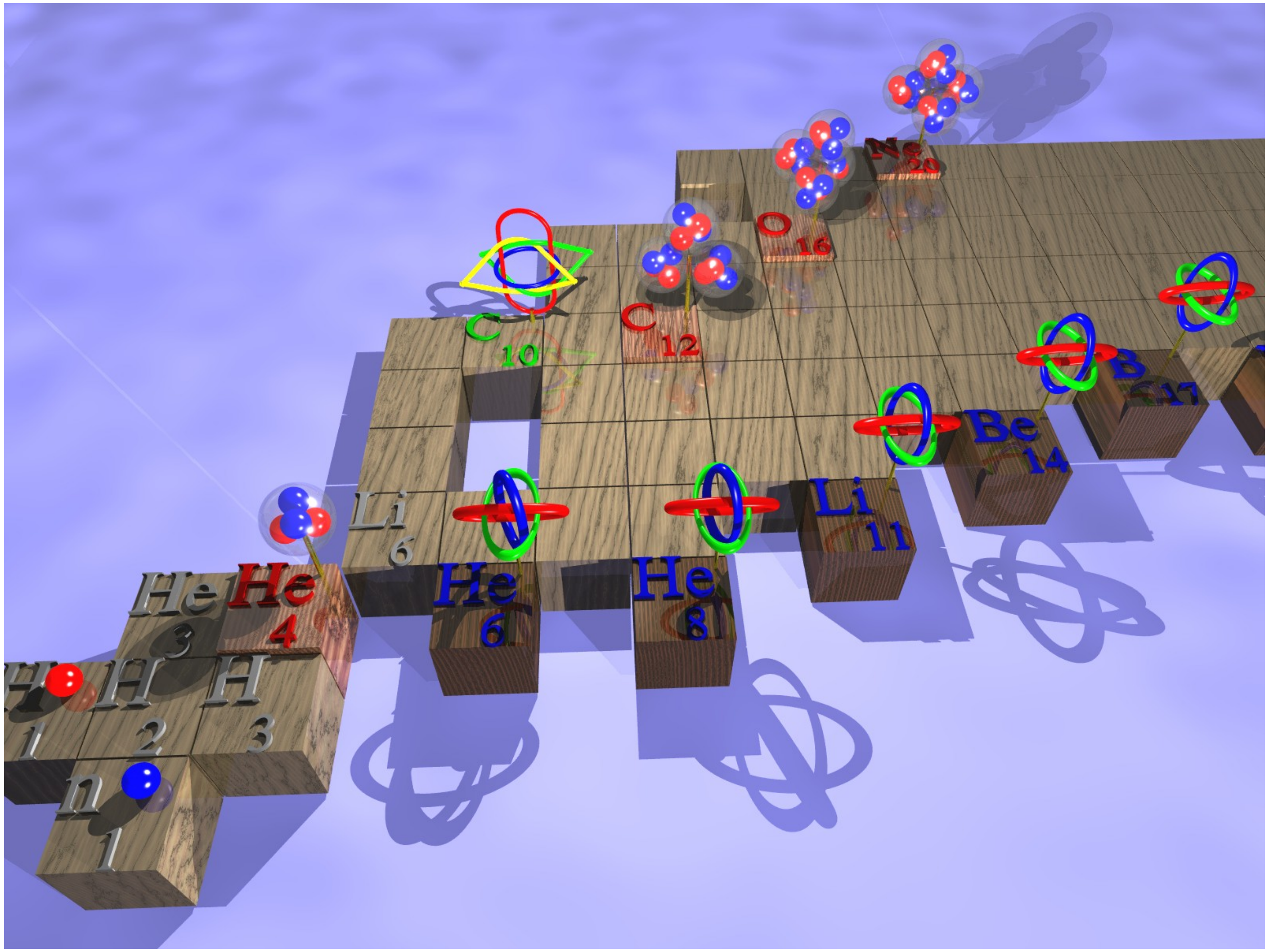
Experiments and analyses aimed at understanding nuclear clustering

Carl Wheldon, Sam Bailey, Tzany Kokalova et al.

