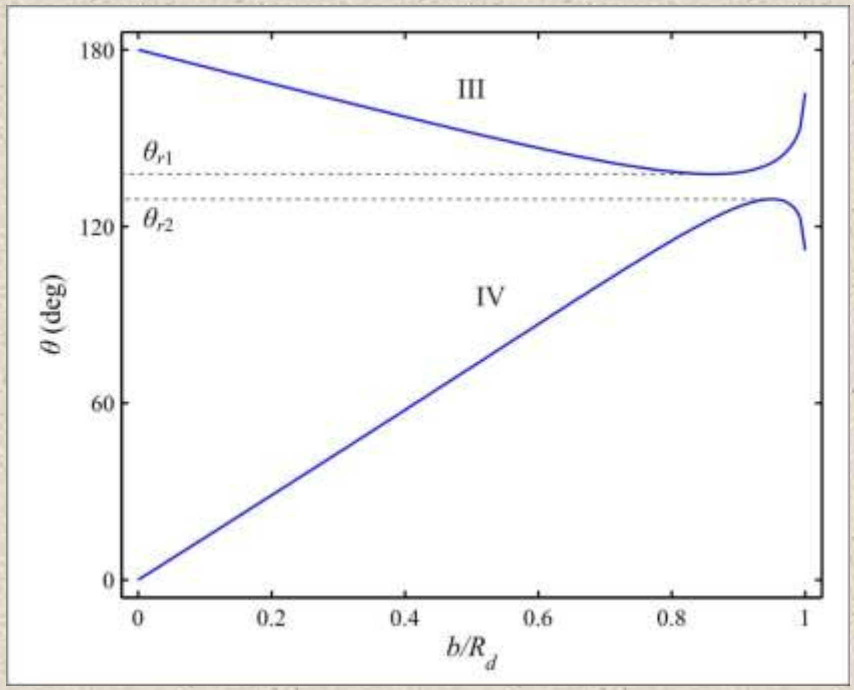
The region between the primary and secondary rainbows is dark.

The supernumerary rainbows – the bright circular bows appearing on the inner side of the primary rainbow.



Theodoric of Freiburg and **Descartes**.
Reflection and refraction of the light ray.
The rays going out from the droplet – a clear classification on the basis of the number of their reflections inside the droplet.

