“Crucial experiments” and the 19th century revolution in optics

- *Aim of this section:*
- 1. Introduce the idea of a “crucial” experiment.
- 2. Outline the general methodological thesis that crucial experiments are a vehicle of (and give a rational account of) theory-change in science.
- 3. Give an outline of a particular historical case of theory change in science – a particular “scientific revolution”: the switch in the early 19th Century from the corpuscular to the wave theory of light.
- 4. Show how crucial experiments have been cited as providing the rationale for this theory-change.
- 5. Show how these accounts of crucial experiments lead to ‘predictions’ about the course of history of science that are at odds with what really happened.
- 6. Show how attempts to explain away this clash lead to theories that are – from a purely descriptive historical point of view – extremely implausible.
- 7. Show why the claims about crucial experiments cannot withstand critical analysis.
- 8. And how this completely changes the way that our historical problem looks.

Crucial experiments

- Suppose we have two rival, i.e. mutually contradictory, theories of the same range of phenomena
- To take a particular example, the theories
- T: light consists of tiny particles fired, machine-gun fashion, by light sources
- T’: light consists of periodic disturbances – waves – transmitted through the ‘aether’.
- A natural suggestion to try to differentiate between them is to find an experiment for which the two theories predict different, incompatible, results.
- If the experiment can be performed, then at most one of the theories T and T’ can get its outcome right.

Crucial experiments

- Suppose one of them, say T’, does get it right
- Then the other theory T is empirically refuted – i.e. shown to be false empirically
- This may not tell us that T’ is true (this would require the assumption that T and T’ were the *only two possible* theories of this range of phenomena)
- But – assuming that there are no other crucial experiments that point in the opposite direction - it does certainly give us a *reason to prefer* T’ to T: we know that T is false, whereas we do not know that T’ is.

Crucial experiments

- Finally suppose that, as in this case, T was the previously accepted theory amongst scientists and T’ is a relatively new rival
- Then, a crucial experiment might well provide a justification for the “scientific revolution” that sees the older T replaced as the accepted theory by the newer T’.
- So the general methodological thesis that we are concerned with says:
- Theory-change in science may be brought about by, and explained as reasonable by, a crucial experiment.

The 19th century revolution in optics

- The corpuscular theory states that light consists of tiny material particles fired by the sun and other light sources, which create the sensation of light by impacting on our eyes.
- There were alternative theories around in the late 17th and 18th centuries – Hooke, Huygens and Euler developed versions of ‘the’ wave theory.
- The basic wave theory states that light consists of vibrations set up by light sources and transmitted through a medium (*which can’t be* the air)
- However, the great majority of 18th Century scientists saw the corpuscular theory as having been put in a dominant position by the work of Newton.

The 19th century revolution in optics

- Both theories could explain certain basic optical phenomena: notably simple reflection and refraction.
- However, two phenomena that Newton had analysed at length seemed to favour unambiguously the corpuscular theory.
- These are:
- 1.(prismatic) dispersion; and
- 2. polarisation.

Prismatic dispersion

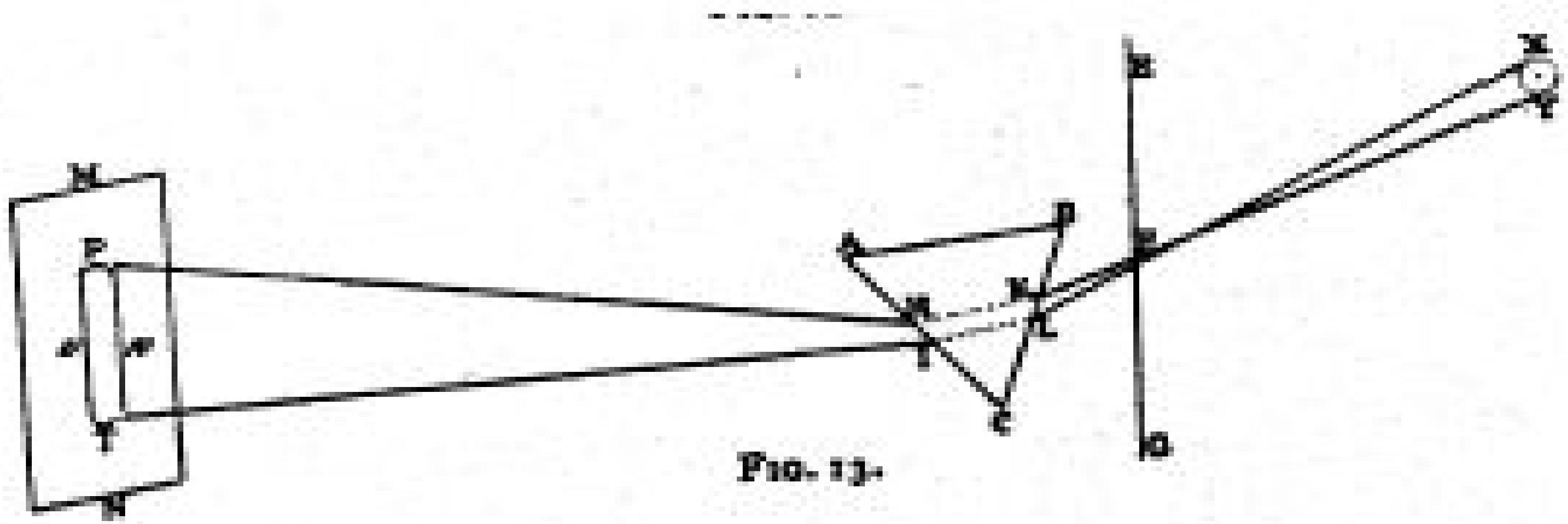


Fig. 13.

