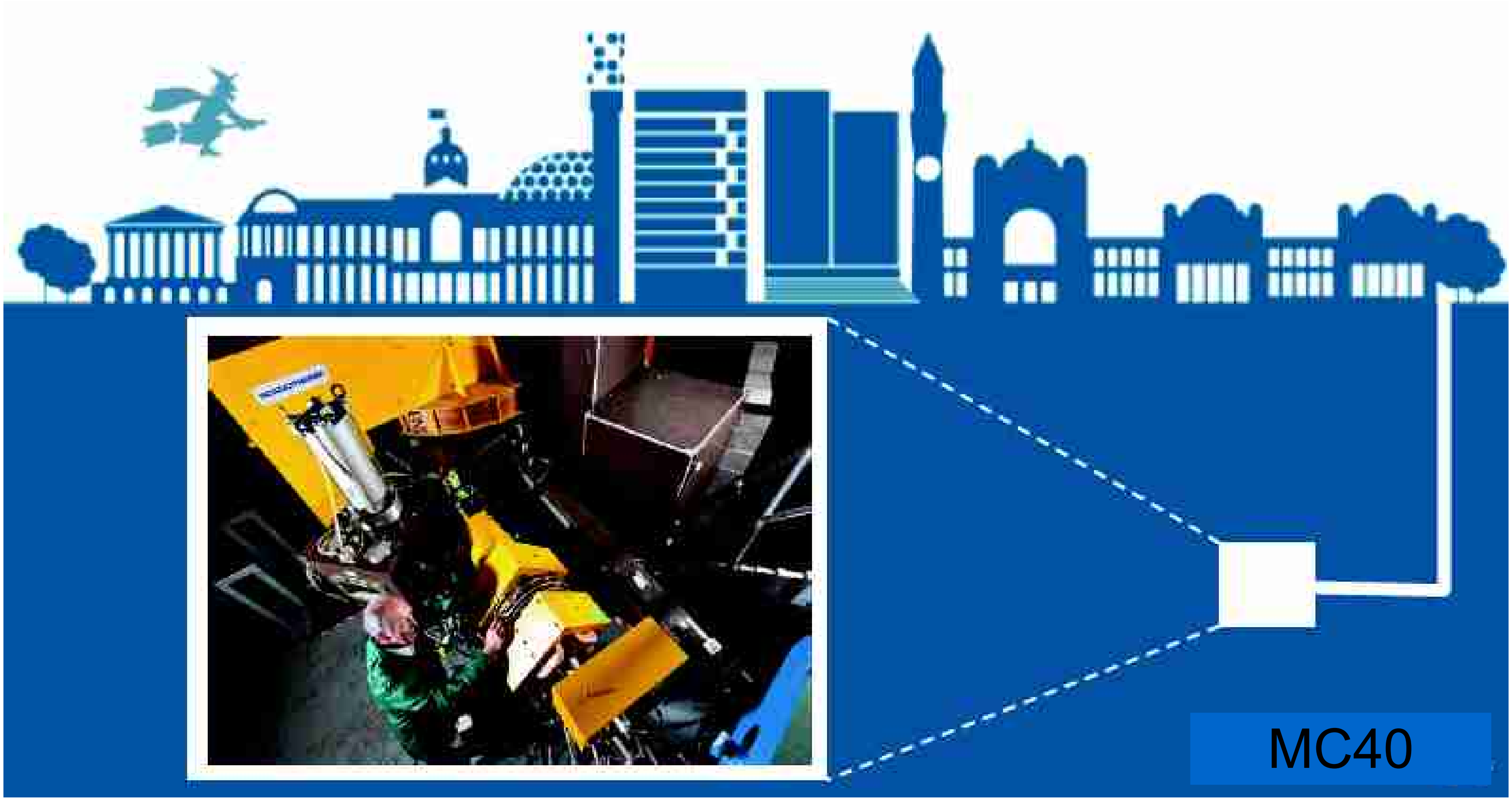
Nuclear Science at Birmingham: training, research and applications

>34 000 Students



Tzany Kokalova Wheldon

Masters Level Courses (Postgraduate):

- **Physics and Technology of Nuclear Reactors** [PTNR] (~50 students/year) – Dr. Paul Norman
- **Radioactive Waste Management and Decommissioning** [NDWM] (~12 students per year)– Dr. Tzany Kokalova Wheldon
- **NTEC** (Nuclear Technology Education Consortium) Birmingham delivers Reactor Physics and Waste Management modules

Undergraduate Courses

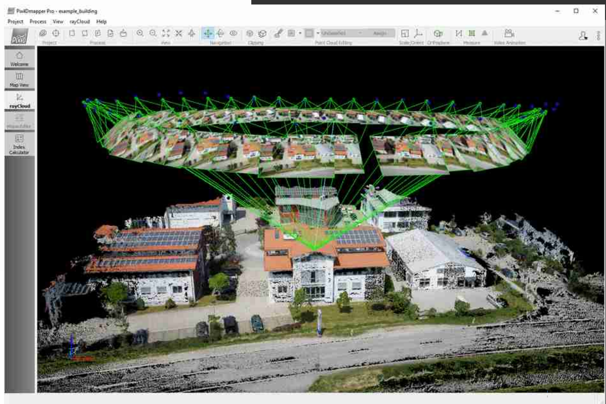
- **4 year Nuclear Engineering** (MEng)
- **3 year Nuclear Science and Materials** (BSc)

(~50 students/year)

Birmingham

3D environment simulations

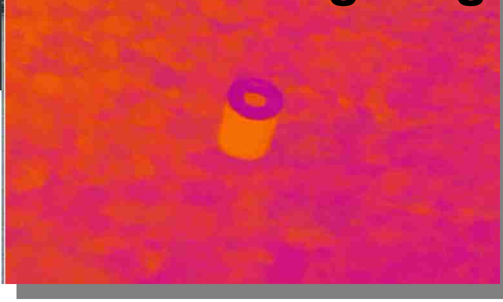
Human Interface Technologies Team



Pix4DMapper

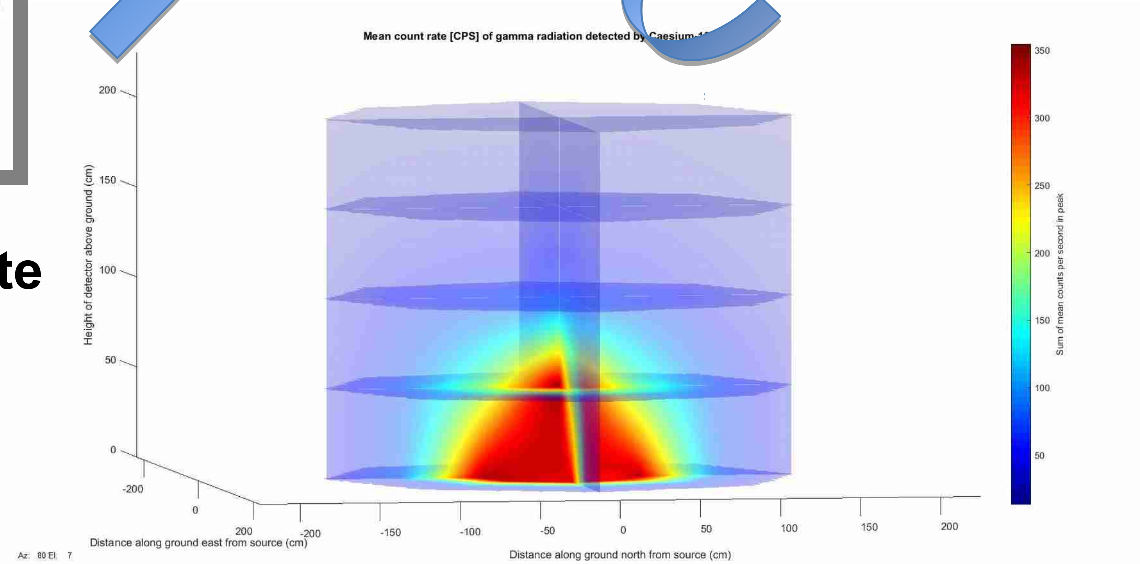
Matrice 100

Thermal Imaging



3D Nuclear Decommissioning and radiation surveys

Adafruit Ultimate GPS

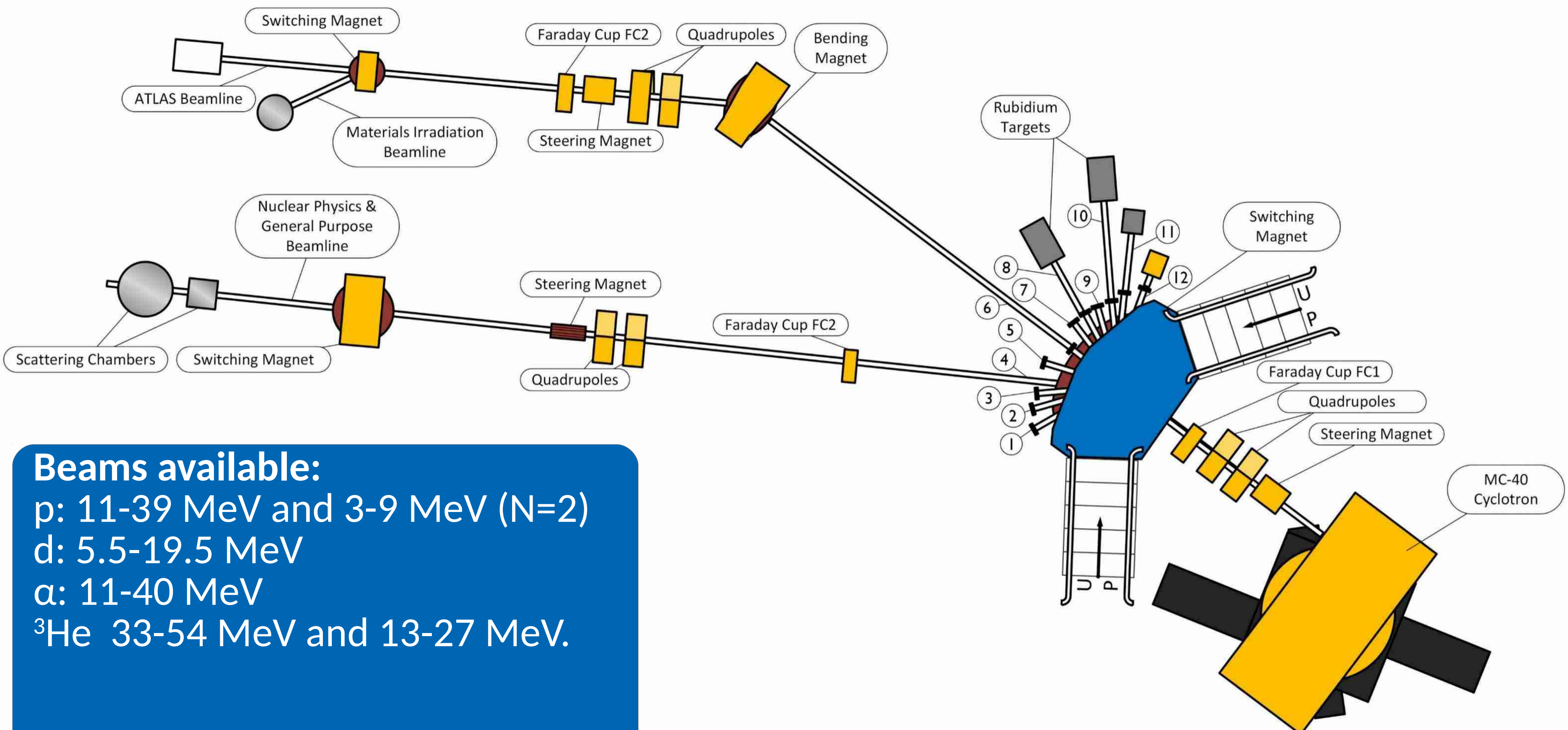


Raspberry Pi 2

Birmingham
Current Research Portfolio

- **Nuclear Materials** (reactor life extension work, materials analysis of radiation damage,….)
- **Nuclear Chemistry** (development of filters of radioactive waste products, e.g. zeolites)
- **Waste Storage** (materials analysis, geological analysis)
- **Biological solutions** (bio-molecules able to lock up heavy metals)
- **Radiation Sensors** (nano-sensors) Nuclear batteries
- **Robotics** (manipulation + sensors) for Decommissioning
- **3D environment simulation** (submarines, medical)
- **Waste assay** (detector development)
- **Policy**
- **Facilities** MC40 Cyclotron