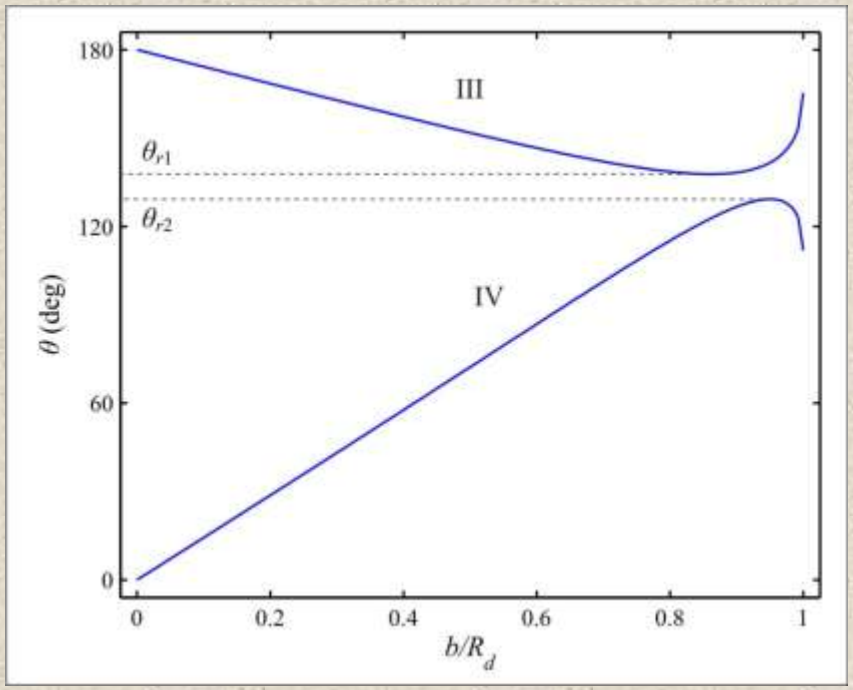


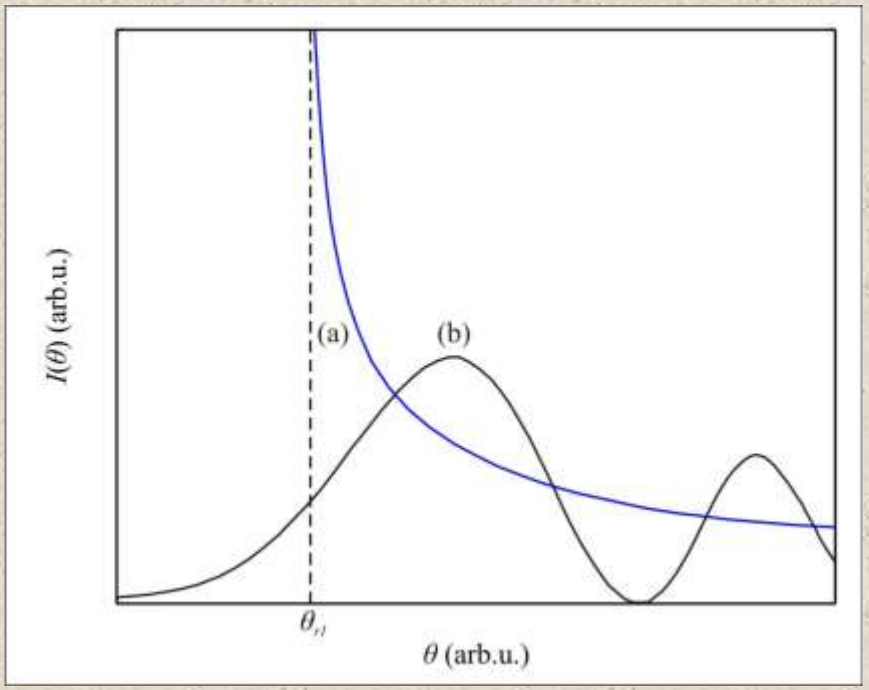


The dependences of the scattering angle of the light ray from the water droplet on its impact parameter for the outgoing rays **from classes III and IV**.

The primary and secondary rainbow angles – $\boldsymbol{\theta_{r1} = 138°}$ and $\boldsymbol{\theta_{r2} = 130°}$. The corresponding angles at which the bright lines are seen – 42° and 50°.

The outgoing rays from classes III and IV can not access the region of scattering angles between θ_{r1} and θ_{r2} – **the Alexander's dark band**.