Newton's "experimentum crucis"

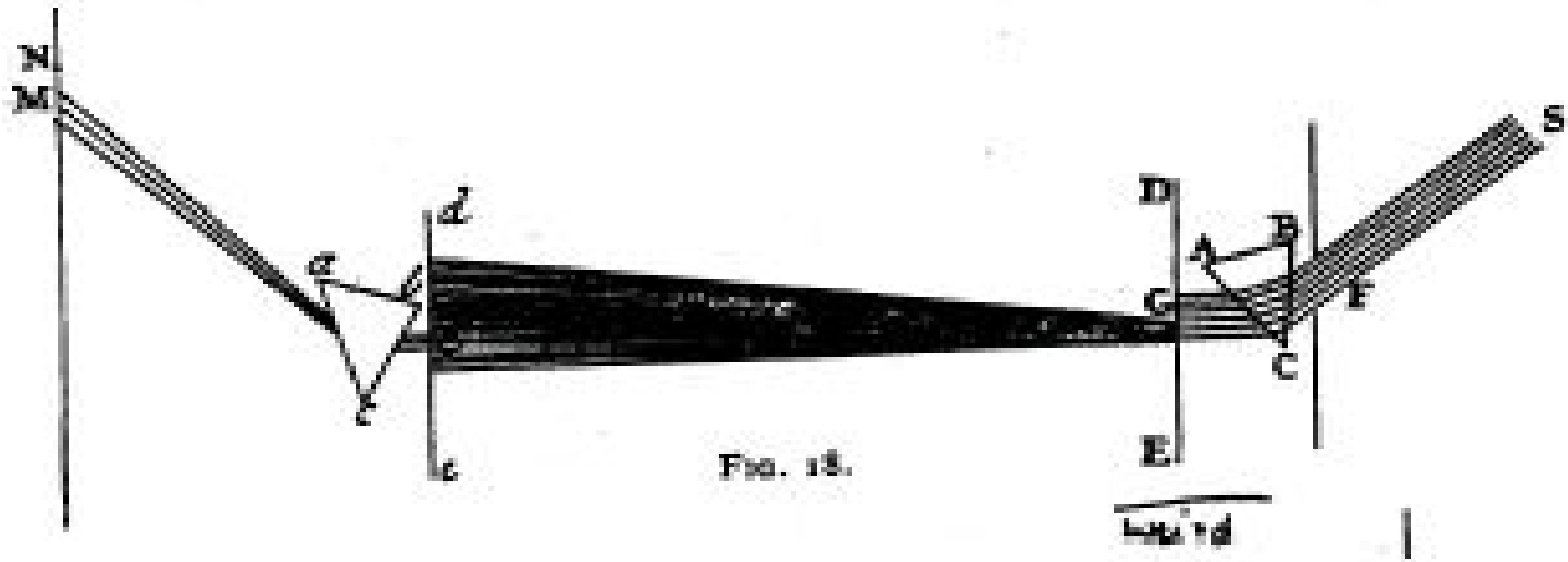


Fig. 18.

Newton’s “experimentum crucis”

- Newton took it that this experiment established that, whatever its ultimate constitution, sunlight must consist of a mixture of pre-existing components that retain their identity when mixed together.
- This was perfectly possible if light consisted of particles – sunlight could be a mixture of particles with different properties which, in isolation would produce the different colours.
- However waves superpose rather than mix: there seems to be no way in which waves of a given wavelength can ‘retain their identity’ when mixed together.

Double Refraction and Polarisation

- Bartholinus discovered that quartz is doubly refractive

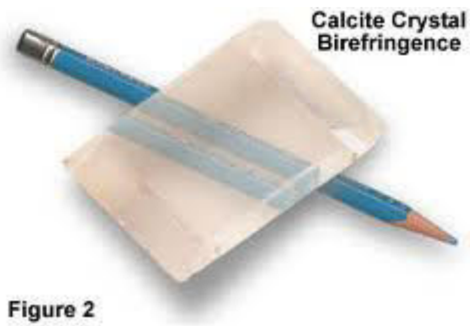
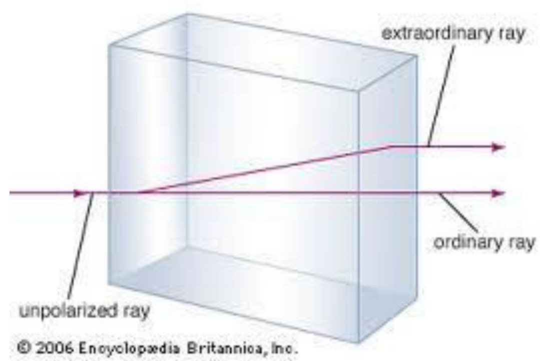