Current cyclotron beam lines



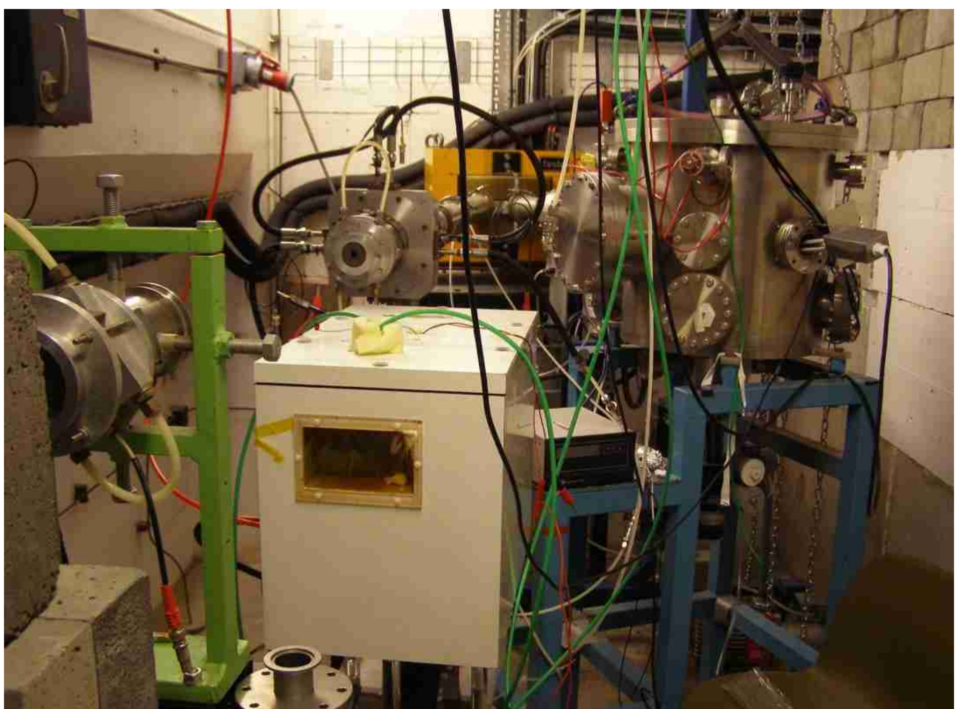
Beams available:
p: 11-39 MeV and 3-9 MeV (N=2)
d: 5.5-19.5 MeV
α: 11-40 MeV
^{3}He 33-54 MeV and 13-27 MeV.

Also 46 MeV $^{14}N^{4+}$ and 70 MeV $^{14}N^{5+}$ for nuclear physics.

Beam lines

High current irradiation cell:
(Left) ATLAS line on the
(Right) Metallurgy chamber

Low current irradiation line:
(Right/upstream) Radiobiology, space applications.
(Left/downstream) Nuclear physics scattering chambers.



Low-energy nuclear physics at the Birmingham MC40 cyclotron

Selected for a Viewpoint in *Physics*

PRL **119,** 132502 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

New Measurement of the Direct 3α Decay from the ^{12}C Hoyle State

R. Smith,[*] Tz. Kokalova,[†] C. Wheldon, J. E. Bishop, M. Freer, N. Curtis, and D. J. Parker
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom
(Received 15 May 2017; revised manuscript received 28 July 2017; published 25 September 2017)

Excited states in certain atomic nuclei possess an unusual structure, where the dominant degrees of freedom are those of α clusters rather than individual nucleons. It has been proposed that the diffuse 3α system of the ^{12}C Hoyle state may behave like a Bose-Einstein condensate, where the α clusters maintain their bosonic identities. By measuring the decay of the Hoyle state into three α particles, we obtained an upper limit for the rare direct 3α decay branch of 0.047%. This value is now at a level comparable with theoretical predictions and could be a sensitive probe of the structure of this state.

DOI: 10.1103/PhysRevLett.119.132502

Cluster physics evolution

1900 – Rutherford and Villard – discovery of the alpha particle.

1938 – Hafstad and Teller – ground-state clusters.

1956 – Morinaga san – Linear chains

1966 – Brink – like Hafstad and Teller but for excited states.

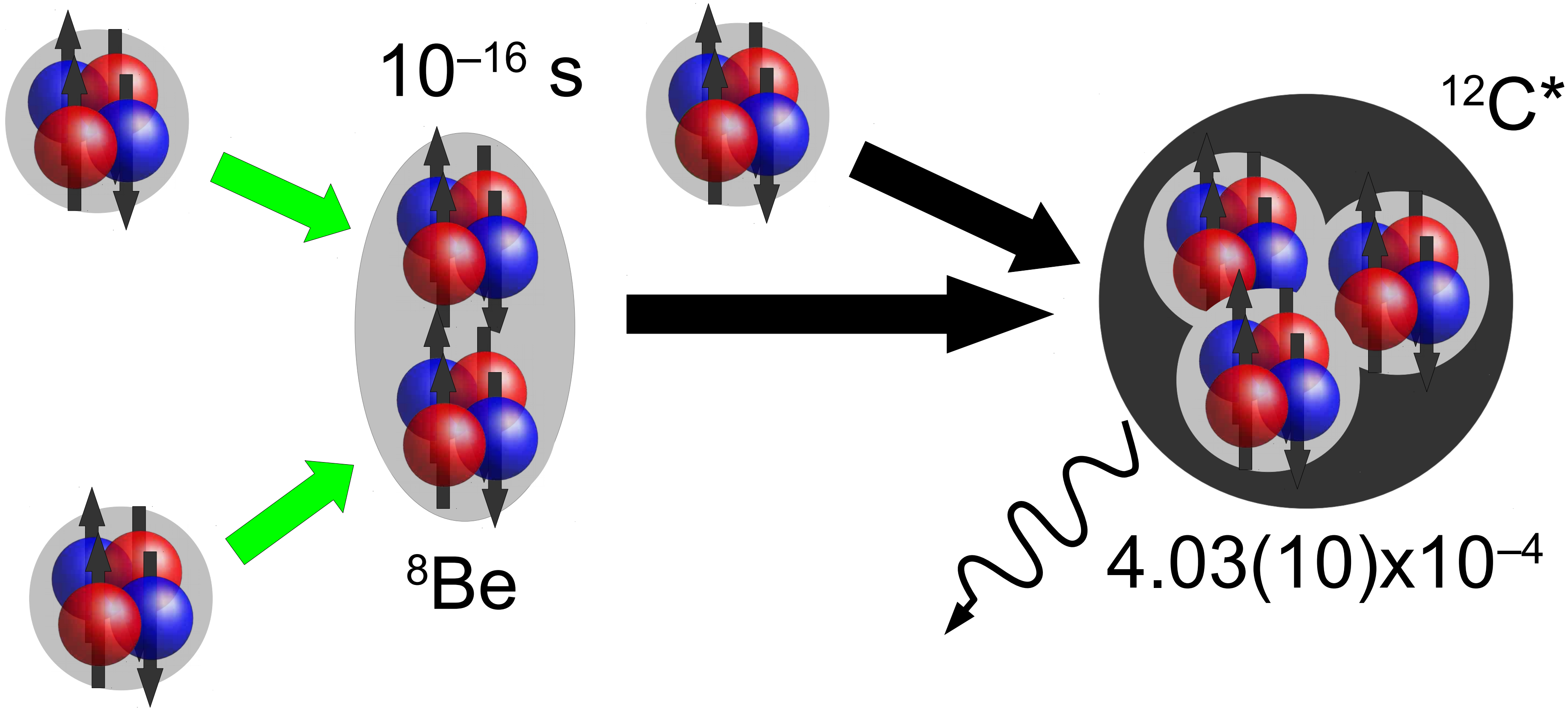
1968 – Ikeda...

Aside: 1952: Hoyle state prediction.

1954: Hoyle state experimental discovery.

The most famous clustered nucleus, ^{12}C

In 1952, Fred Hoyle predicted the existence of a state near 7.68 MeV [a]. Established at 7.654 MeV.



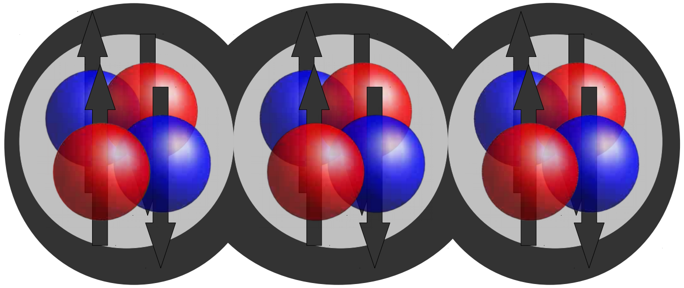
Schematic of the triple alpha process at $T \sim 10^8$ K.

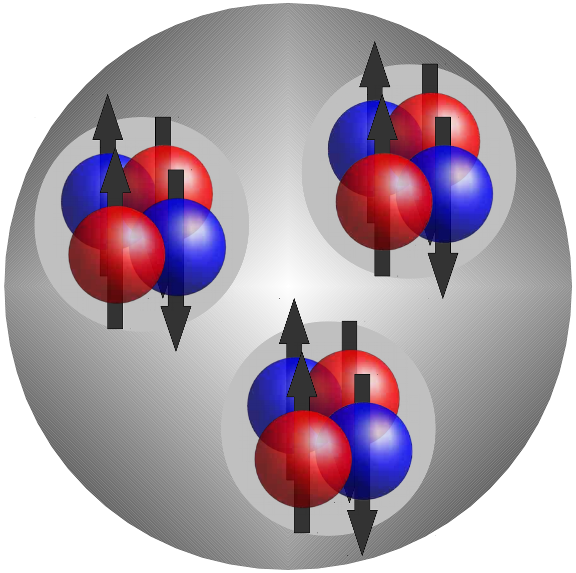
[a] F. Hoyle, D. N. F. Dunbar, W.A. Wenzel, and W. Whaling, Phys. Rev. 92, 1095 (1953).

