Bubble Chamber Pictures for the Classroom

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CERN High School Teachers Programme 2006
Introductory Remarks

Bubble chamber pictures popular
- beautiful (\(\ddots\) ‘cool’?)
- illustrate visually and qualitatively many phenomena/principles
  
  **Eq**
  - \(E = mc^2\)
  - Momentum conservation
  - Statistical nature of quantum phenomena
  - Collisions
  - Decays
  - Accelerated charges radiate (mobile!)

Purpose of these lectures

- ‘Comfort layer of knowledge’ for teacher
- To invite you to think of contributing to the bubble chamber activity
Plan

Lecture 1

Background Information

- How do we establish the existence of substructure?
  - Discrete spectra
  - Rutherford type experiments

- The Spectrum of Hadrons
  - Strongly interacting particles (or particles that feel the strong nuclear force)
  - Dominated by the Bubble Chamber

- The Bubble Chamber

- Conservation laws

Lecture 2

The Bubble Chamber Web Site

- Teachers explore BC website for ~1 hour
- Session for questions
  - Reactions
  - Suggestions for improvements, activities...
Visible and H atom Spectrum

Visible Spectrum

The visible spectrum is continuous and ranges from blue to red light.

Hydrogen Line Spectrum

The visible hydrogen spectrum is composed of discrete lines. Shown are the colors of the photons in the visible region that are emitted by excited hydrogen atoms.

Both pictures are from Zumdahl, Introductory Chemistry: A Foundation

ATOMS ARE CONFINED ELECTRON WAVES

\[ E_2 - E_1 = \frac{E_2 - E_1}{h} \]
Evidence for sub-structure of proton and other so-called elementary particles

- Discrete spectrum of "hadrons" (strongly interacting particles)
- Deep inelastic scattering

Here: not analysis of spectrum to get at quark properties but to introduce bubble chamber and its part in discovering the spectrum
Typical particle physics experiment

- **FIXED TARGET**
- **ACCELERATOR**
- **TARGET**
- **DETECTOR**

**FOUND:** discrete mass spectrum
- Not all masses are created in nature (even if the energy is available)

QM + Relativity

The story of the discovery of the discrete mass spectrum was dominated by the BUBBLE CHAMBER
Historical Introduction

1950

ATOM - electrons held near nucleus by 'exchange of virtual photons'

NUCLEUS - neutrons and protons held together by 'exchange of virtual pions'

BUT: μ and 'strange particles' did not fit into this neat picture

For the next 15 years or so, with the bubble chamber as a major tool, many more particles were found.

Examination of the properties of these particles led to the prediction of the existence of quarks.

The 'stable' particles: π, K, n, p, Λ, Σ^0, Σ^- etc.

Unstable particles (lifetimes \( \sim 10^{-23}\) second) which are excited states of the stable particles
DISCOVERY OF KAON

neutral decay

charged decay
**Meson Spectrum**

- **Mass in MeV/c²**

<table>
<thead>
<tr>
<th>1400</th>
<th>1200</th>
<th>1000</th>
<th>800</th>
<th>600</th>
<th>400</th>
<th>200</th>
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</thead>
</table>

- \( K^- \)
- \( \eta \)
- \( K^+ \)

- **π⁻ π⁺ π⁺**

- Travel far enough for decays to be seen (most!)

- Decay within immeasurably short distance; detected in 'effective mass' plots as bumps.
So what? Only some masses $\Rightarrow$ only some energies
\[ \Rightarrow QM + \text{constituents} \]
$\Rightarrow$ spectroscopic evidence for quarks
When the nucleus revealed its presently known spectrum, we may have hoped to have before us the essential ingredients for the understanding of its structure, just as the Balmer formula of the hydrogen spectrum gave Bohr the clue for its dynamics.
THE BUBBLE CHAMBER

When charged particles force their way through a specially prepared liquid (such as superheated hydrogen), they leave trails of bubbles which can be photographed to give a permanent record of the particles' trajectories.

- The Physical Principles of Particle Detectors
- A Simple Estimate of the Mass of the Photon
- A Lot can Happen in a few Milliseconds of a Second
THE CERN 2m BUBBLE CHAMBER
Typical particle physics experiment

Beam

Shoot in something you know

Target

Measure what comes out in a 'detector'

Bubble chamber is both target and detector

E.g. hydrogen

Typical beam energy ~ 6 GeV
To ionize atom ~ 10 eV

[Highly relativistic particle loses ~ 0.25 MeV/cm in H₂]
COLLISIONS and DECAYS

e.g. "COLLISION"

Q: \( \pi^+ + \pi^- \rightarrow \pi^+ + \pi^- - 1 \)

"Kink" (CHARGED DECAY)

"Vee" (NEUTRAL DECAY)
Thanks to John Kinson, University of Birmingham
\[ K^- p \rightarrow K^0 p \pi^- \]

<table>
<thead>
<tr>
<th></th>
<th>( p_x ) (GeV/c)</th>
<th>( p_y )</th>
<th>( p_z )</th>
<th>( E ) (GeV)</th>
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</thead>
<tbody>
<tr>
<td>( K^- )</td>
<td>8.26131</td>
<td>-0.15642</td>
<td>0.01320</td>
<td>8.27753</td>
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<tr>
<td>( p )</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.93828</td>
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<tr>
<td>( \pi^- )</td>
<td>4.49326</td>
<td>0.73621</td>
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<td>4.58391</td>
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<tr>
<td>( p )</td>
<td>0.32496</td>
<td>-0.45360</td>
<td>0.04282</td>
<td>1.09250</td>
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<tr>
<td>( K^0 )</td>
<td>3.44322</td>
<td>-0.43912</td>
<td>0.48159</td>
<td>3.53952</td>
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**DATA PROCESSING**

Aim: To get as close as possible to measuring energy \( E \) and momentum \( p \) of all particles taking part in the interactions.
DATA PROCESSING

1. SCANNING

Find all 'events' and classify them

eg

\[ N(\text{prongs}) = 4 \]
\[ N(\text{higgs}) = 1 \]
\[ N(\text{vees}) = 2 \]

Classified as a 412 event
Measurer feeds into computer, for each track, the co-ordinates of several views (so that the event can be reconstructed in 3 dimensions).