Figure 2

Double Refraction and Polarisation

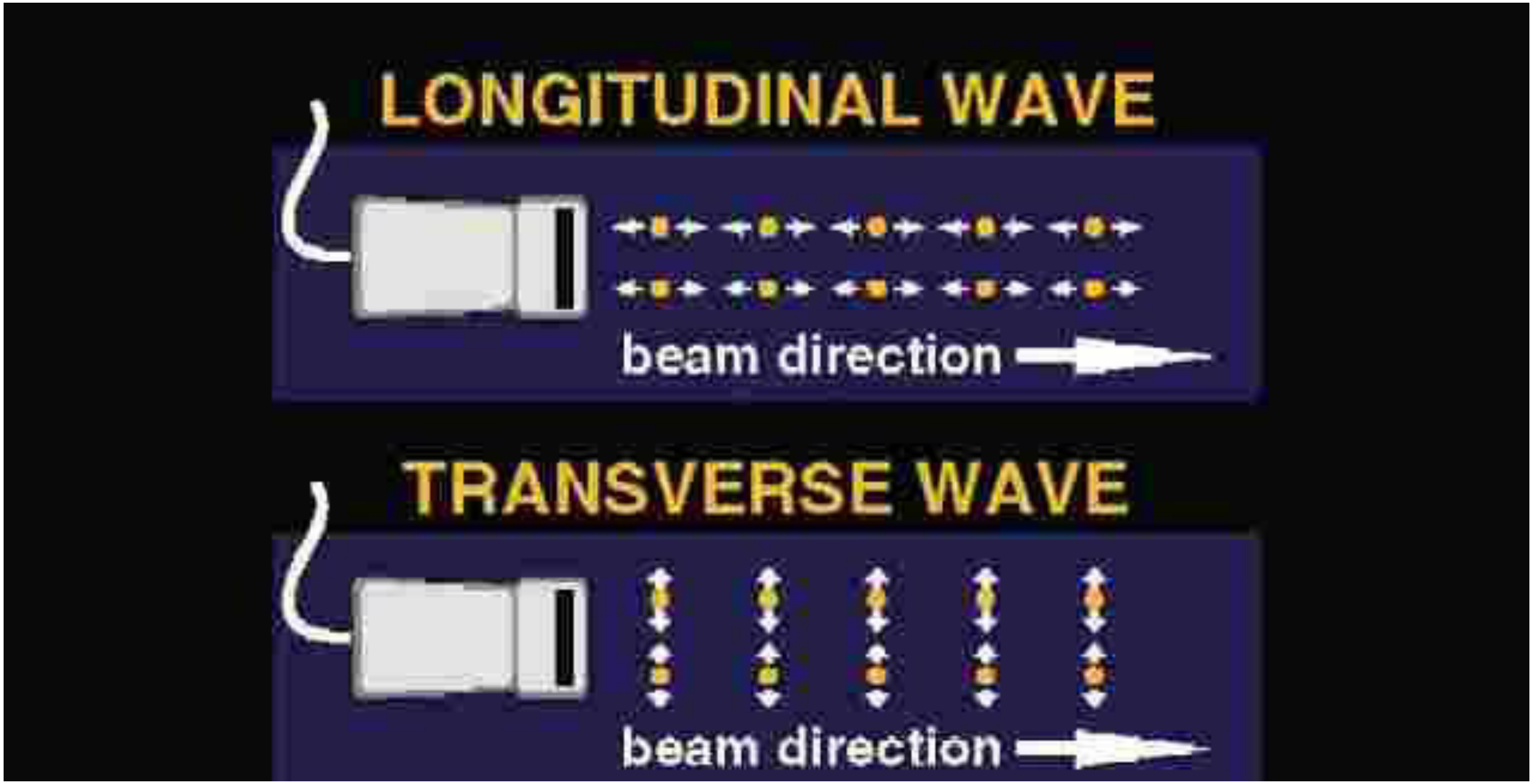


Polarisation

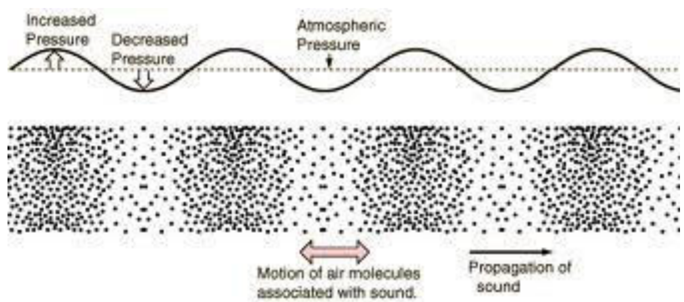
- What happens when you revolve a second quartz crystal around either beam generated by the first.
- In this sense the two refracted beams produced by a birefringent crystal are polarised – i.e. sided.
- That is they exhibit different features depending on how you slice them – i.e. different features in different planes through the direction of propagation.
- Newton showed that this was consistent with the corpuscular theory.
- Individual particles can be supposed to have an axis; a beam is polarised when all the axes are aligned.

Polarisation and the wave theory

- But how could a beam be ‘sided’ if it consisted of waves?
- Two types of wave: longitudinal and transverse



A sound wave in air is longitudinal



Polarisation and the wave theory

- Facts:
- 1. A longitudinal wave is, by definition, symmetric about its direction of propagation
- 2. A transverse wave on the other hand is sided
- 3. Fluids can only transmit longitudinal waves
- 4. Only solids can transmit transverse waves (through their resistance to shear)
- 5. Everyone assumed that the ‘luminiferous aether’ is a fluid
- (How could the planets move so freely through it if it were solid??)

The 19th century revolution in optics

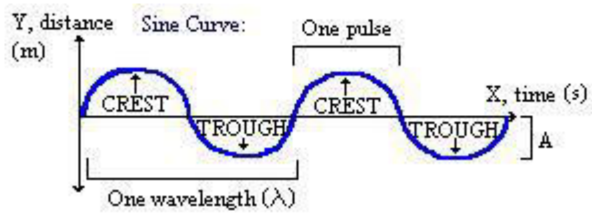
- So in the 18th century it was generally accepted that Newton had shown the corpuscular theory to be superior
- However, by the early 1830s, pretty well all competent scientists acknowledged the superiority of the wave theory of light.
- What does this theory claim and what led to this “scientific revolution”?

‘The’ wave theory of light

- The wave theory is based very firmly on the analogy with sound.
- In the case of the transmission of sound, no matter is transmitted.
- Instead the sound source sets up certain vibrations which are then taken up by the molecules of air, which then induce vibrations in adjacent molecules and so on.
- The oscillations of the individual air molecules are periodic and the overall disturbance constitutes a wave in the medium, in this case air.
- Of course, the medium of transmission of light cannot be air, since light, unlike sound, travels through a vacuum.

‘The’ wave theory of light

- So the wave theory states that light sources set up vibrations of particular frequencies which are then communicated to, and transmitted through, the aether.



- Why the switch from the corpuscular theory to the wave theory?