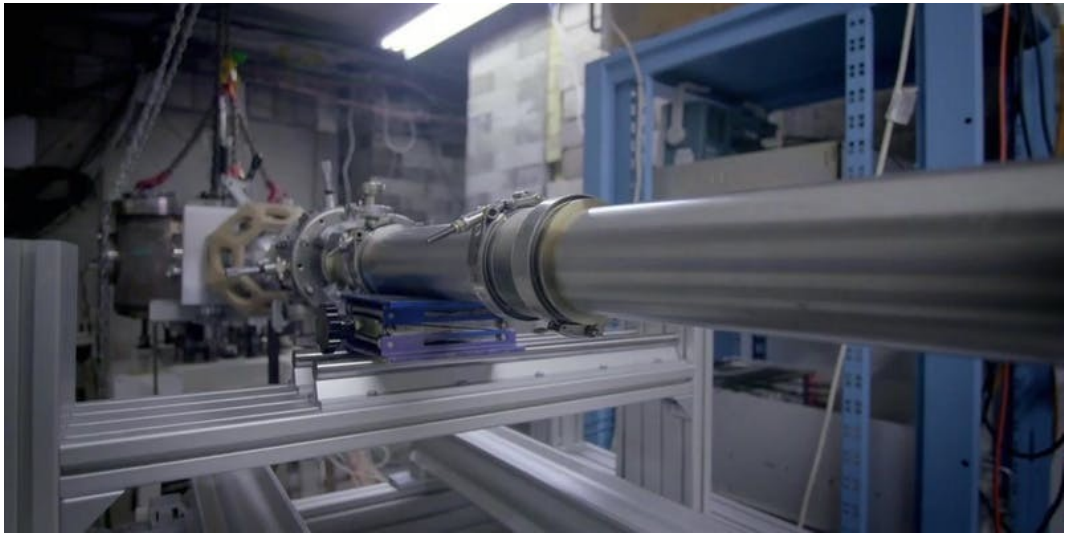


Outline

- Birmingham overview
- Clustering in the *fp* shell
- Resonant scattering – TTIK
- The search for signatures
- Results

- Machine learning
- Back to the future

The Birmingham Cyclotron facility



Birmingham overview

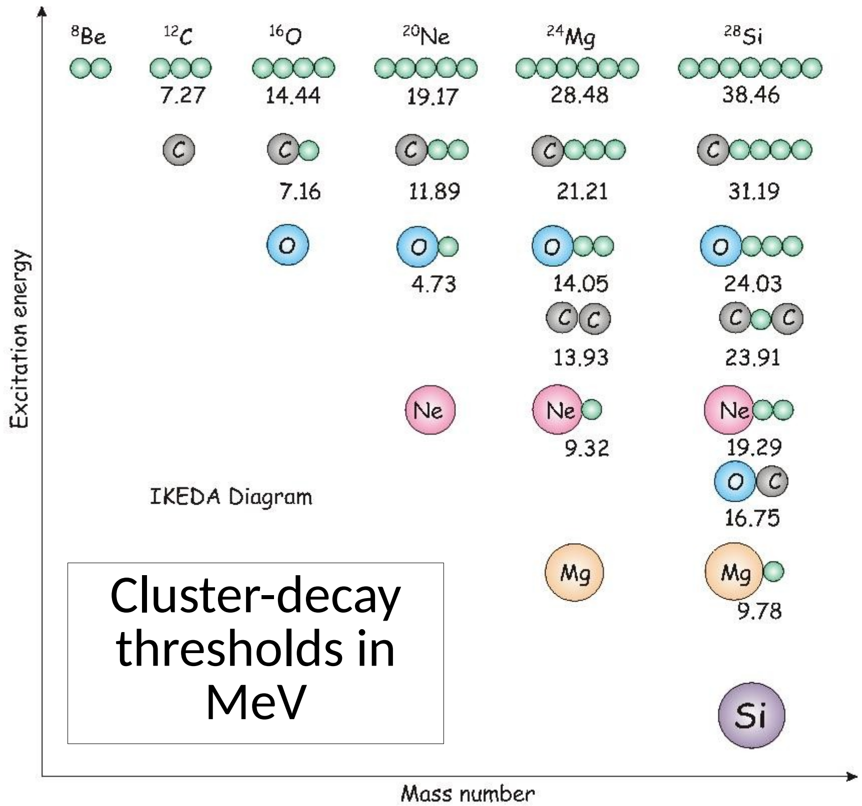
- Limit on the direct 3-body decay of the ^{12}C Hoyle state (Thursday morning's talk).

Robin Smith

- Clustering in ^{18}O via measurement of absolute decay widths (talk moved to Monday afternoon).