Co-ordinates of ‘fiducial’ crosses on the bubble chamber walls are also measured (their positions are accurately known reference points).
Computer calculates the best curve fitting the measurements (with errors)

Then the momentum from the radius of curvature

\[ \frac{mv^2}{r} = Bq \rho \Rightarrow \rho = (Bq/r) \]

(Corrections are made to allow for the slowing down of the particle as it deposits energy)

(Electrons are hardest to measure because they spiral unpredictably.)

\[ \text{Synchrotron radiation} \]

\[ \text{Bremsstrahlung (braking radiation)} \]
RELATING WHAT WE CAN MEASURE ON BUBBLE CHAMBER PICTURES TO QUANTITIES THAT TELL US HOW PARTICLES ARE MOVING.

- **Number of Bubbles per Centimetre** (some tracks look more 'solid' than others) gives speed of particle.
- **Range** (distance particle travels before stopping).

Particle stops when all its energy has been used up, making bubbles as it forces it way through the liquid.

**Speed** $v = \frac{\text{distance}}{\text{time}}$

**Momentum** $p = mv$

**Kinetic Energy** $E = \frac{1}{2}mv^2$

also $E = \frac{p^2}{2m}$

Knowing any two of $v$, $p$, and $E$ — can calculate $m$ → **WEIGH THE PARTICLE**!
How can we 'weigh' a particle?

Using $E^2 = p^2 c^2 + m^2 c^4$

$$m^2 = \frac{E^2 - \beta^2 c^2}{c^4}$$

$$= \frac{(E_1 + E_2)^2 - (P_1 + P_2)^2 c^2}{c^4}$$
Come and weigh a photon!

Vertex V1 (raw measurement)

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>$\beta_x$ (MeV$_c$)</th>
<th>$\beta_y$ (MeV$_c$)</th>
<th>$\beta_z$ (MeV$_c$)</th>
<th>Comment</th>
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<tbody>
<tr>
<td>1159</td>
<td>541</td>
<td>340</td>
<td>235</td>
<td>p by ID</td>
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<tr>
<td>195</td>
<td>80</td>
<td>-13</td>
<td>109</td>
<td>Unique $\ell^-$</td>
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</table>

$m_{\pi} =$

Gamma G1 (raw measurement)

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$\phi$</th>
<th>$\phi_0$</th>
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<tbody>
<tr>
<td>81</td>
<td>76</td>
<td>-18</td>
</tr>
<tr>
<td>257</td>
<td>247</td>
<td>-54</td>
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</table>

$e^+$  

$e^-$

$m_{\pi} =$

Gamma G2 (raw measurement)

<table>
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<th>$\theta$</th>
<th>$\phi$</th>
<th>$\phi_0$</th>
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<tbody>
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<td>38</td>
<td>22</td>
<td>-21</td>
</tr>
<tr>
<td>113</td>
<td>63</td>
<td>-63</td>
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$e^+$  

$e^-$

$m_{\pi} =$
# PRIMARY VERTEX TRACKS

<table>
<thead>
<tr>
<th>Track Label</th>
<th>E</th>
<th>px</th>
<th>py</th>
<th>pz</th>
<th>Comment</th>
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<tr>
<td>A01</td>
<td>1146</td>
<td>1022</td>
<td>404</td>
<td>-295</td>
<td>π⁺ probably</td>
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<tr>
<td>A02</td>
<td>24696</td>
<td>24375</td>
<td>-2353</td>
<td>-3196</td>
<td>μ⁻ in EMI</td>
</tr>
<tr>
<td>A03</td>
<td>1003</td>
<td>217</td>
<td>178</td>
<td>-217</td>
<td>Stopping p</td>
</tr>
<tr>
<td>G1</td>
<td>318</td>
<td>307</td>
<td>-61</td>
<td>58</td>
<td>Fitted ϒ⁺</td>
</tr>
<tr>
<td>G2</td>
<td>141</td>
<td>84</td>
<td>-76</td>
<td>84</td>
<td>Fitted ϒ⁻</td>
</tr>
<tr>
<td>V1</td>
<td>1371</td>
<td>633</td>
<td>319</td>
<td>364</td>
<td>Λ⁰ → pπ⁻</td>
</tr>
</tbody>
</table>

**Problem**

Evaluate the effective mass of the two photons ϒ⁺ and ϒ⁻.

**Sketch Solution**

\[
M(G1\oplus G2) = \sqrt{(318+141)^2 - (307+84)^2 - (-61-76)^2 - (-58+84)^2} = 137\,\text{MeV}
\]

This is the mass of the Ω⁺ (approx.)

\[\Omega^0 \rightarrow \Xi\chi\]

Kinematics programme gets 'improved' fitted values by constraining the ϒ's to pass through the primary vertex A.