Crucial experiments and the wave revolution

- One very often cited account is that the ‘revolution’ was brought about by a couple of crucial experiments.
- These experiments were first performed and reported by Thomas Young in the first years of the 19^{th} century.

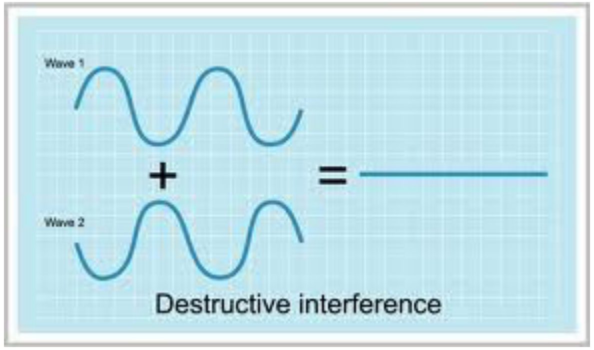
Crucial experiments and the wave revolution

- 1. The two slit experiment
- 2. Horse hair diffraction experiment.
- These two experiments – at any rate in retrospect – seem to establish the existence of light *interference*
- And in particular the phenomenon of *destructive* interference
- We will concentrate on the two slit experiment

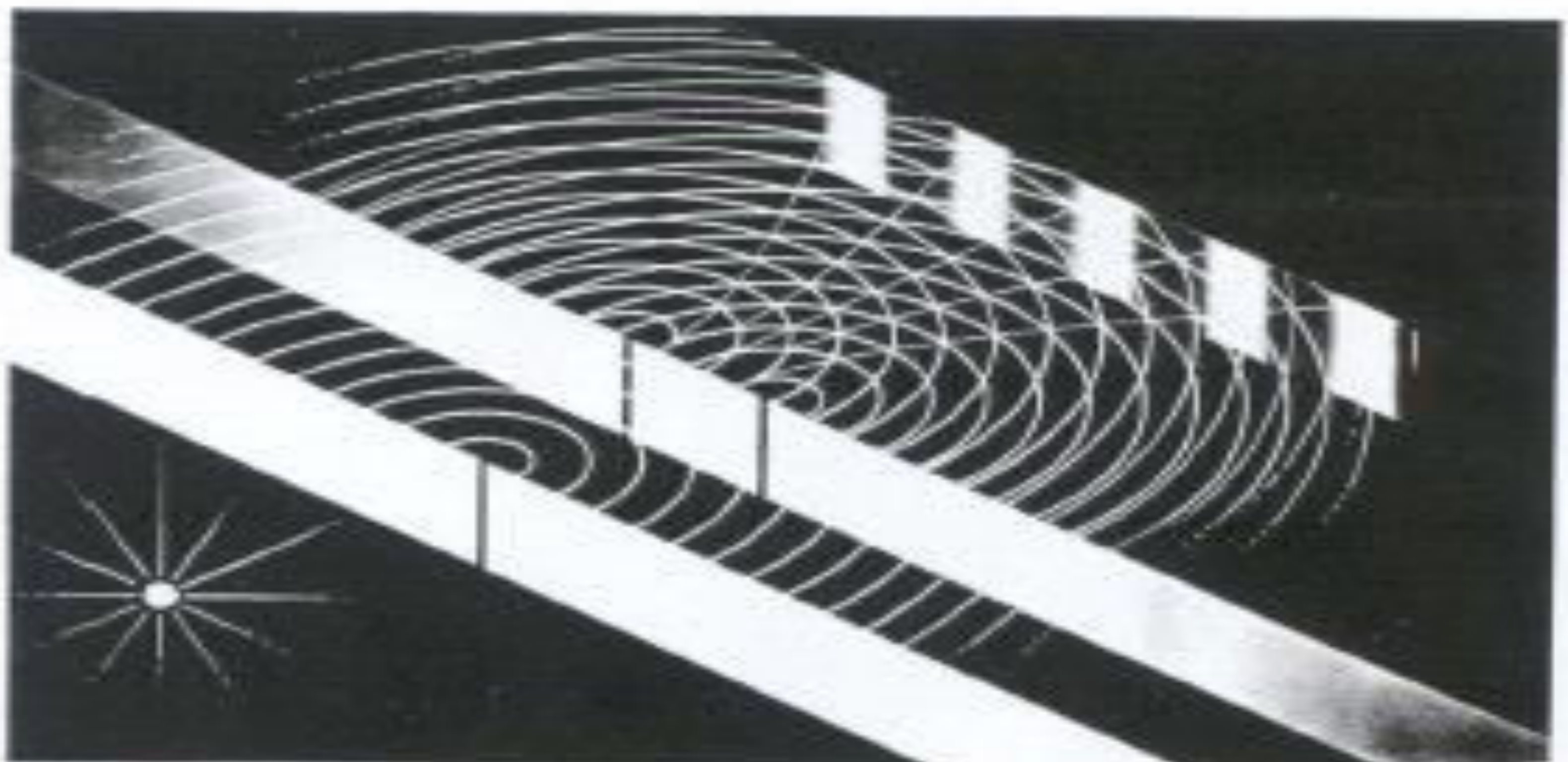
Crucial experiments and the wave revolution

- The wave theory predicts interference (all waves interfere)
- Whereas the corpuscular theory is surely incompatible with interference, and in particular with *destructive* interference.
- (You can’t add particles to particles so that they ‘cancel one another out’.)