Stuart Pirrie

Clustering in the *fp* shell



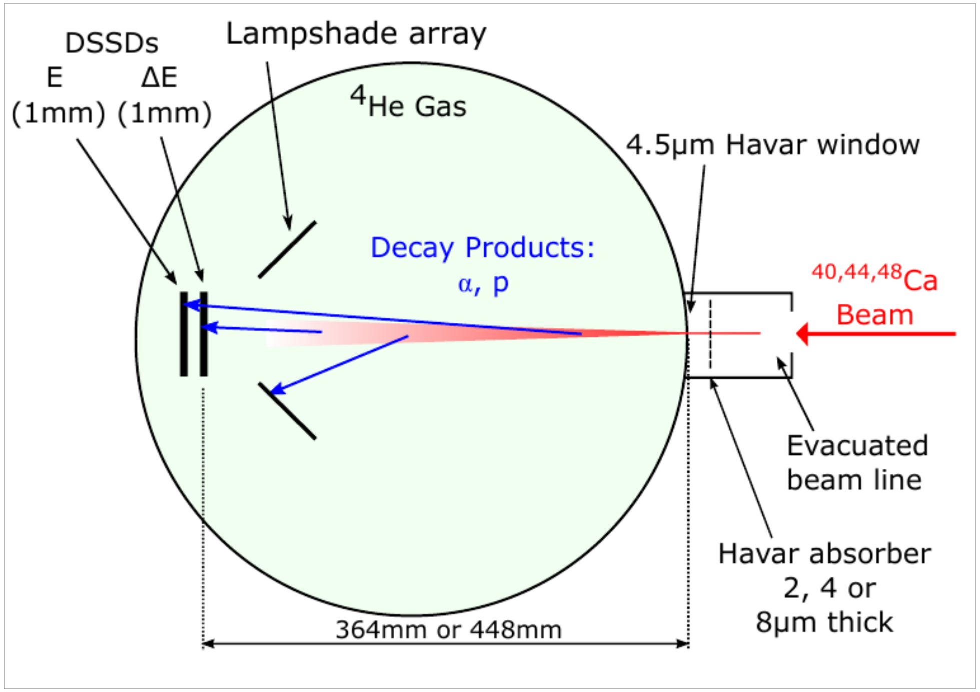
Clustering typically appears close to the cluster-decay thresholds.

The nucleus needs sufficient excitation energy to dissolve, *e.g.* into α-particles.

For heavier nuclei level densities increase rapidly above the particle thresholds.

- **Titanium-44** – shown both experimentally and theoretically to exhibit alpha-cluster and mean-field structures, $^{40}Ca + \alpha$.
- If ^{40}Ca is a ‘good’ core, what about more neutron rich Ca isotopes, $^{44,48}Ca$?
- In these medium-mass nuclei spectra become complex making analysis difficult.