The Hoyle state structure, historically

– Three α cluster – Linear chain

Cluster model: large moment of inertia
H. Morinaga, Phys. Rev. 101 (1956) 254.



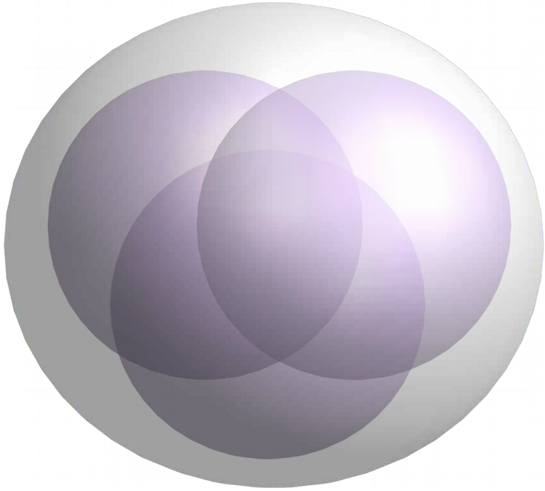


– Gas-like state of three α particles

Large radius, see *e.g.* H. Horiuchi, Prog. Theor. Phys. **51** (1974) 1266.

– Three α condensate

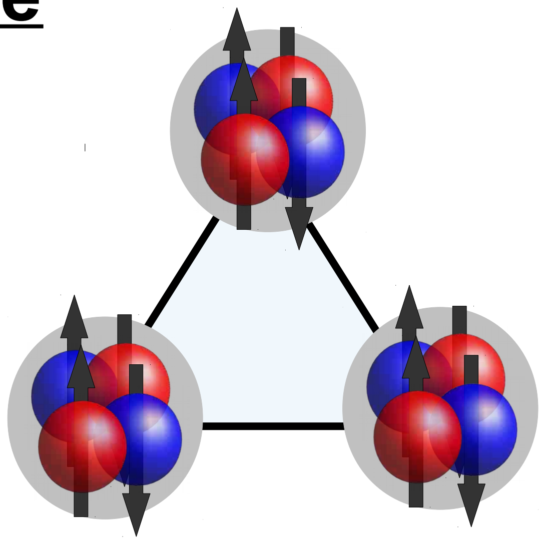
A. Tohsaki *et al.*, Phys. Rev. Lett. **87** (2001) 19250.



The Hoyle state structure, historically

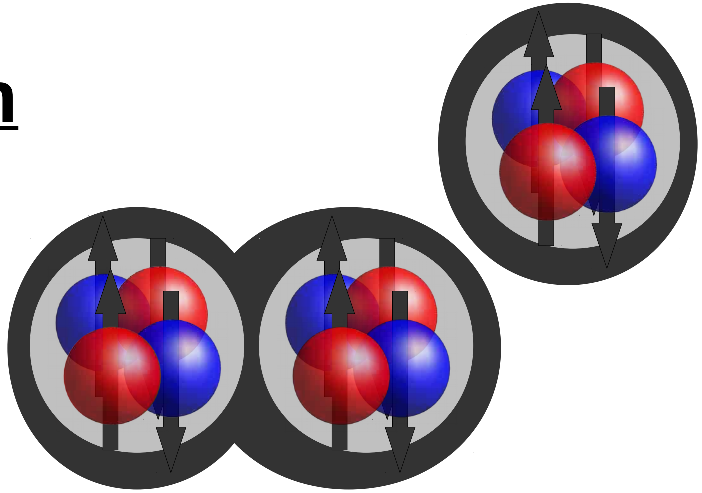
– **Three α cluster – equilateral triangle**

Algebraic model: breathing vibration
R. Bijker and F. Iachello;
Phys. Rev. C **61**, 067305 (2000).



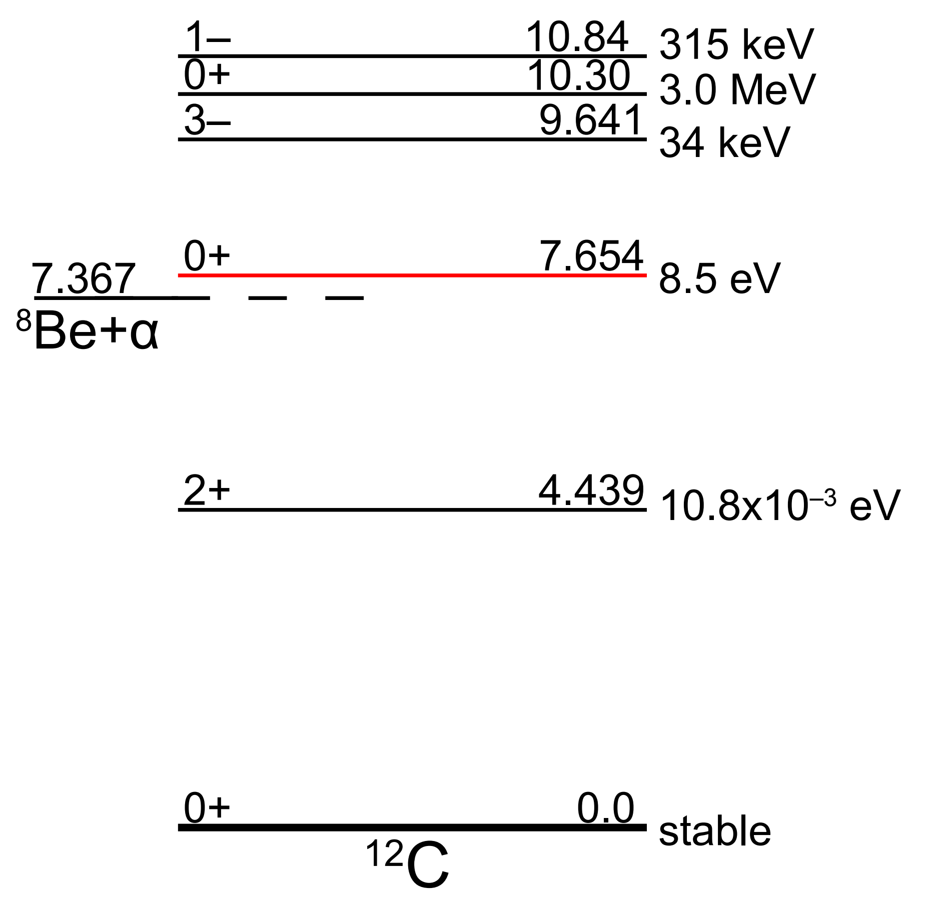
– ***Ab inito* lattice QCD – bent arm**

E. Epelbaum *et al.*,
Phys. Rev. Lett. **109** (2012) 252501.



Carbon-12 – Hoyle state

Carbon-12 – 7.654 MeV 0^+ state.



- Precise structure not fully established.
- Structure not well described by the shell model.
- Large overlap with a 3α-structure [b].
- Large radius.

[b] Y. Funaki *et al.*, Phys. Rev. **C67** (2003) 051306 and H. Matsumura and Y. Suzuki, Nucl. Phys. **A739** (2004) 238.

Calculations

Faddeev three-body predictions treating the system as 3α bosons [2]. The results are insensitive to the α-α interaction chosen.

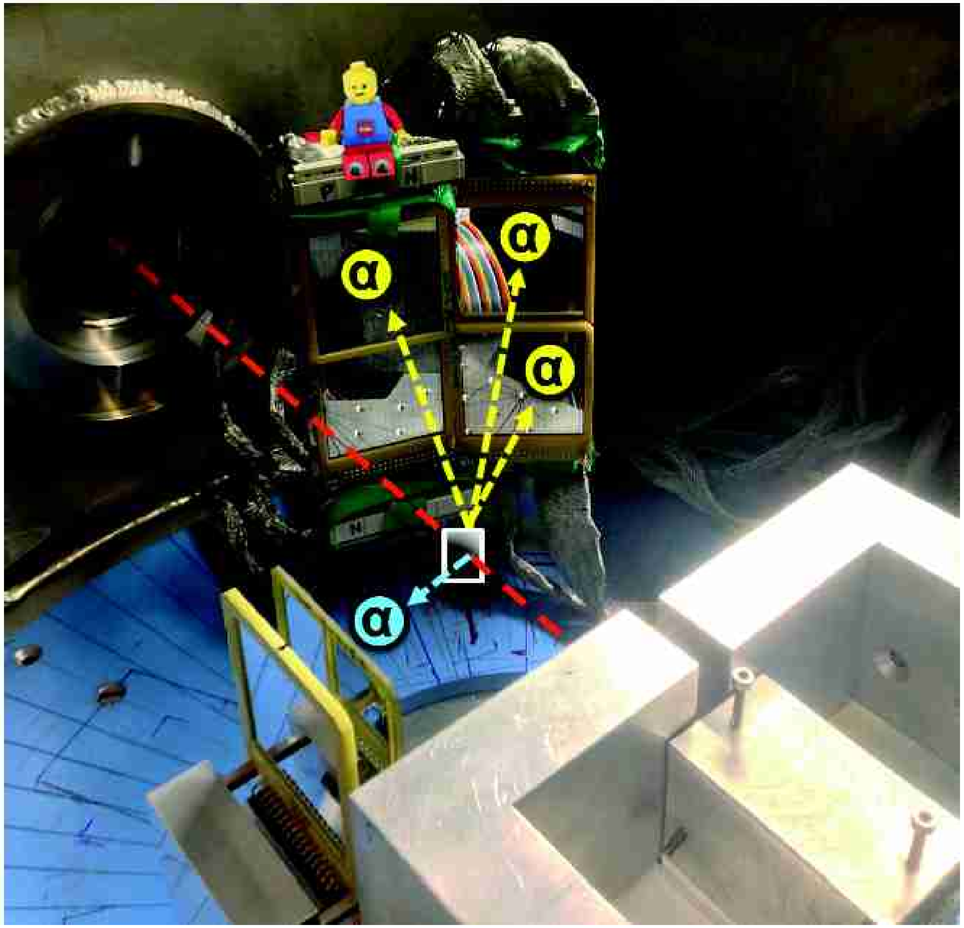
Predictions:

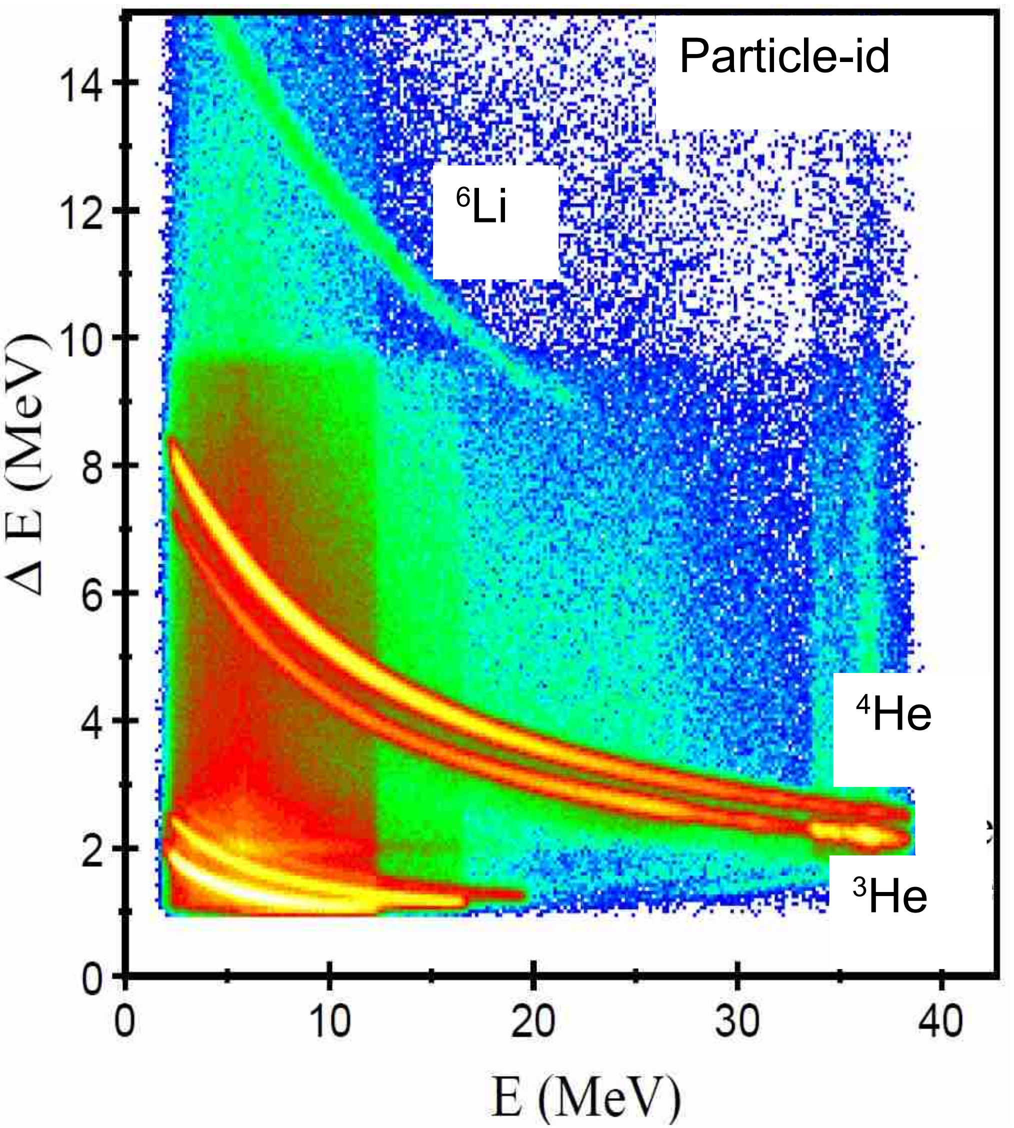
Sequential decay > 99%,

Direct decay < 1%.

[2] S. Ishikawa, Phys. Rev. C **90** (2014) 061604.

Experimental set-up





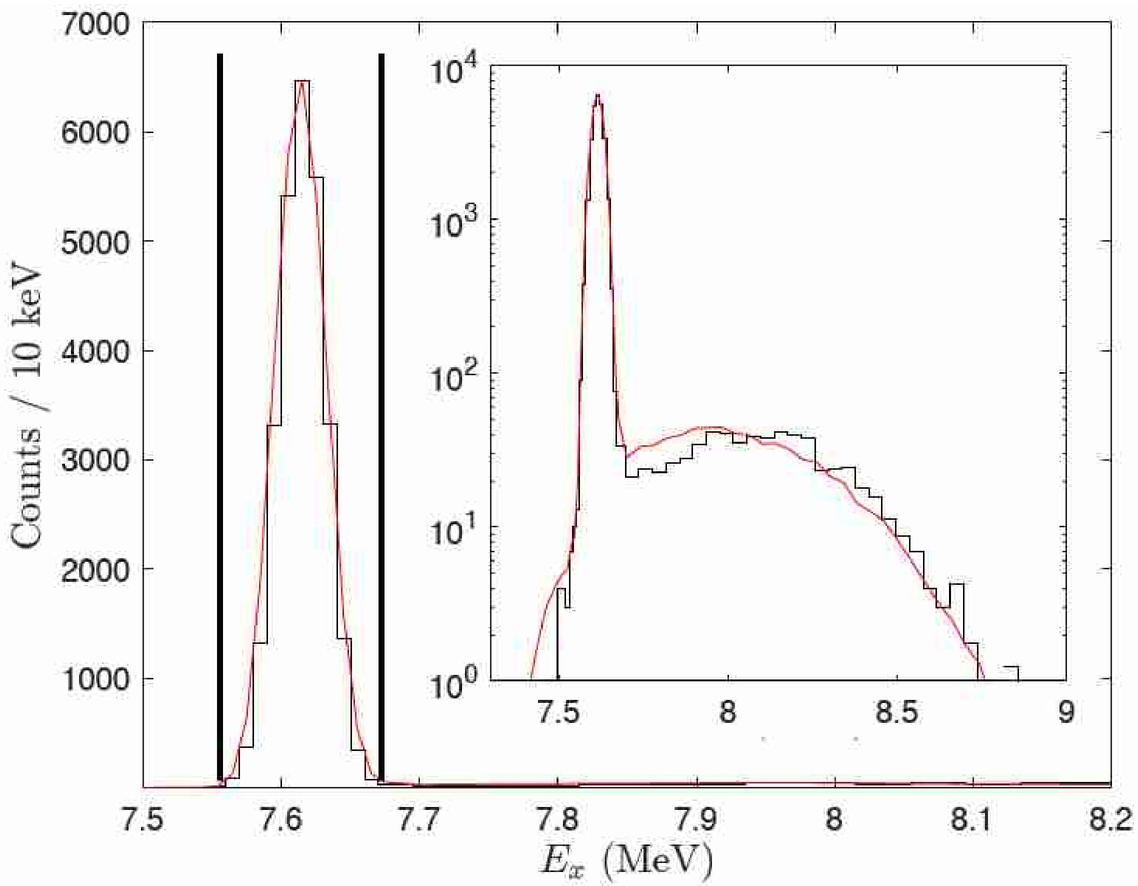
Left of the beam:

DSSD dE-E telescope.

Right of the beam:

Four DSSDs in a 2x2 grid (the Quad).

Statistics



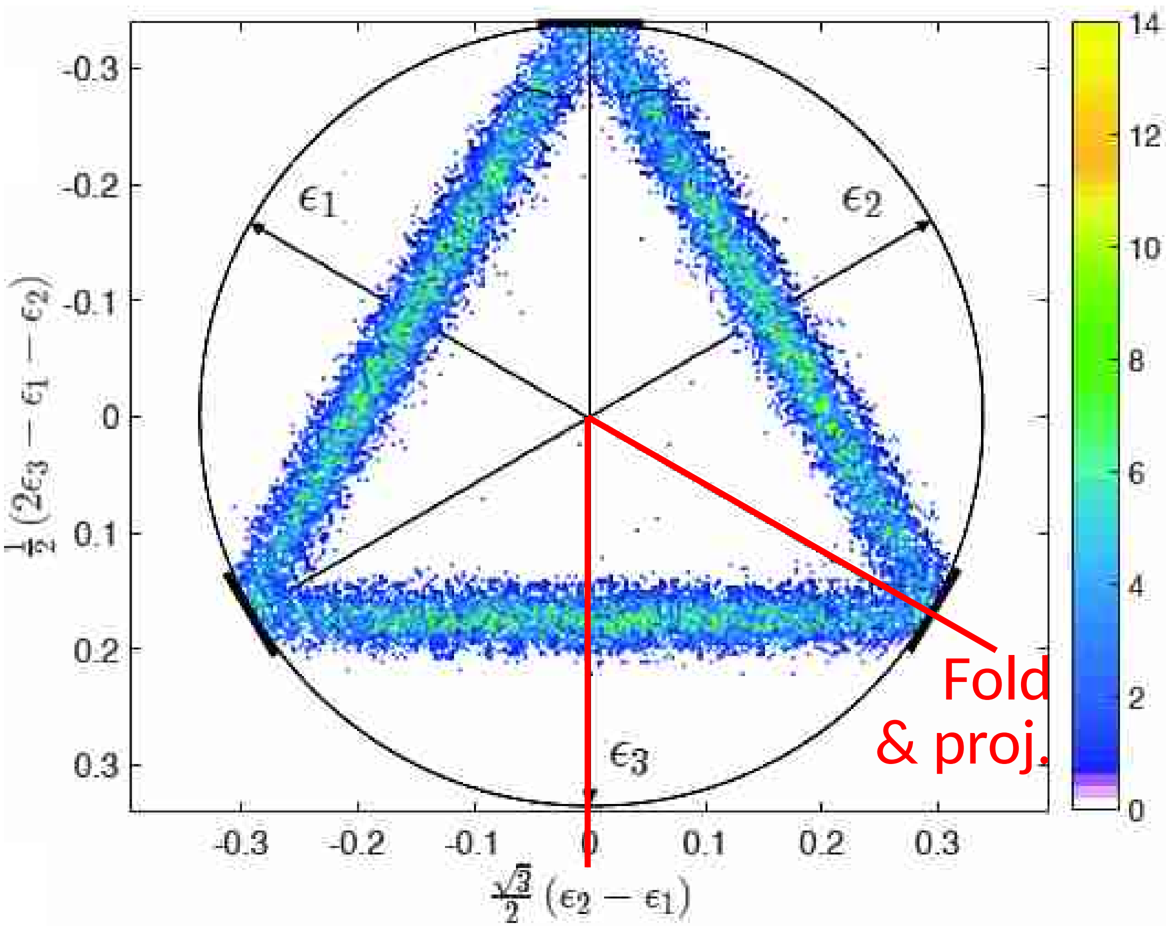
Detector geometry optimised to α- particles striking separate DSSDs ($2.4x10^4$ events) as this

.

Events with two αs in one detector also considered ($6.9x10^4$ events).

93,000 Hoyle decays 60 hrs.
Background → event mixing 0.03% (randoms).