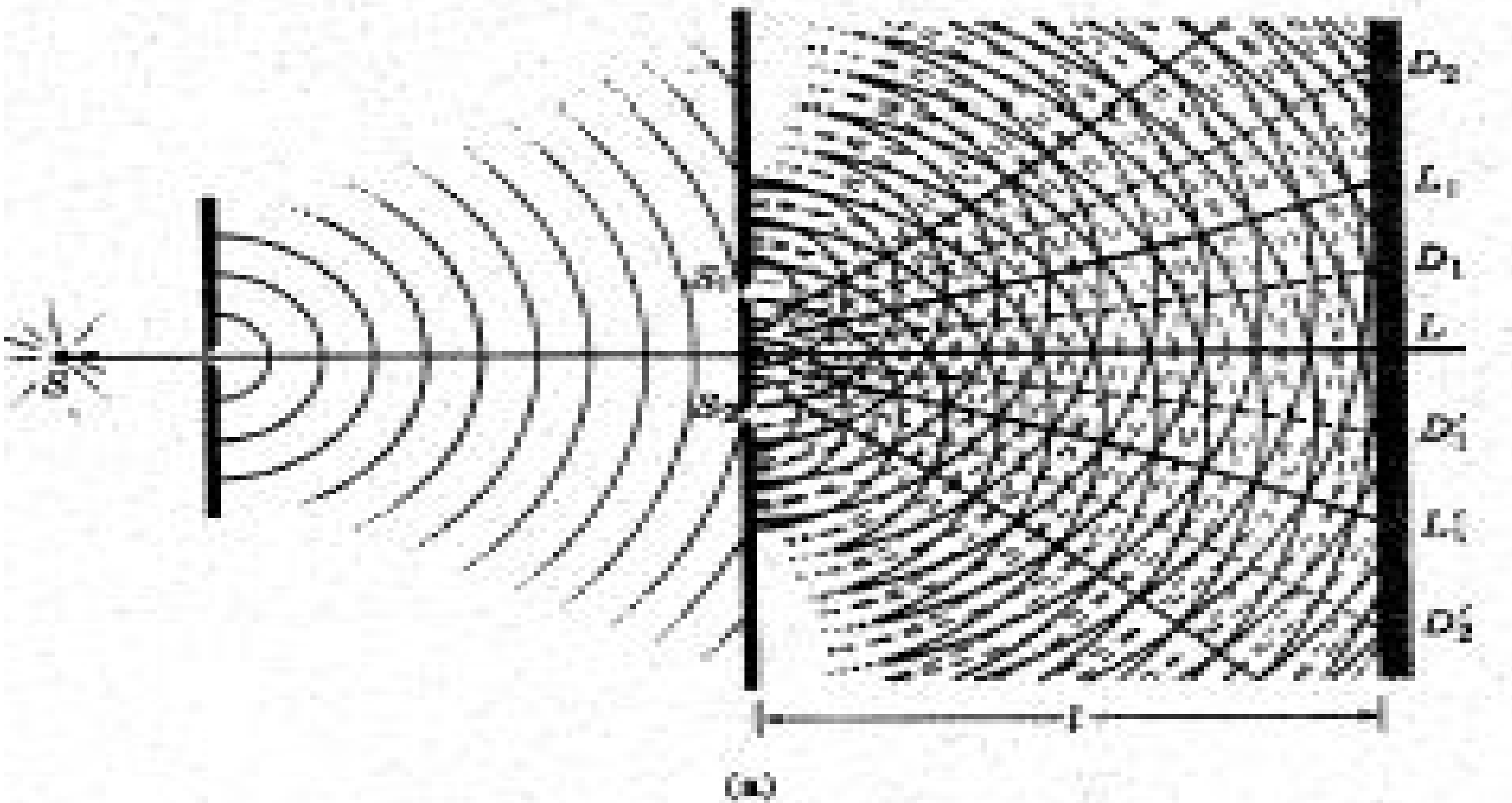
Destructive interference



The two-slit experiment



The two-slit experiment



The outcome of the 2-slit experiment

- What would you expect the corpuscular theory to predict as outcome?
- Well if the initial light is a spray of little ‘bullets’ at all angles then – assuming nothing ‘funny’ happens at the two slits - you would expect one splodge of light corresponding to ‘bullets’ coming through slit 1 and one splodge corresponding to slit 2 (with just a few, presumably almost negligible rebounds from the edges).

The outcome of the 2-slit experiment

FIG. 30.9. Photograph of an interference pattern of light from a double slit. (By permission, from Sears' *Optics*, Addison-Wesley, 1949.)

Crucial experiments and the wave revolution

- Hence the two slit experiment does indeed seem to be a crucial experiment between the corpuscular theory.
- Historical fact: this experiment was first done in 1802; but the wave theory of light only became (arguably) generally accepted in the 1820s.
- It would seem that scientists at the time failed to realise the true impact of this result
- Historians have developed three explanations of this failure
- Each of them invokes “external” factors in Lakatos’s sense

Crucial experiments and the wave revolution

- These are:
- The “Newton worship” explanation
- The “obscurity of style” explanation
- The “character assassination” explanation

Crucial experiments and the wave revolution

- These are all extremely implausible on any serious view of the history (see reading)
- Take for example the ‘Newton worship’ explanation: essentially that no one could get a fair hearing at the time if they held views that Sir Isaac had rejected
- ?? Laplace – speed of sound, Newton miscalculated and there is in fact no need for god??
- Or the ‘character assassination’? [Brougham]
- Their implausibility would be explained if they were aimed at a *non-problem*.
- That is, if the “failure” to see that Young’s results unambiguously refuted the corpuscular theory and hence established the rational/intellectual superiority of the wave theory was not in fact a failure at all.

Crucial experiments and the wave revolution

- So is the crucial experiment story correct?
- Historical fact: experimental results that we now explain as interference (or diffraction) effects had been known about since 1665 (Grimaldi)
- And corpuscular theorists had ideas about how to explain them within their own theory.