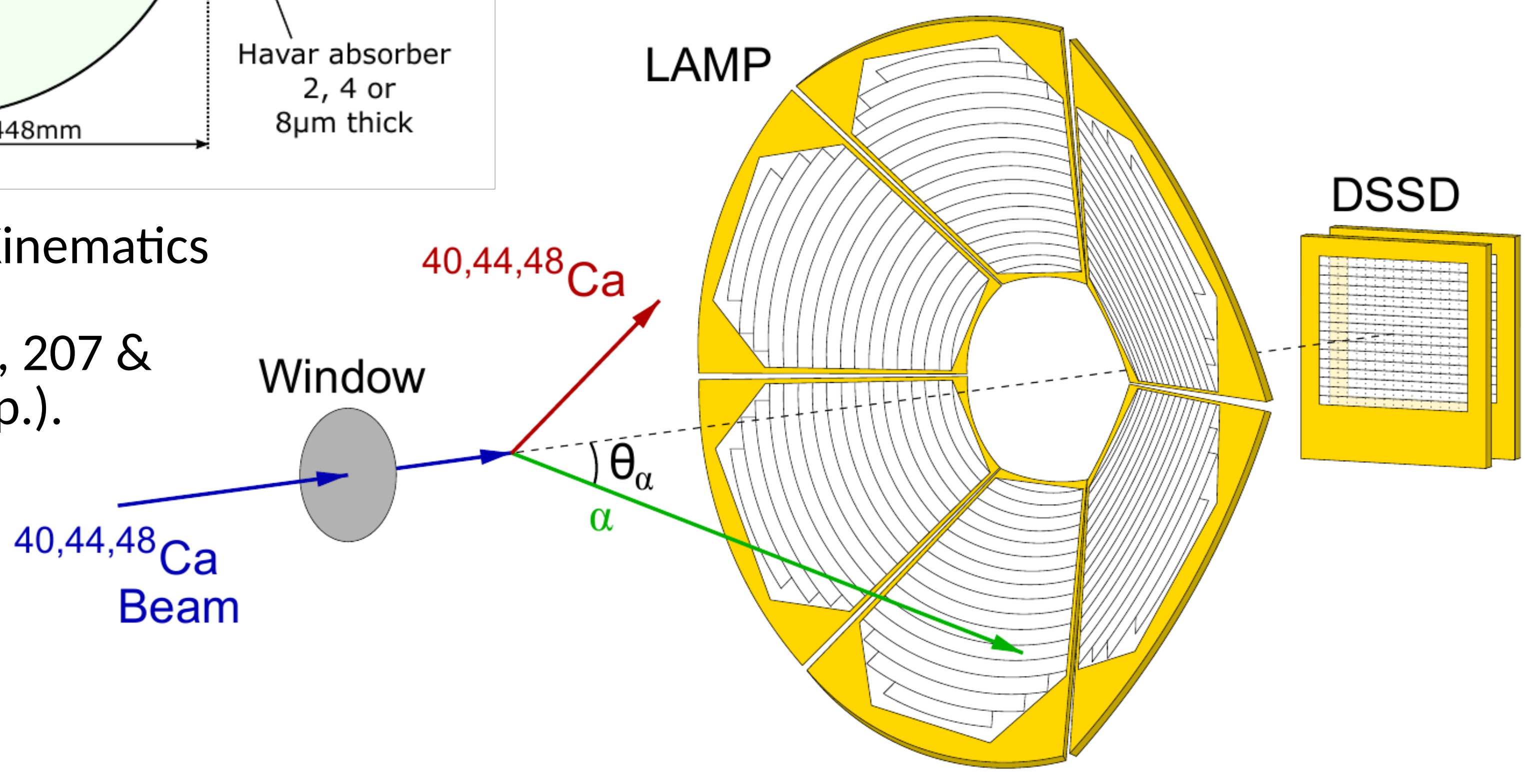
Resonant scattering – TTIK:



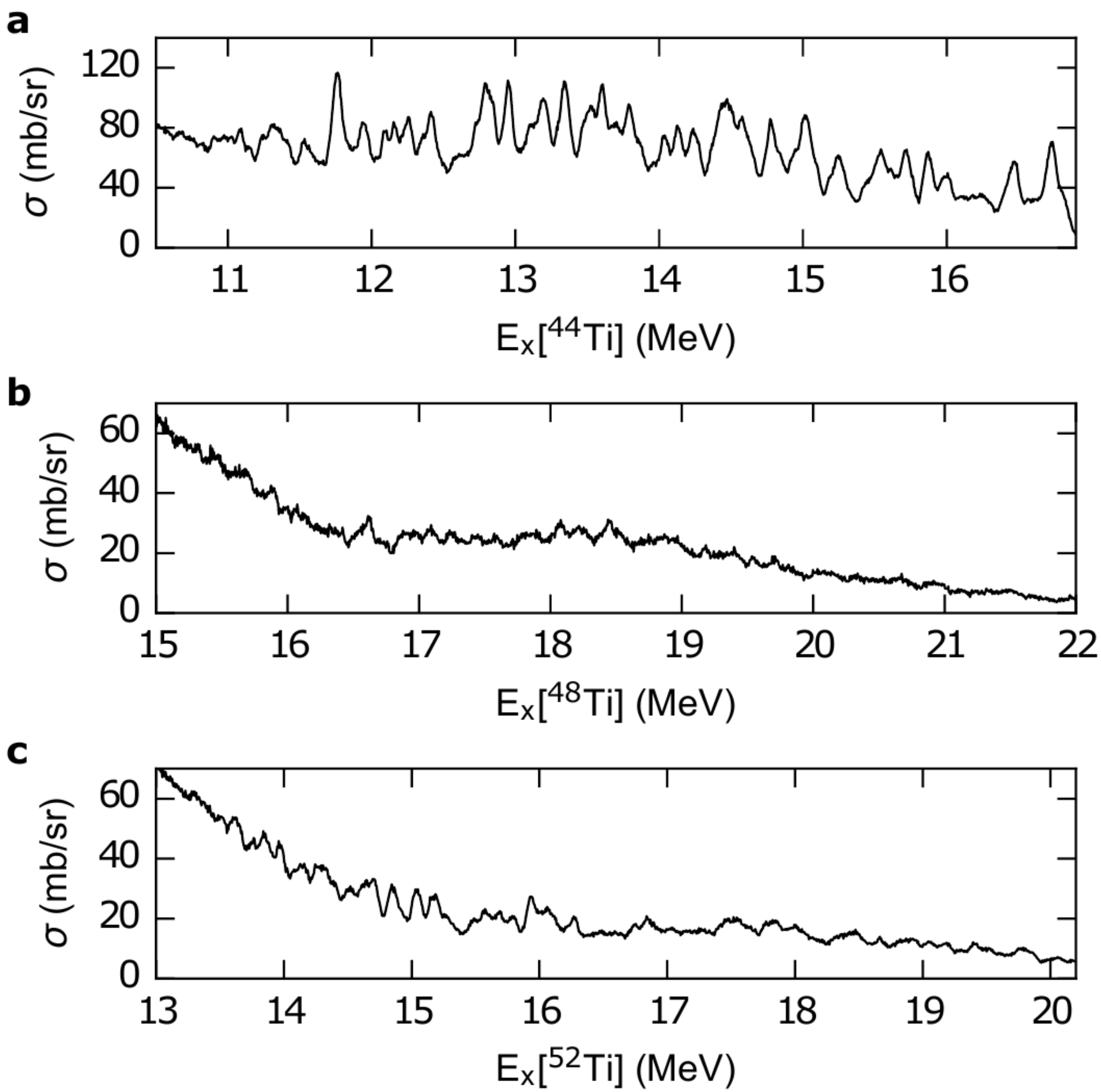
- Gas as target and energy-loss medium.
- Pressure tuned to stop beam before detector telescope.
- Smooth, continuous energy measurement
- Window introduces energy (i.e. position) uncertainty.
- 180° in COM – Rutherford scattering minimum.

Thick **T**arget **I**nverse **K**inematics

Beam energies of 180, 207 & 234 MeV (^{40,44,48}Ca resp.).



The search for signatures – experimental spectra



- Spectra from the zero-degree telescope, E_{res} = 45 keV.
- Alpha's identified and excitation energy reconstructed using energy loss correction.
- Data at large angles become smeared due to energy (position) uncertainty.
- Typically, an *R*-Matrix analysis would be performed.
- Difficult and time consuming even with data from several angles.

How to proceed?

The continuous wavelet transform (CWT)

The CWT provides a decomposition of the spectra into **a continuous range of scales δE.**
The wavelet transform, $W_\psi(E, \delta E)$, of a spectrum, $\sigma(E)$ $(d\sigma(E)/d\Omega)$, represents the contribution of a given scale to the spectrum at a specific energy, E, and is defined as

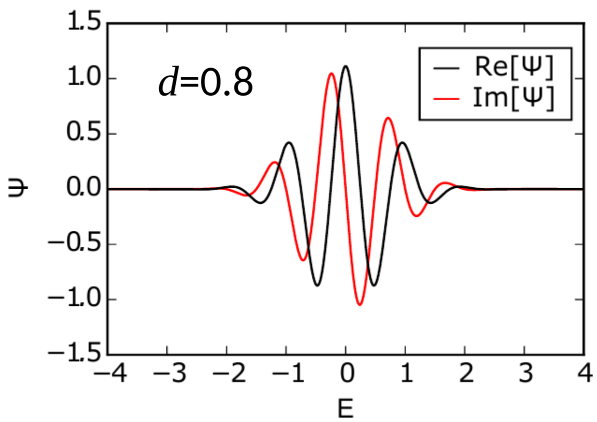
$$W_\Psi(E, \delta E) = \frac{1}{\sqrt{\delta E}} \int_{-\infty}^{\infty} \sigma(\epsilon) \Psi \left(\frac{\epsilon - E}{\delta E} \right) d\epsilon$$

where is a dummy variable used to facilitate the integration and $\Psi(E)$ is an appropriately chosen wavelet. The wavelet power spectrum $P_\psi(\delta E)$ represents the contribution of a given scale to the entire spectrum and is calculated by integrating $|W_\psi(E, \delta E)|^2$ over all E,

$$P_\Psi(\delta E) = \int_{-\infty}^{\infty} |W_\Psi(E, \delta E)|^2 \, dE \, .$$