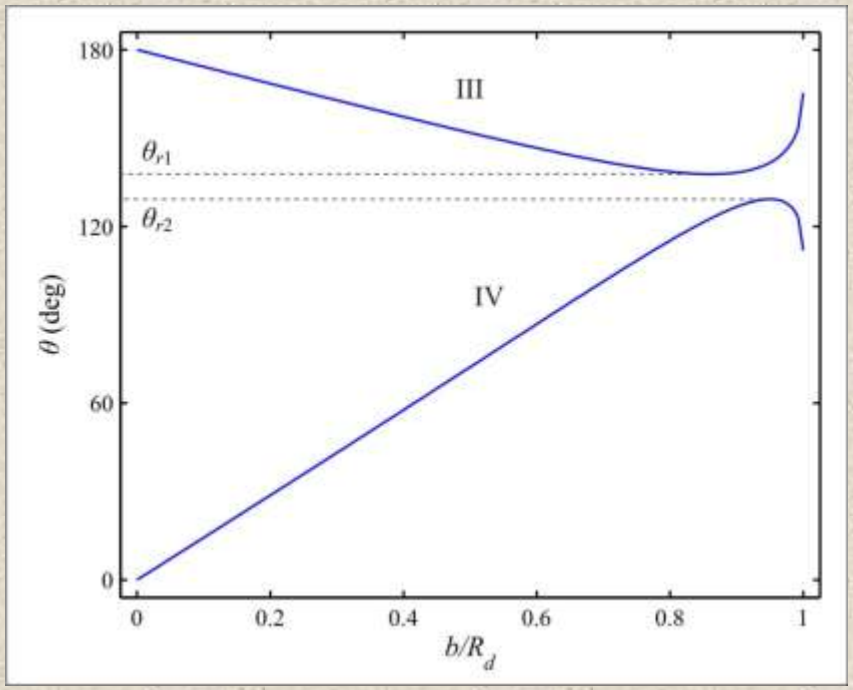


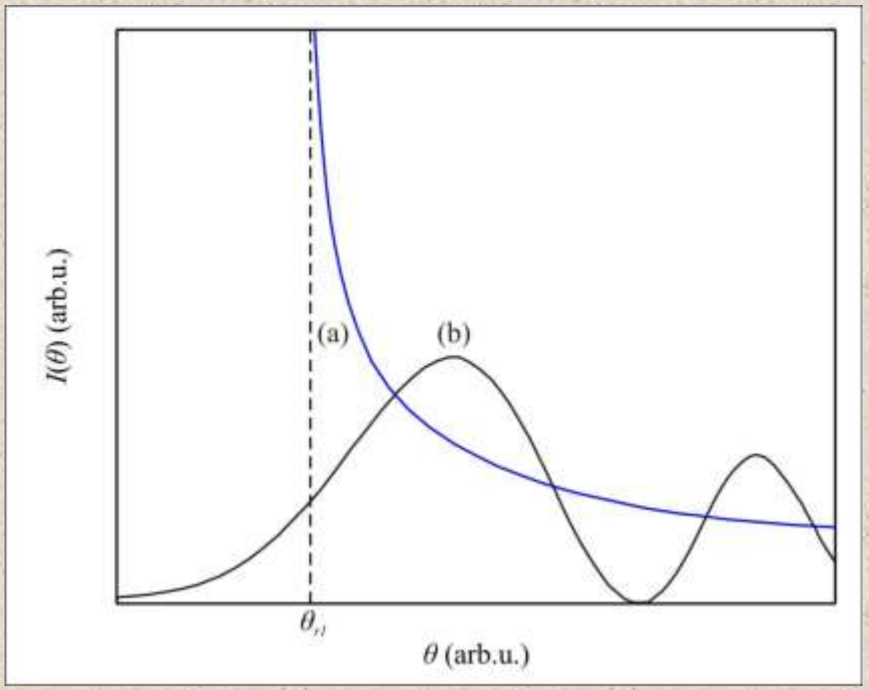


The intensity of light scattered from the water droplet as a function of its scattering angle **tends to infinity** when its changes toward θ_{r1} or θ_{r2} from the bright side of the rainbow.

Newton.

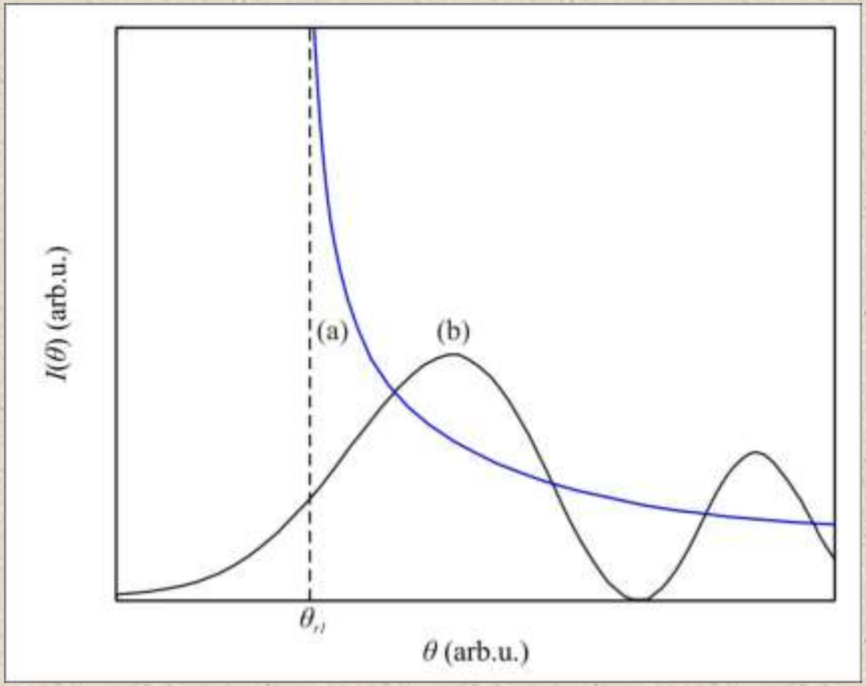
The essential characteristic of a meteorological rainbow – **an abrupt change of the intensity of scattered light** across the rainbow angle, rather that the appearance of the bows of different colors.