Cru ave

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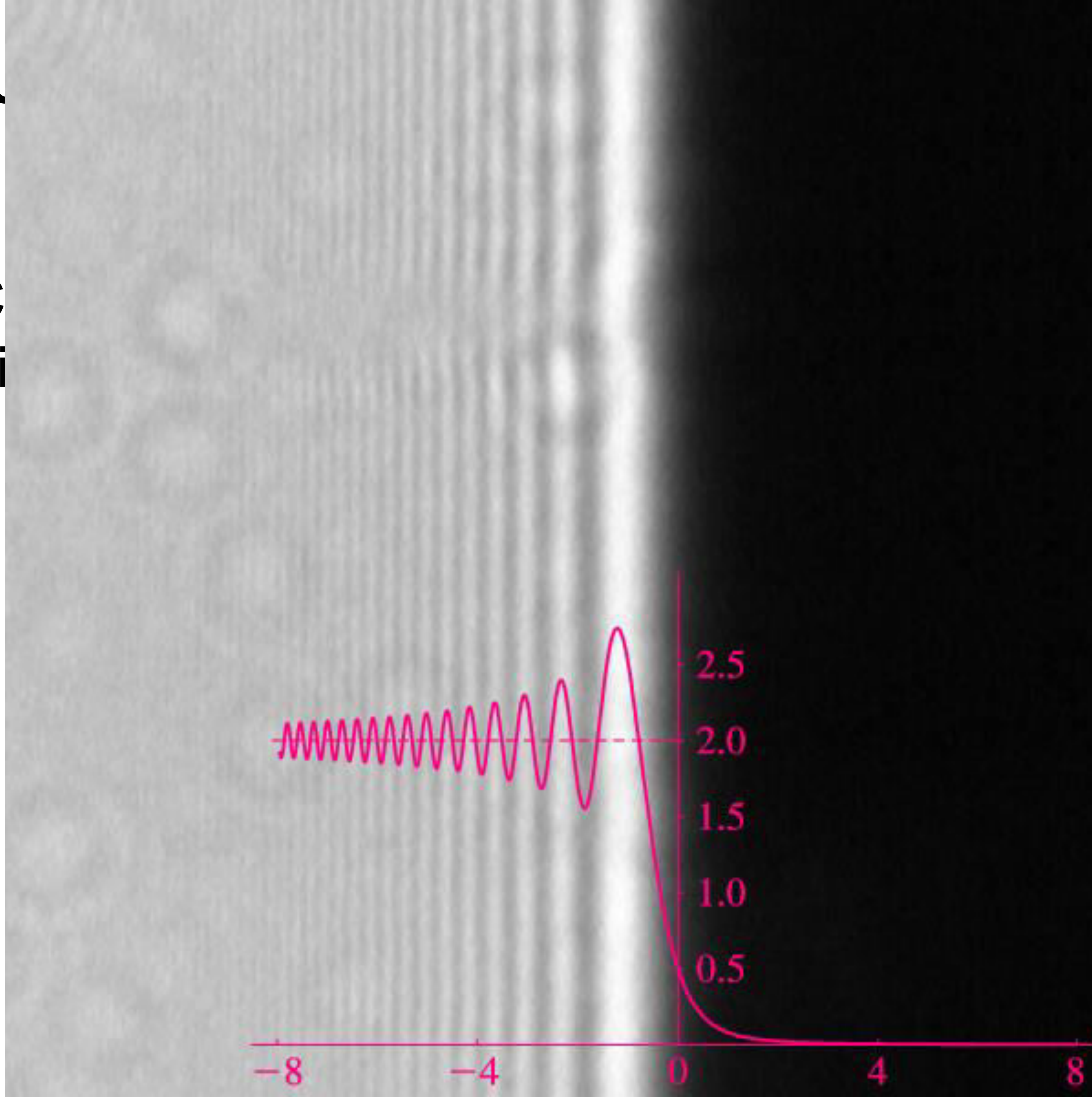


Crucial experiments and the wave revolution

- Corpuscular explanation of straightedge diffraction
- Clearly since some particles must be supposed to be repelled and some attracted
- (a) attractive *and* repulsive forces; and
- (b) some differentiation of the particles had to be assumed.

Crucial experiments and the wave revolution

- Other possibilities – such as explaining interference as a *physiological* effect - were mooted, but this attractive/repulsive forces idea was the main one.
- Corpuscularists set out to work out what assumptions about these forces needed to be made to explain the known fringe effects.

Crucial experiments and the wave revolution

- In this situation, it seems reasonable for them to hold that the two-slit arrangement was a very complicated case – they would eventually explain it, but first they had to deal with simpler cases.
- (There is an extra feature with the two slit result – but even this could be given an outline explanation.)

Crucial experiments and the wave revolution

- At least as importantly, there were experimental results that were just as problematic *at the time* for the rival wave theory as these results of Young were for the corpuscular theory
- 1. Brougham's two candles
- 2. Dispersion
- 3. Polarisation

Crucial experiments and the wave revolution

- Historiographical problem here is that hindsight tends to blur the picture
- But *at the time* ..
- This particular case of alleged crucial experiments precisely confirms Duhem’s thesis about crucial experiments in general

Duhem's analysis of "crucial experiments"

- No question of a crucial experiment *proving* a theory (here the wave theory)
- (This would require the assumption that the wave and corpuscular theories are the *only possible* theories of light.)
- More interestingly, Duhem points out that there is no direct experimental disproof of the kind envisaged in the crucial experiment account.

Duhem's analysis of "crucial experiments"

- Duhem has 3 main points:
- 1. Although we talk of testing single scientific theories – like Newton's or Maxwell's theory – by deducing empirically checkable consequences from them, this is never strictly true: we always *need auxiliary assumptions*.
- So never T ⊢ O; always T&A ⊢ O

Duhem’s analysis of “crucial experiments”

- 2. In the case of some theories – the corpuscular and wave theories of light are prime examples – the ‘central theory’ T itself breaks down into a “core” assumption (light is *some sort* of particle subject to *some sort* of forces) and more specific assumptions (particles producing red light are more massive than those producing violet light ….)