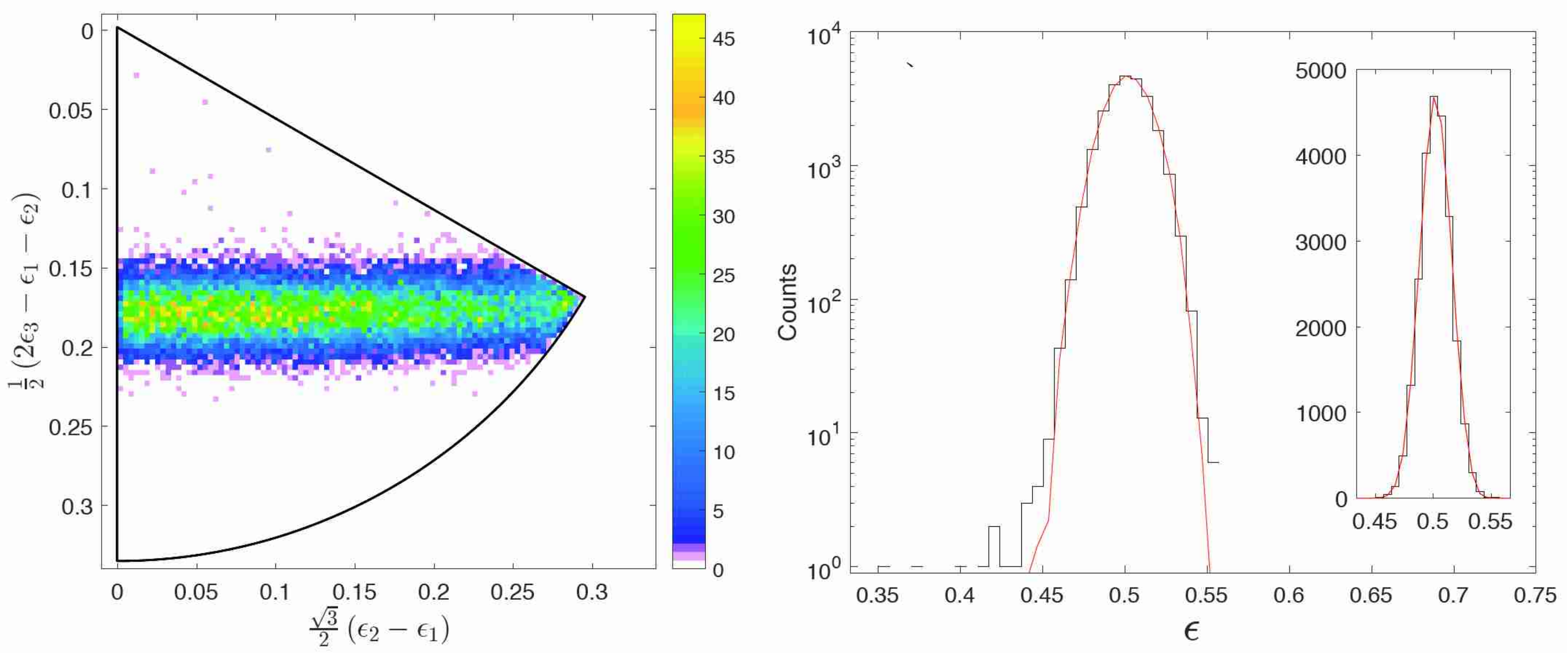
Analysis – 3-axis Dalitz plot



Shown here are the 3α in separate detectors = $2.4\text{x}10^4$ events (out of a total of $9.3\text{x}10^4$ events).

Fractional energies:
ε1 + ε2 + ε3 = 1.
Momenta: **p**1+**p**2+**p**3 = 0.

Experimental results – folded Dalitz plots

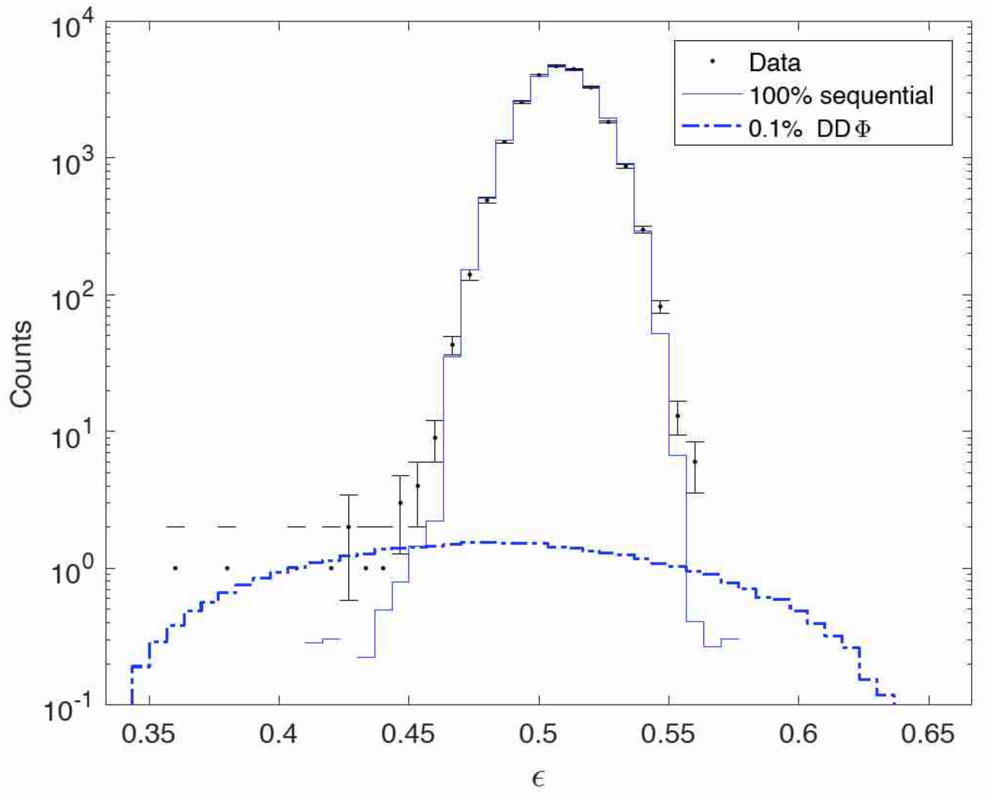


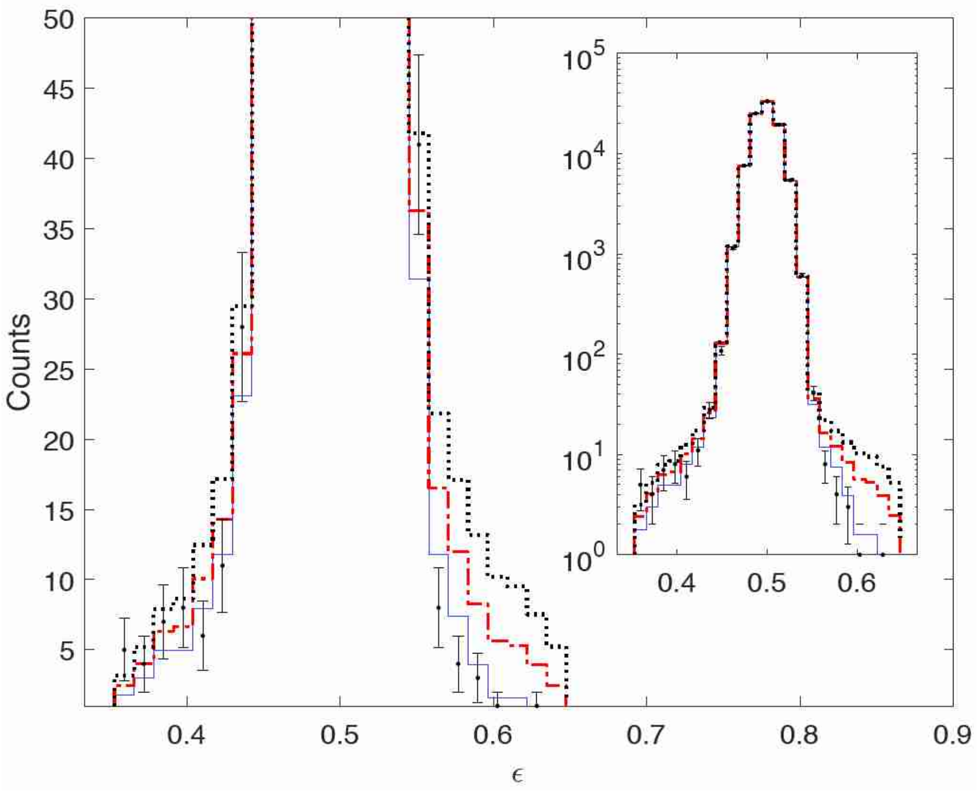
A total of 9.3×10^4 events.

Simulations and branching ratio

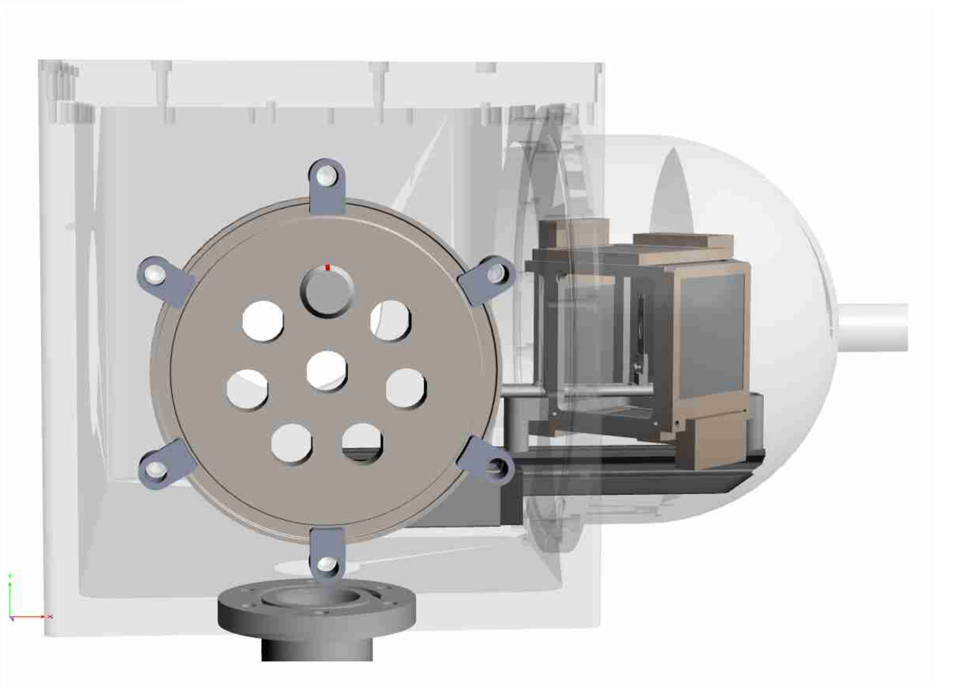
Monte-Carlo simulations, χ^2/DoF = 1.08 for 100% sequential decay.

0% direct branch,
0.05% direct 3α branch,
0.1% direct 3α branch.