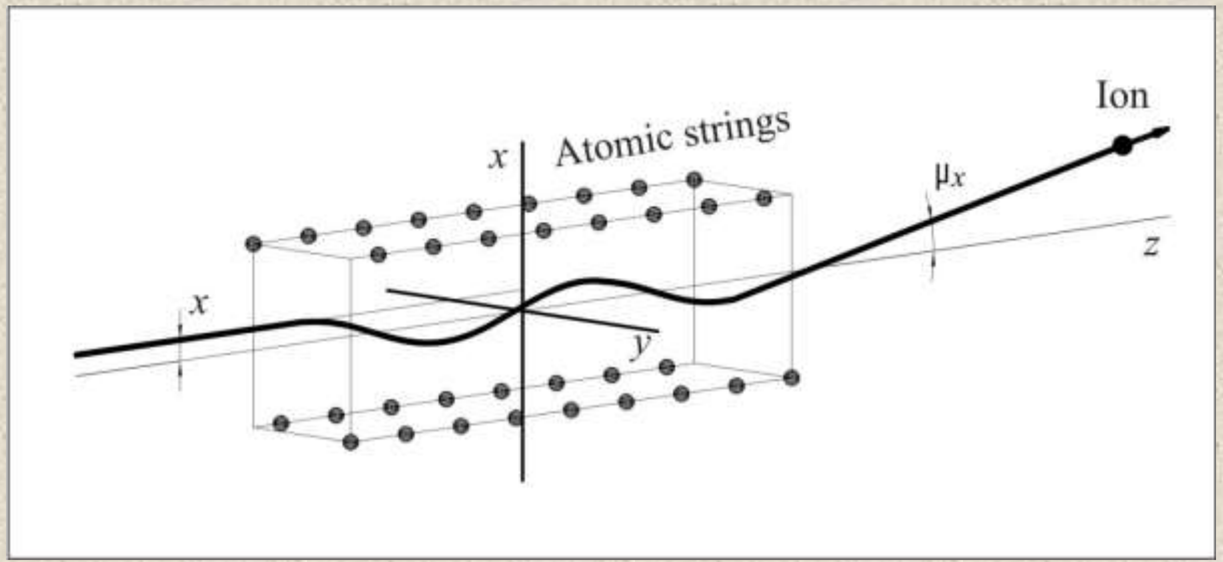
Young and **Airy**.
The effect of interference of the light scattered from the water droplet – the supernumerary rainbows.

The abrupt change of the intensity of light scattered from a water droplet in the vicinities of θ_{r1} and θ_{r2} – accurate modeling by catastrophe theory (Thom, 1975).
The meteorological rainbow effect – **a catastrophic effect**.



The outgoing light beam is more than a simple sum of the scattered rays.
The supernumerary rainbow effect – **a gestalt, synergistic or emergent effect**.
The meteorological rainbows are complex phenomena.