Duhem's analysis of "crucial experiments"

- 3. Hence the full deductive structure of any test is
- Core theory
- Specific assumptions
- Auxiliaries
- ____________
- Therefore, O

Duhem's analysis of "crucial experiments"

- So if what we observe is not O, but rather O' (⊢ not-O) we cannot conclude that the core theory is false,
- nor even that either the core theory or one of the specific but still central theories is false
- but only that at least one assumption from the set of core, specific and auxiliary assumptions is false.
- If the logical structure were T ⊢ O and ¬O then we could indeed infer ¬T
- But if $(C \ \& \ S_1 \ \& \ ...\&S_n \ \& \ A_1\& \ ... \ \&A_m) \vdash O$ then
- $\neg O \vdash \neg(C \ \& \ S_1 \ \& \ ...\&S_n \ \& \ A_1\& \ ... \ \&A_m) \ \ \Xi$

$\neg C \vee \neg S_1 \vee ...\neg S_n \vee \neg A_1 \vee ... \vee \neg A_m$

Duhem's analysis of "crucial experiments"

- This fits the historical case perfectly
- Corpuscularists took it that the interference and diffraction results refuted (or rather indicated the need for a change in) some specific or auxiliary assumption rather than in the core corpuscular theory.
- And *similarly* the wave theorists took it that the dispersion and polarisation results refuted (or rather indicated the need for a change in) some specific or auxiliary assumption rather than their core wave theory
- NB this does not mean that experiments that two theories seem to predict different outcomes for are not especially important in science only that they are not crucial in the sense we are considering.

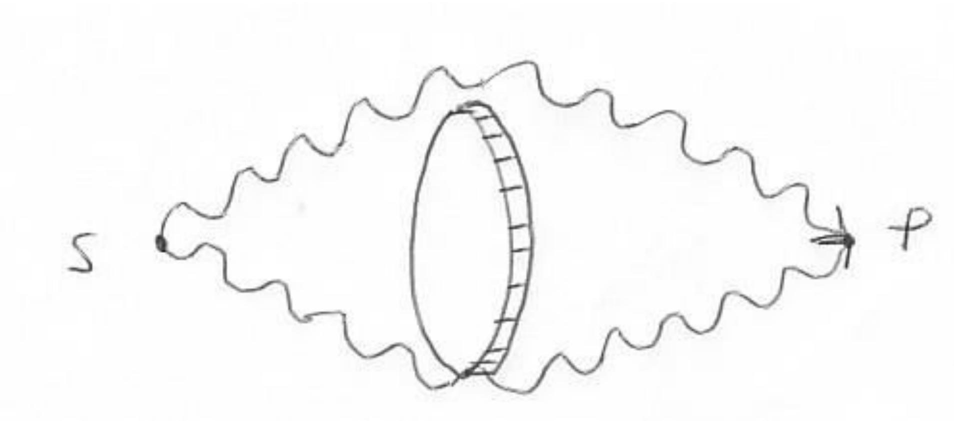
The rationale for the wave ‘revolution’

- So what *did* lead to the change of theory amongst scientists at the time interested in optics?
- Basically, when the corpuscular programme turned out to be “degenerating”
- that is, when it turned out that the corpuscular programme could only deal with its empirical problems in an *ad hoc* way.

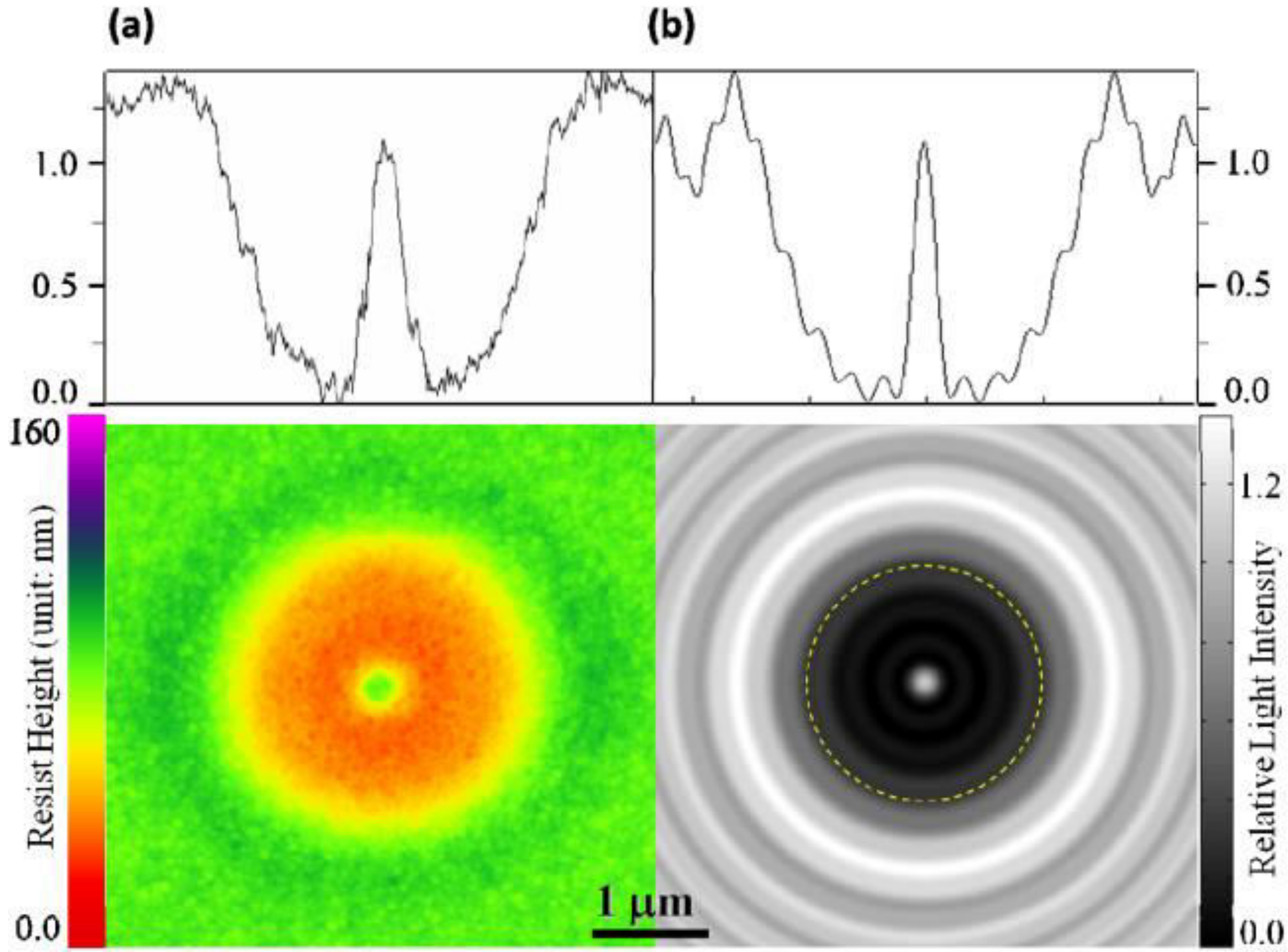
The rationale for the wave 'revolution'