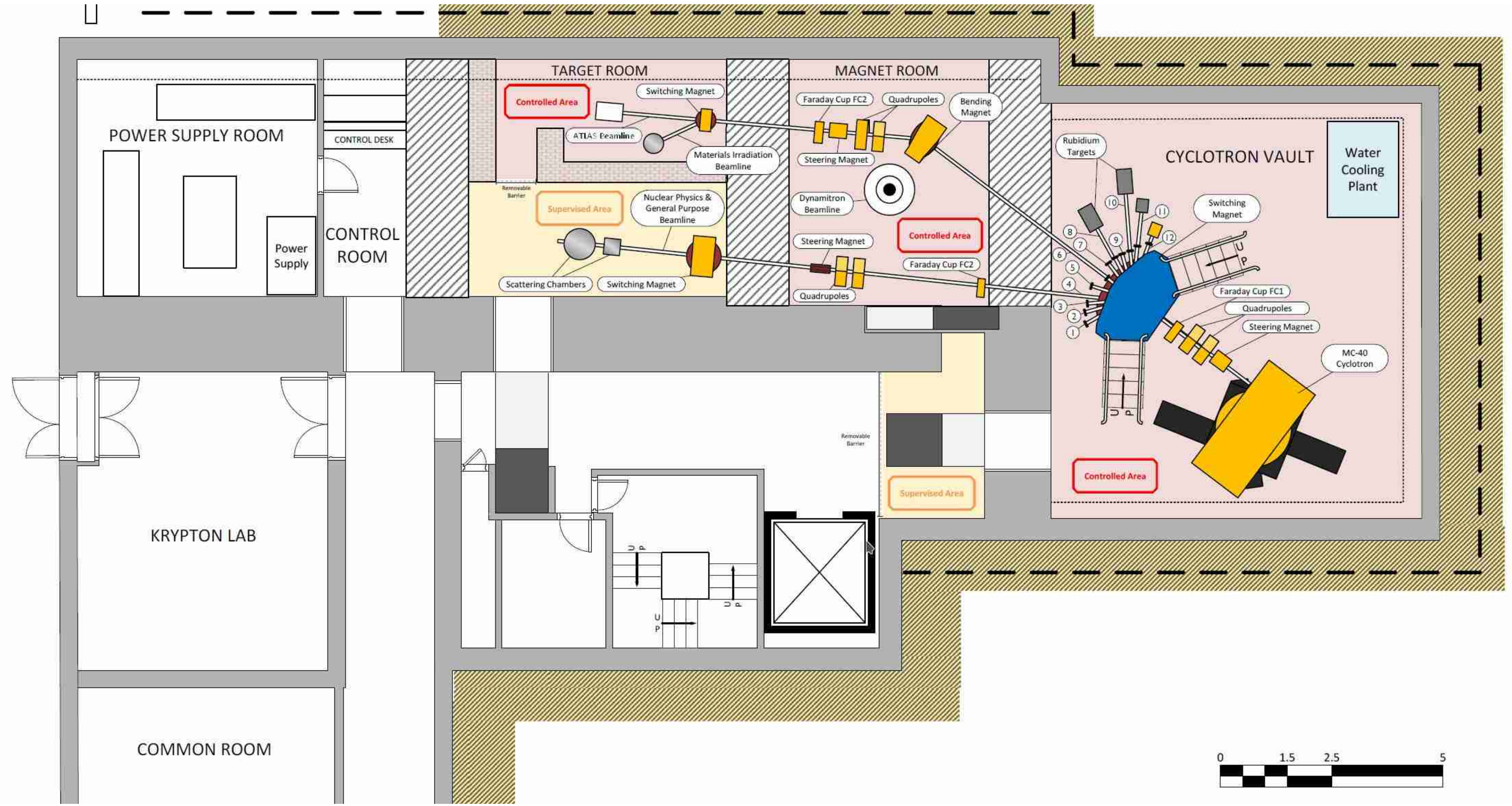


….and beyond – transition-rate measurements



- Gamma-branches needed to demonstrate collective enhancement – common structure.
- $LaBr_3$ detectors – high efficiency, good timing resolution for coincidence timing.

Orientation



MC40 cyclotron – uses

Hot filament ion source

Beams available:
p: 11-39 MeV and 3-9 MeV (N=2)
d: 5.5-19.5 MeV
α: 11-40 MeV
^{3}He 33-54 MeV and 13-27 MeV.

Also 46 MeV $^{14}N^{4+}$ and 70 MeV $^{14}N^{5+}$ for nuclear physics.

- Producing positron emitting nuclides for Engineering PET [NOT FDG[1]].
- Producing ^{81}Rb for ^{81m}Kr generators.
- Thin Layer Activation (formula 1).
- Other isotope production:
  - ^{69}Ge for labelling oil,
  - ^{62}Zn supplied to St Thomas' Hospital, London,
  - Various irradiations for NPL.
- Radiation effects studies:
  - Radiobiology + dosimetry (proton imaging),
  - Space electronics etc.,
  - ATLAS components,
  - Metallurgy of nuclear materials.
- Nuclear physics
  - Research,
  - Undergraduate research projects,
  - Postgraduate training (hands-on experiment course).

[1]FDG = fluorodeoxyglucose.

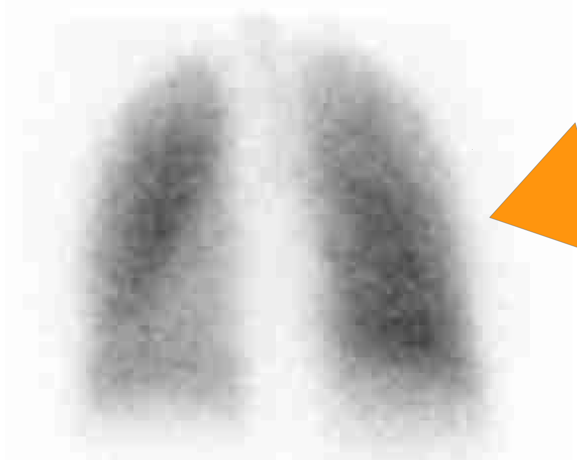
Positron emission particle tracking (PEPT)

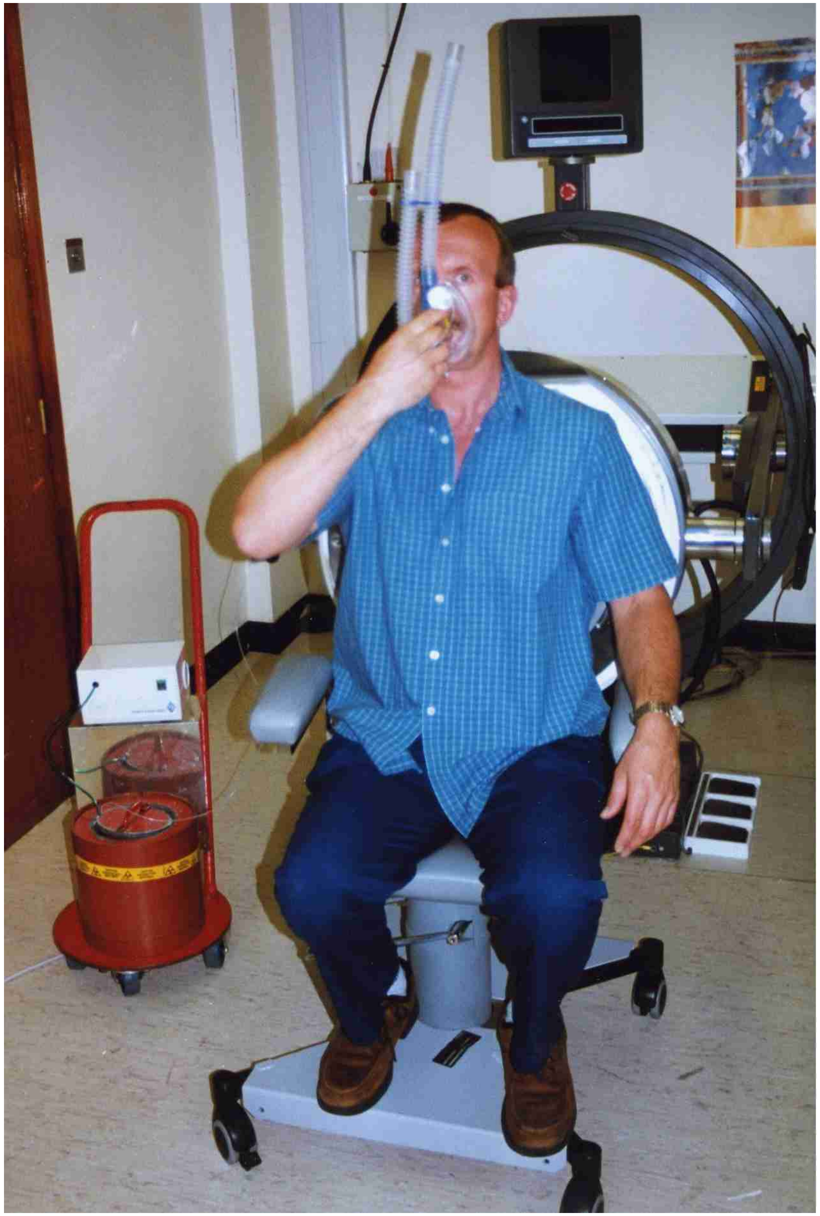
Label a single particle (*e.g.* grain of sand) with positron-emitter (usually ^{18}F from ^{3}He on natural oxygen or p+Oxigen) and track it as it moves inside equipment

MC40 cyclotron – uses

^{81}Rb (4.6 h)

- Parent of ^{81m}Kr (gas), which decays (13s) to ground state emitting 190 keV gamma; (parent/daughter generator).
- ^{81m}Kr used for imaging lung function using gamma camera





Production 5 evenings per week, 50 weeks per year

Rubidium/krypton production

<u>Rubidium statistics:</u> since 2006 made rubidium for 37390 generators.

– 1 for a successful production run,
– 0.5 for a run where production was less than requested
– 0 for a complete failure.

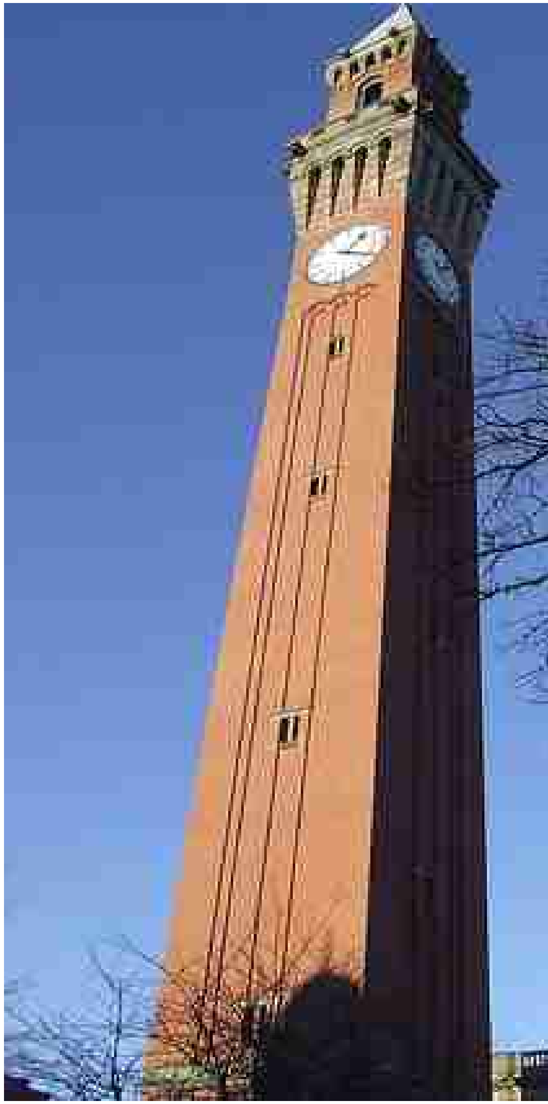
On this basis:
– 2018 (to Apr) 94.1%. Main issue was August break down (loose magnetic channel).

Overall since 2006, success rate 96.1%.

- **NEW** Production of Tb in collaboration with NPL (see also next talk)

Thanks for your attention.

(Birmingham in the sunshine)



The tallest free-standing clock tower in the world.

Rubidium-81 production

Using the technique developed at Medical Research Council (MRC) Cyclotron Unit (Hammersmith Hospital, London):

- Irradiate target containing ^{82}Kr gas (6 bar pressure) with 27 MeV protons (30 μA).
- ^{81}Rb is produced and deposits on walls of target.
- At end of irradiation, recover ^{82}Kr gas cryostatically.
- Then elute ^{81}Rb from target: 3 x 40ml transferred to dispensing room.
- Finally evacuate target ready for reuse.
- Currently making approx 60 generators per week – fairly stable.