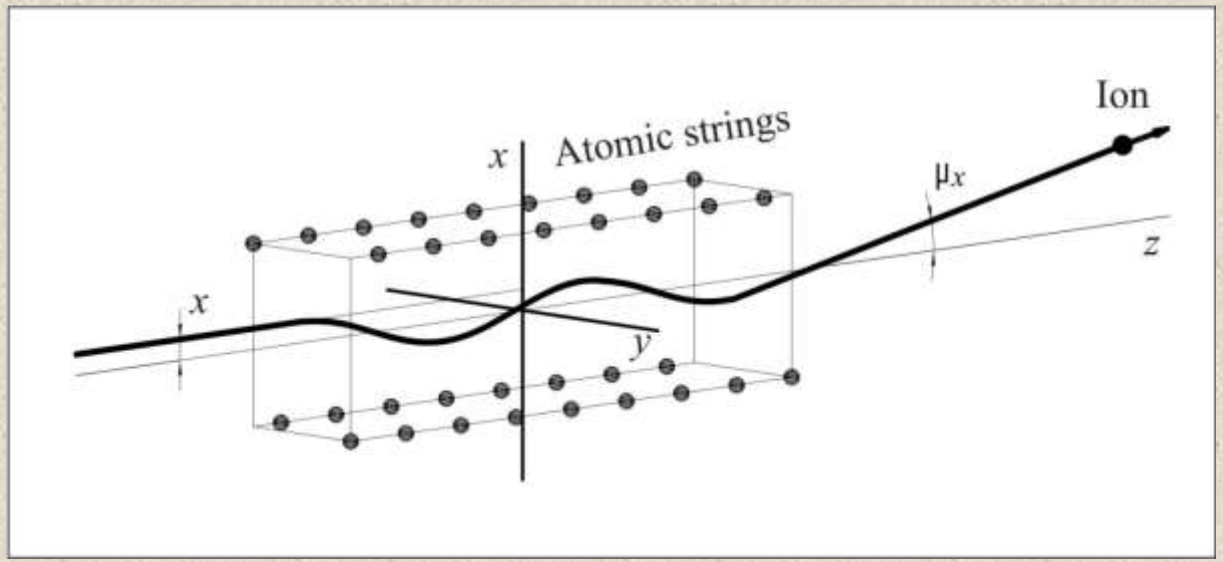
3. Crystal rainbow effect



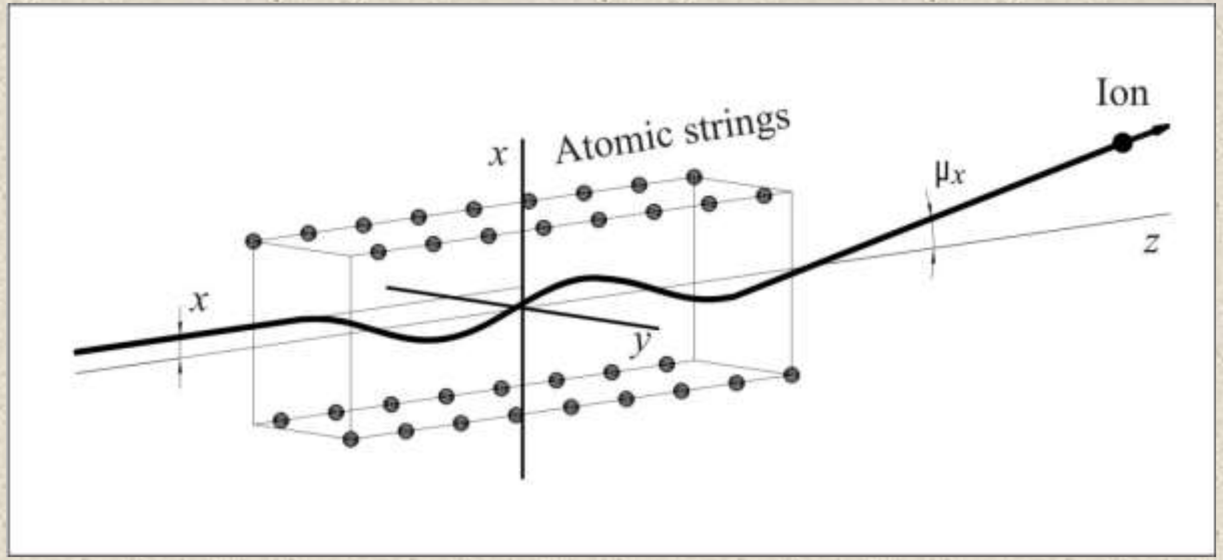
The process of ion transmission through an axial channel of a very thin crystal (Nešković, 1986). The ion differential transmission cross-section, being a variable determining the intensity of transmitted ions, is

$$\sigma = \frac{1}{|J|},$$

where J is a function of the partial derivatives of θ_x and θ_y.