In the following analysis the complex Morlet wavelet is used to characterise the periodic features in the spectrum. **This can be thought of as a windowed Fourier Transform,** and is defined as

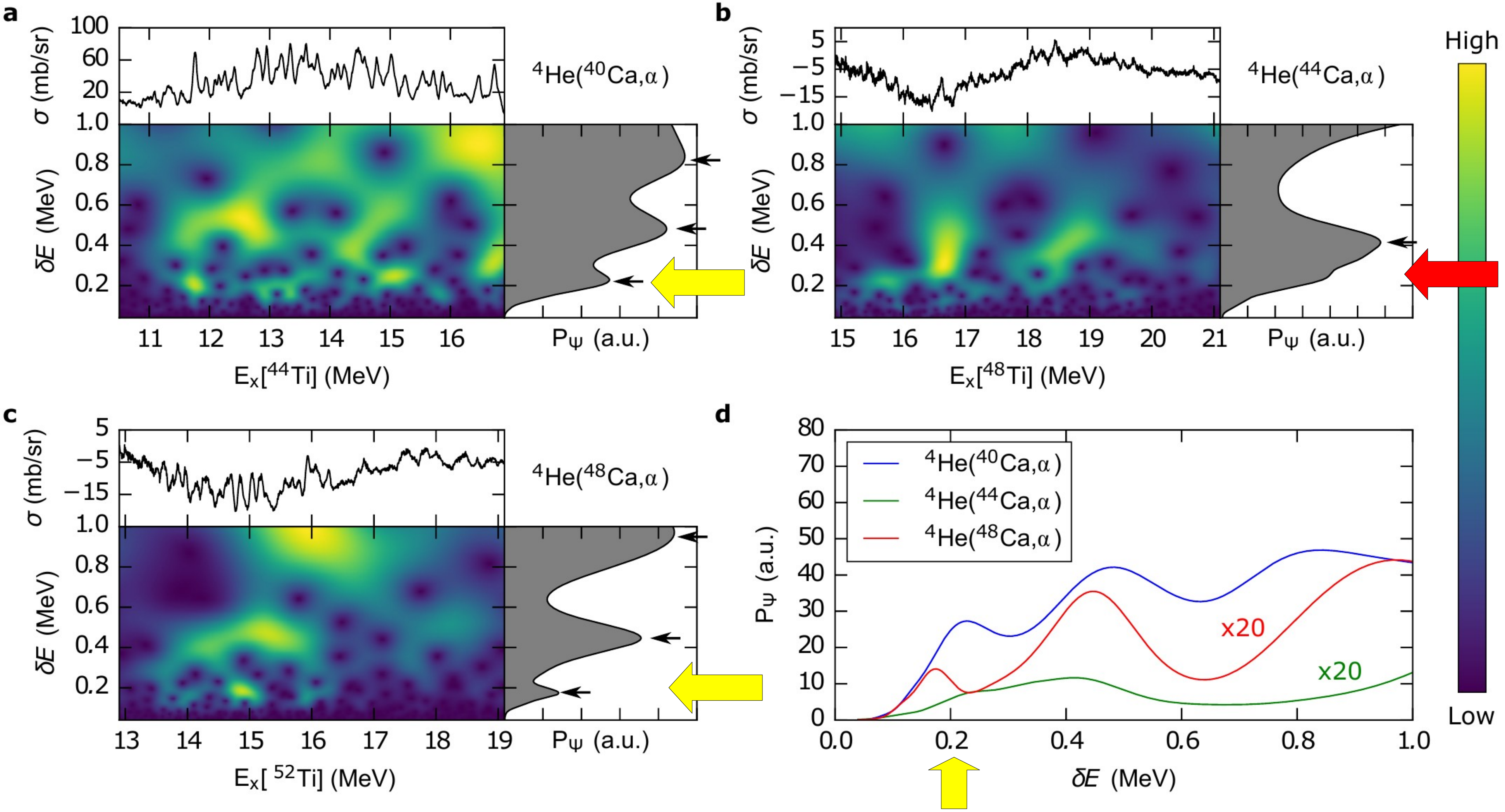
$$\Psi(E) = \left(d\sqrt{\pi}\right)^{1/2} \exp\left(-i2\pi E\right) \exp\left(-\frac{E}{2d^2}\right) ,$$



where d dictates the size of the Gaussian envelope, and in this work was chosen empirically to be 0.8.