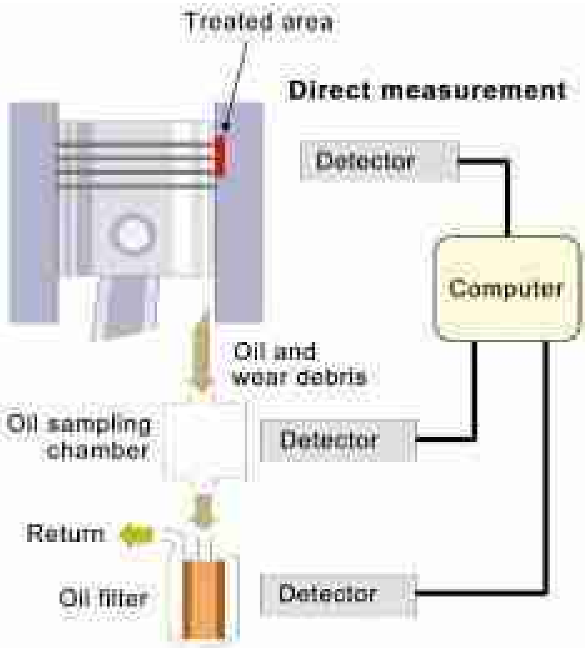
Entire procedure is controlled by Beckhoff Programmable Logic Controller (PLC).

Same PLC has gradually been extended to control cyclotron interlocks *etc*.

Thin layer activation

For measuring **wear** on components (especially automotive parts, for R&D):

- Irradiate surface with beam to create long-lived radionuclide in well-defined surface layer (typically ~ 50 μm deep).
- Subsequently monitor surface removal by detecting gamma-rays either from remaining layer or from wear debris.



Steel:

- $^{56}Fe(p,n)^{56}Co$ (77 days, 0.85 MeV and 1.24 MeV gammas).
- $^{56}Fe(d,n)^{57}Co$ (270 days, 0.122 MeV gammas).

Can activate different surfaces with each for simultaneous studies.

Aluminium:

- $^{27}Al(^{3}He, 2\alpha)\ ^{22}Na$ (2.7 yrs, 0.511 MeV & 1.27 MeV gammas)

Diamond-like carbon (DLC) coatings

- $^{12}C(^{3}He, 2\alpha)^{7}Be$ (53 days, 0.47 MeV gamma).

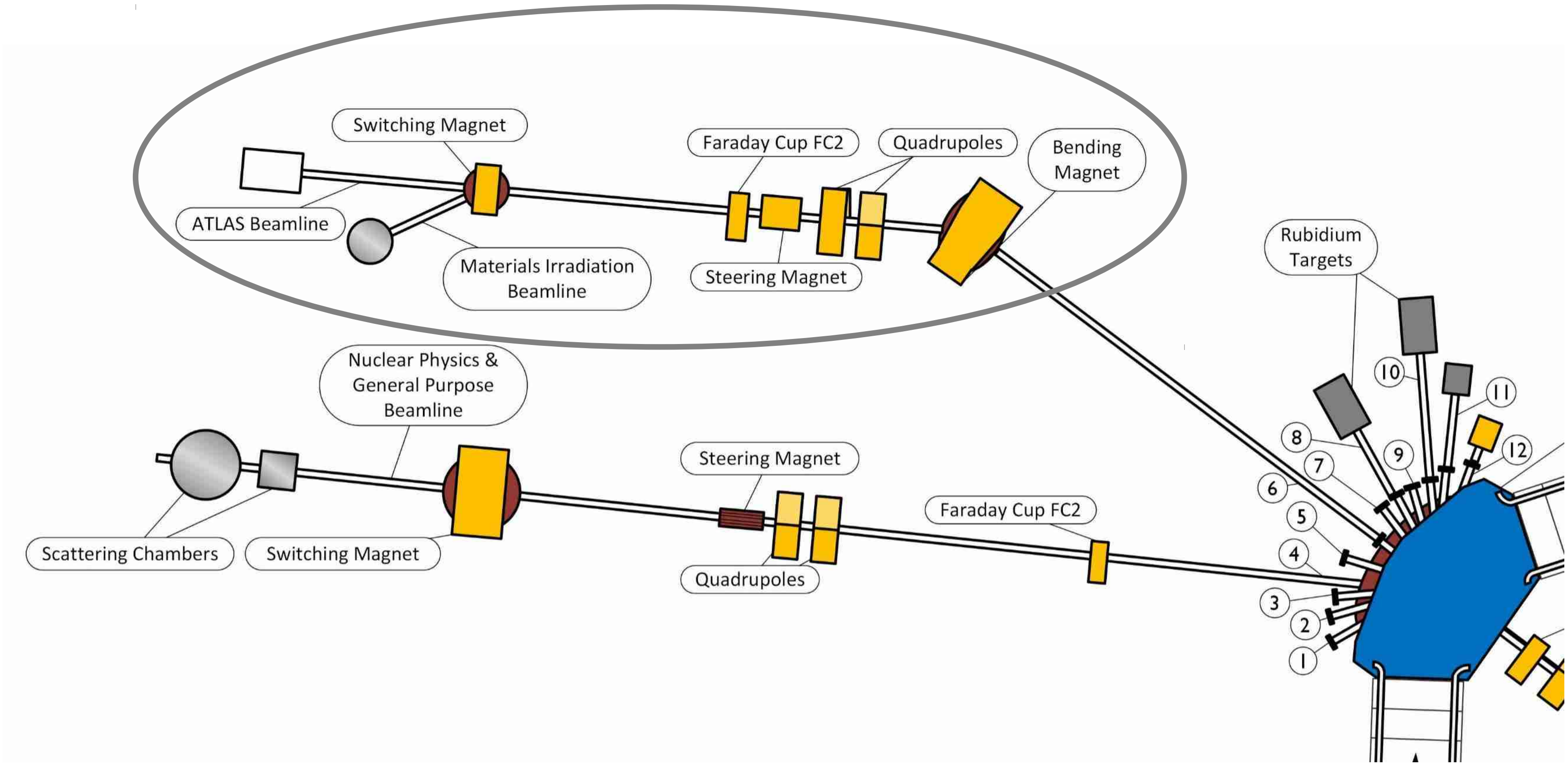
The team

Robin Smith, Tzany Kokalova, Carl Wheldon, Jack Bishop, Martin Freer, Neil Curtis, David Parker

The analysis was part of the Ph.D work of Robin Smith at Birmingham

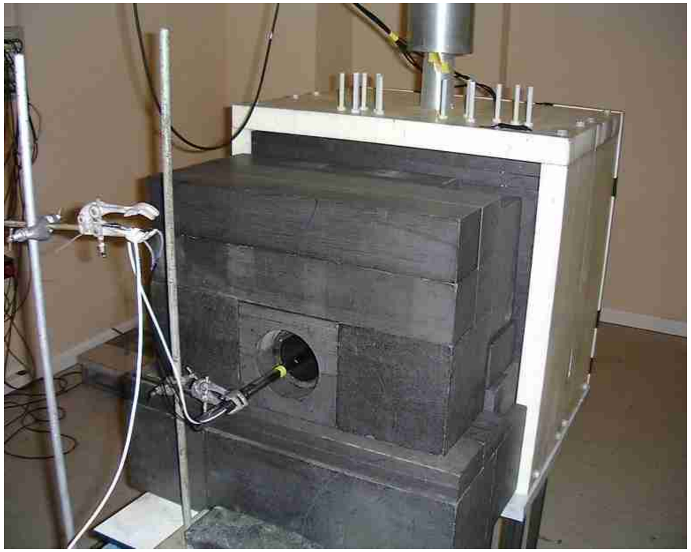
Beam lines

More recently, we were asked to provide high dose-rate damage studies (LHC ATLAS group and metallurgy) so extended a second beam-line into a specially shielded area.



The Dynamitron – present capabilities

RDI 3MV Dynamitron
(1970 – v. soon)
3 MeV (1-2 mA) of protons on ^{nat}Li (B'ham developed target).
Neutron sources is > $1x10^{12}$ n/s at 1 mA at 2.8 MeV.
Peak epithermal fluence ~$2x10^{8}$ $n/cm^{2}/s$



Future neutron facilitly

Hyperion: A single-ended electrostatic accelerator, 50 mA+ capability

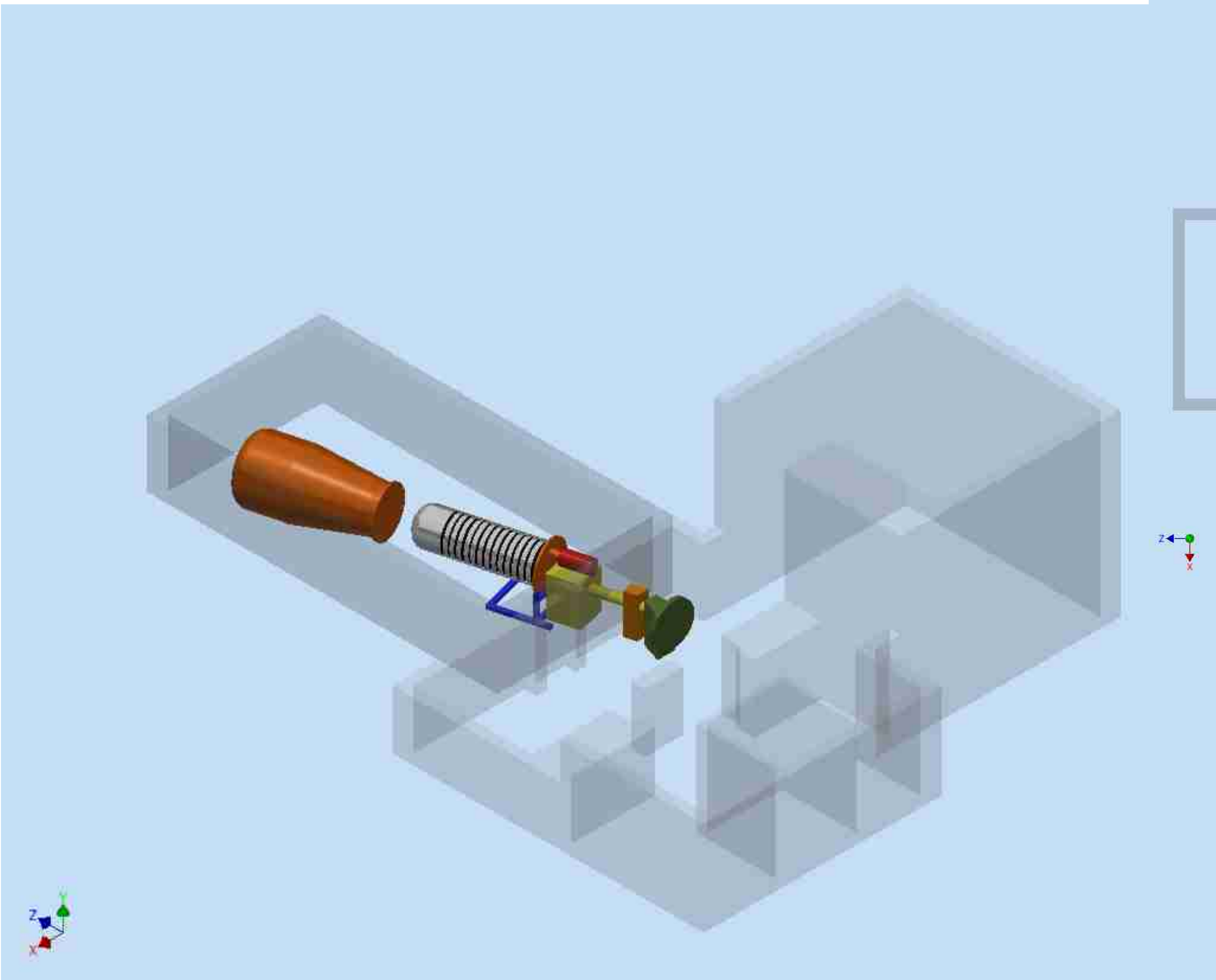
Now sold by Neutron Therapeutics as part of accelerator BNCT facilities, including a developed high power Li target.