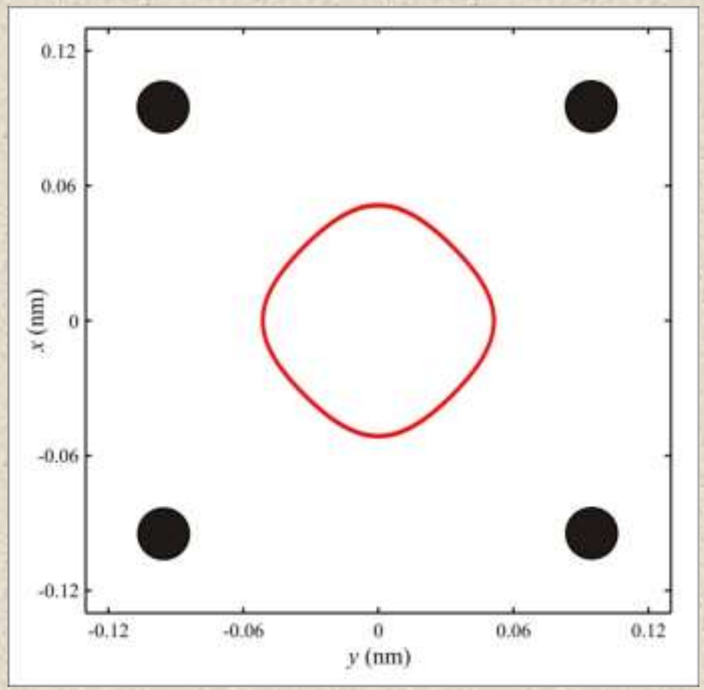
Experimental observation of the crystal rainbow effect – in the Oak Ridge National Laboratory (Krause *et al*., 1986; Krause *et al*., 1994), and at the National University of Singapore (Dang *et al*., 2011; Motapothula *et al*., 2012a; Motapothula *et al*., 2012b; Motapothula *et al*., 2014).