- While the wave theory turned out to progress – i.e. its versions turned out to be independently testable and confirmed.
- It was Fresnel not Young who made the wave theory progressive – starting in the 1820s: exactly when the superiority of the wave theory started to gain general acceptance.
- So the historiographical problem that we started with fades away.
- Examples of progressive steps
- 1. 'White spot'
- 2. Conical refraction

White spot



White spot



(a)
(b)
1.0
0.5
0.0
1.0
0.5
0.0
160
Resist Height (unit: nm)
0.0
1 μm
1.2
Relative Light Intensity
0.0

Fresnel switches to transverse waves

- As mentioned generally assumed that light was a longitudinal wave.
- However when the two slit experiment was modified by Fresnel and Arago so that the light coming through the two slits was ‘ oppositely’ polarised, the interference fringes disappeared
- If light waves were longitudinal they must always interfere when parallel (or very nearly so)
- Fresnel concluded that the waves cannot be longitudinal

Fresnel switches to transverse waves

- Only other simple possibility – transverse
- This would solve the problem of the Fresnel-Arago experiment
- But this is ad hoc in itself (and has the massive conceptual problem that the aether must be a solid)
- However Hamilton showed that the switch to transverse waves has the (of course unintended) consequence that light passing through certain types of crystal will exhibit *conical refraction*
- This entirely surprising result was confirmed by Humphrey Lloyd in 1833.

Conical refraction

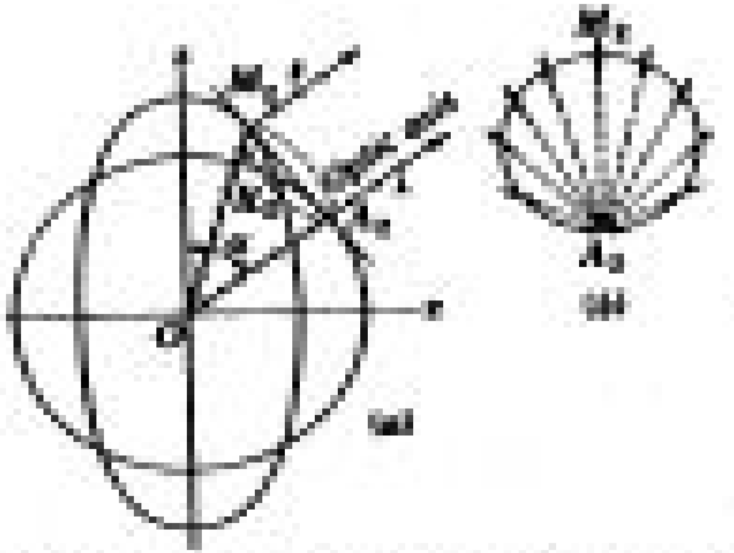


Fig. [illegible]. (a) Geometry of internal conical refraction. (b) End view of internal conically refracted light, showing the directions of vibration.

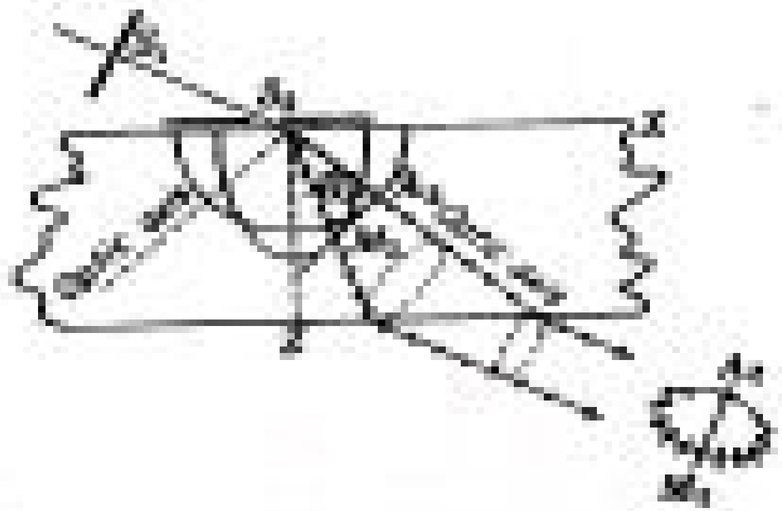


Fig. [illegible]. Internal conical refraction in a biaxial crystal plate.

The rationale for the wave ‘revolution’

- This (Lakatosian) account leads to the expectation that the ‘revolution’ would occur exactly when it did.
- Whereas, as we saw, the ‘crucial experiment’ account can only be made consistent with history by adopting external explanations with no independent historical support.