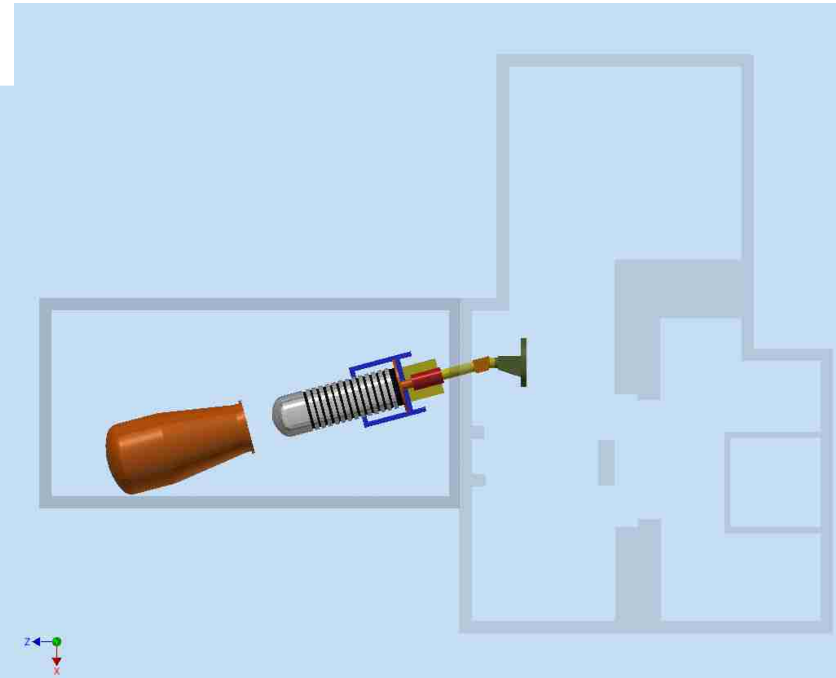
Easily achievable levels - Standard Hyperion Dynamitron at 30 mA protons specified

Neutron Therapeutics target –
fast neutrons at 1.8 x 10^{11} n/cm^2/s.

Thermal neutrons at 6.6 x 10^9 n/cm^2/s

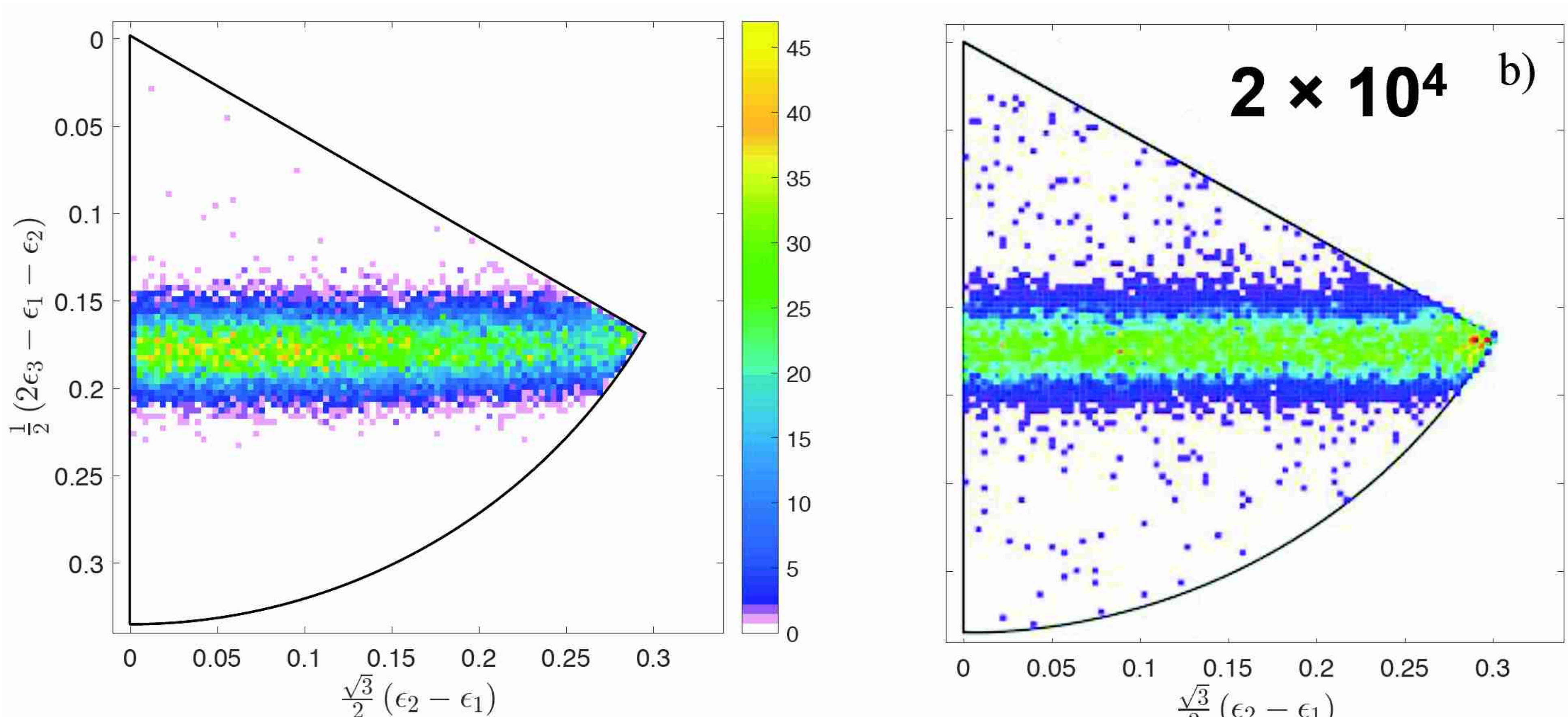
Building overview



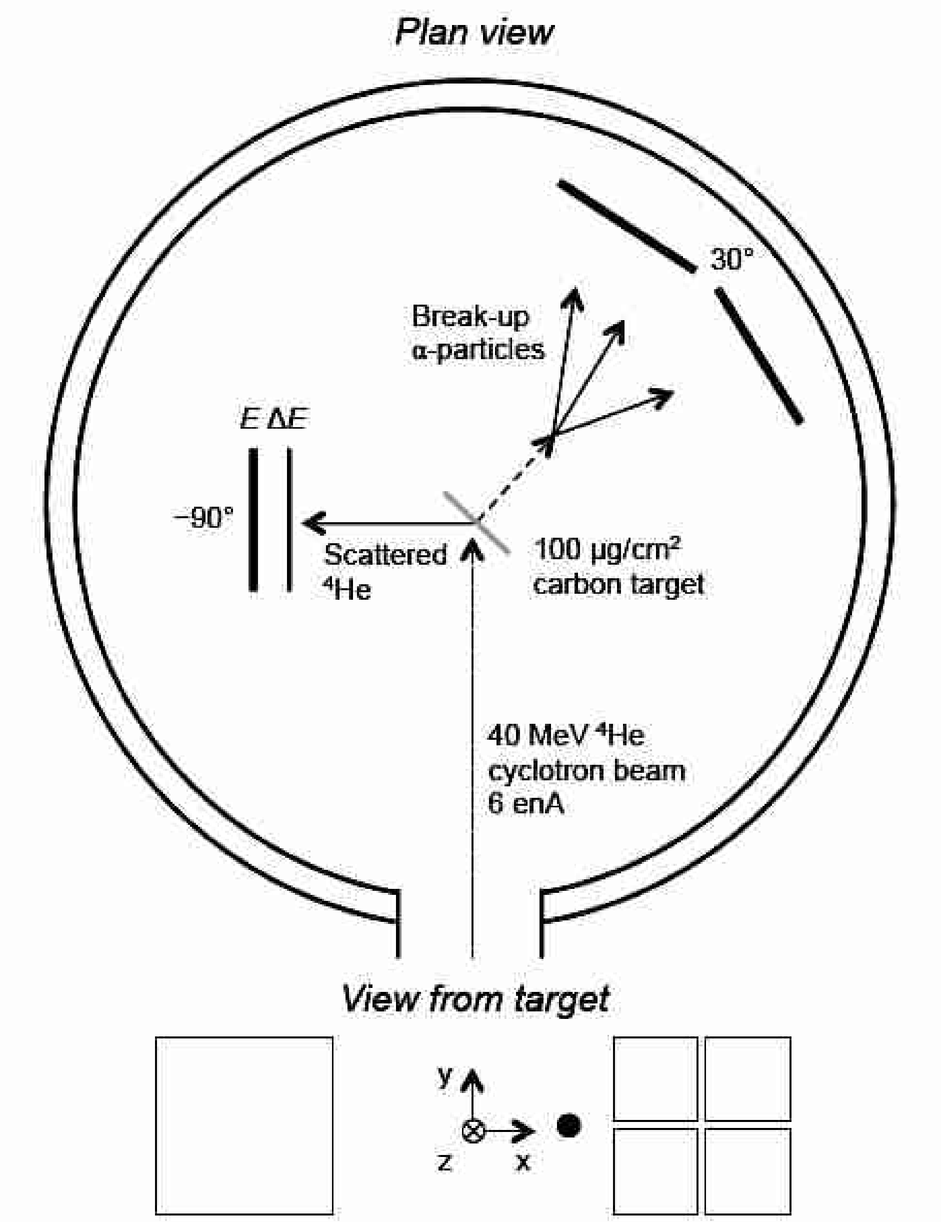


Building offers opportunities for expanding the basement (MC40 cyclotron) level.

Experimental results – folded Dalitz plots



Experimental set-up



Measurement of the $^{12}C(^{4}He,\alpha)3\alpha$ reaction at 40 MeV in complete kinematics;

– all final-state particles detected.

Tracer particles of PEPT

Most are labelled with ^{18}F (half-life 110 min.) produced by cyclotron irradiation of oxygen [$^{16}O(^{3}He, p)^{18}F$]:

- “Large” (>1mm) particles of silica, alumina *etc.* are directly activated – activity firmly fixed in bulk
- Smaller particles, and other materials (plastics *etc.*) are indirectly labelled – produce ^{18}F in solution and then attach it to particle using appropriate surface chemistry (bridging ions, *etc.*) - these tracer particles are generally OK except in aqueous environments, when the activity rapidly leaches off again.

For aqueous environments, we have developed other radioisotope labels. For example, ^{66}Ga (9 hours) produced by proton irradiation of Zn, followed by cation exchange separation.