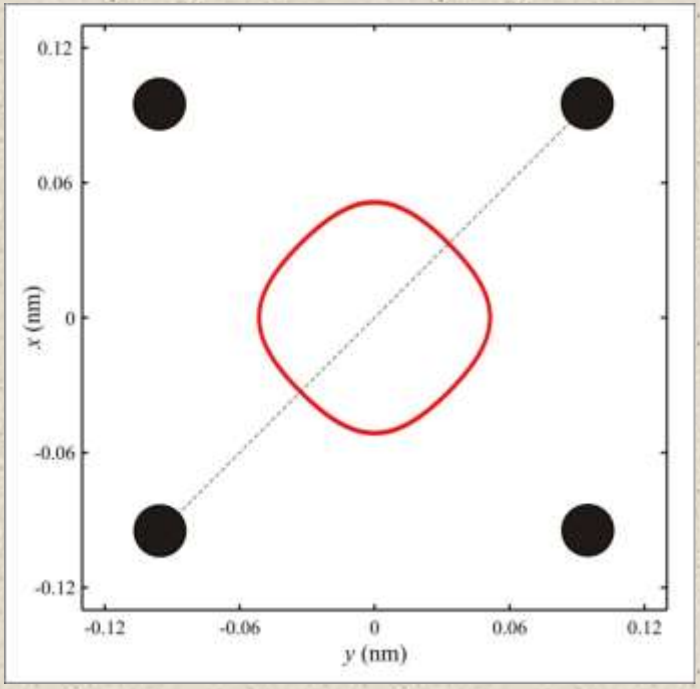
The variable J can be expressed as

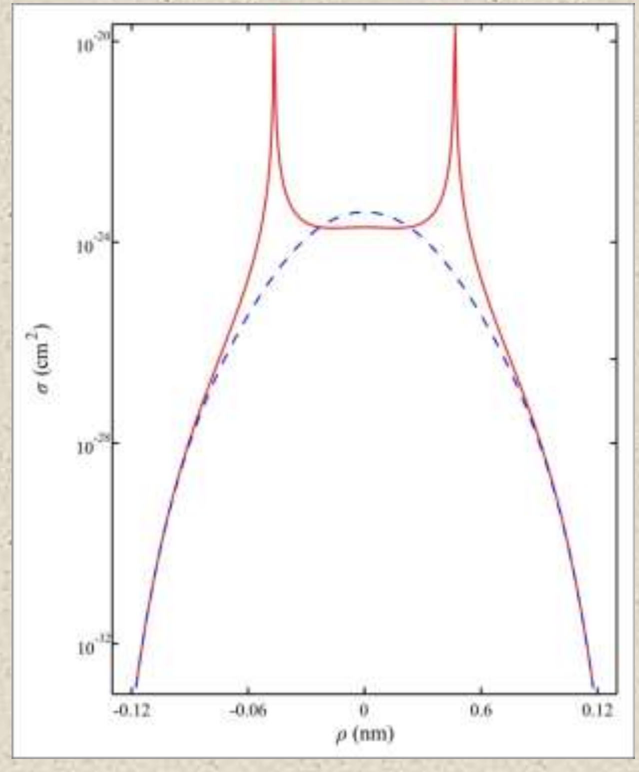
$$J = J_0 + J',$$

where J_0 is a sum of terms describing the ion scattering from the individual atomic strings, while J' is a sum of terms describing the coupling between the pairs of atomic strings as seen by the ion.
The equation $J = 0$ defines the rainbow lines in the impact parameter plane and in the transmission angle plane.

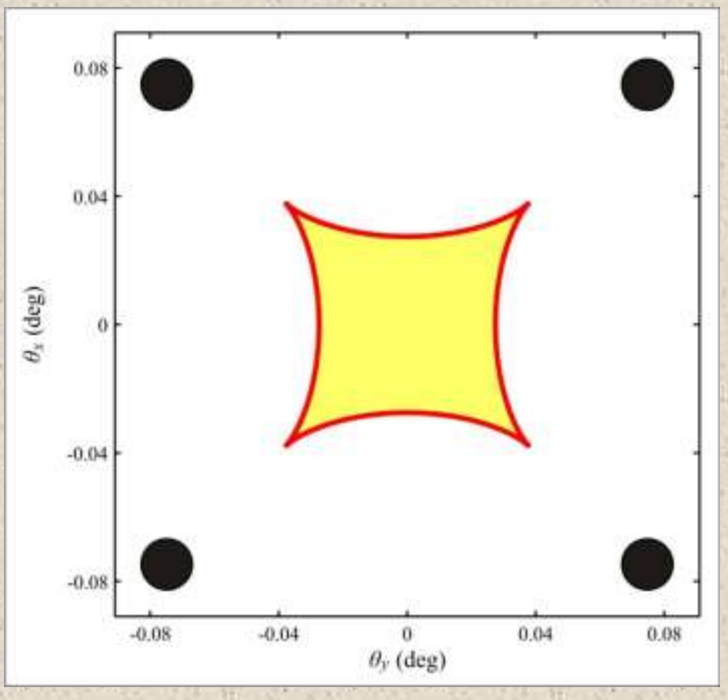


The transmission of protons of energy of 7 MeV through the <100> channel of the 140 nm thick Si crystal.

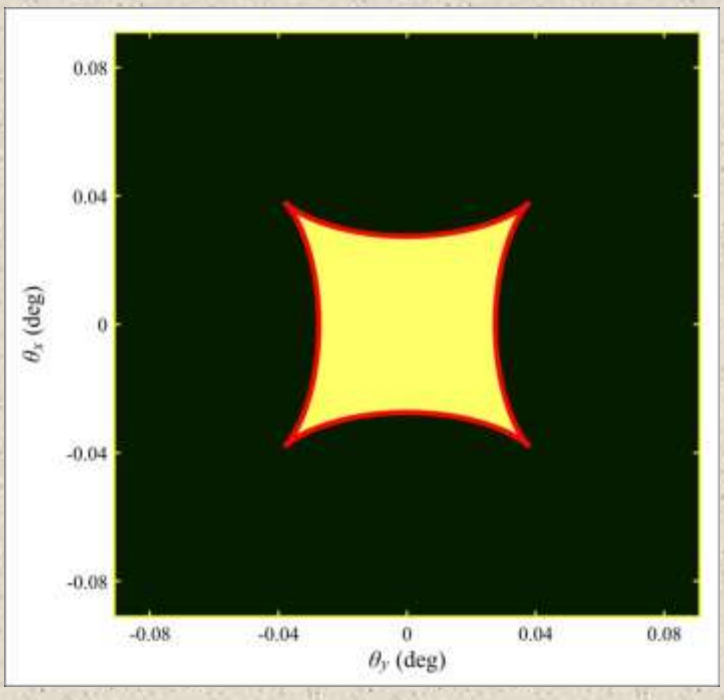


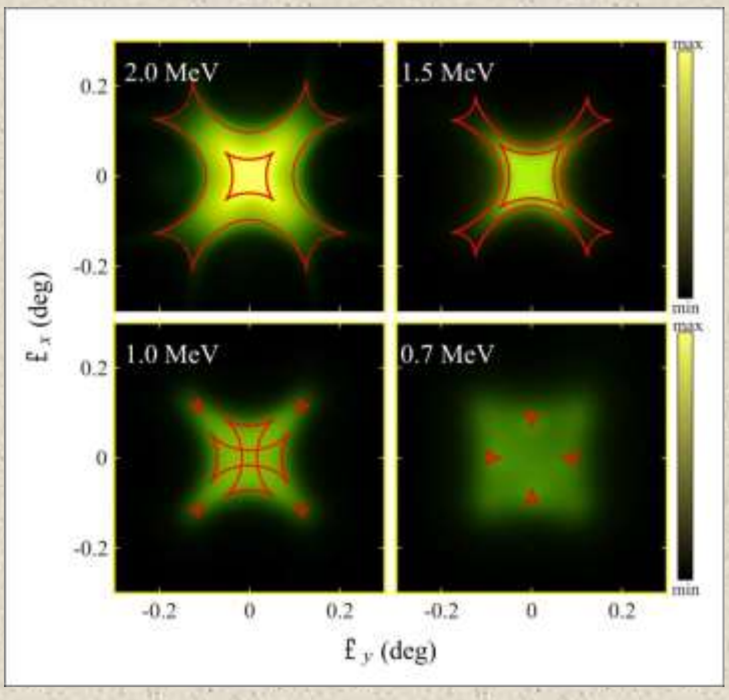


The crystal is more than a simple sum of the atomic strings.
The crystal rainbow effect – an interference effect, *i.e.*, **a gestalt, synergistic or emergent effect**.
The crystal rainbows are complex phenomena.



The rainbow line in the transmission angle plane for 7 MeV protons transmitted through the <100> channel of a 140 nm thick Si crystal.
The crystal rainbow effect – very accurate modeling by catastrophe theory (Nešković and Perović, 1987).
The crystal rainbow effect – **a catastrophic effect**.

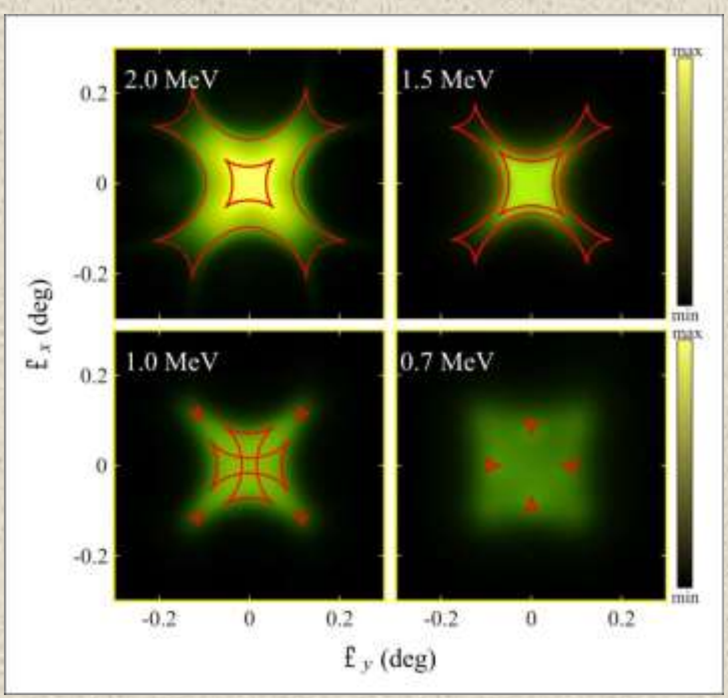




A sequence of **high-resolution measurements with the focused proton microbeams** of energies of 2.0, 1.5, 1.0, and 0.7 MeV directed into the <100> channels of a 55 nm thick Si crystal – performed by a group from the National University of Singapore and analyzed by a group from the Vinča Institute of Nuclear Sciences (Petrović *et al.*, 2015).

The rainbow patterns appear as **the ''skeletons'' of the distributions**.

4. Conclusions



The meteorological rainbows and the crystal rainbows are catastrophic and complex.