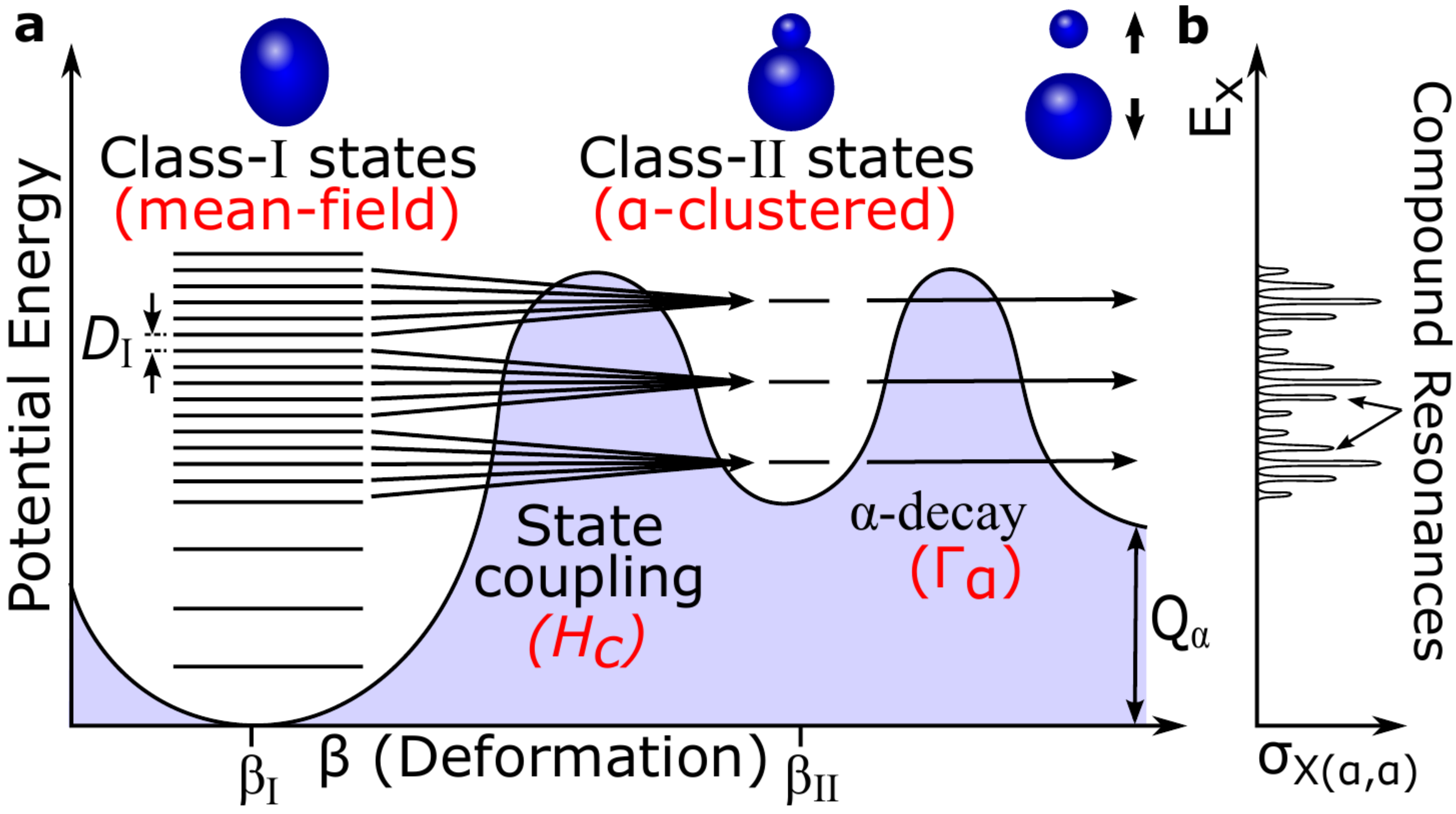
Complex Morlet wavelet: J.C. van den Berg, *Wavelets in Physics* Cambridge University Press (2004).

Spectrograms, power spectrum and signature



Characteristic scale δE~0.2 MeV arises because a set of fragmented α-clustered states all have a partially α-clustered structure similar to originating state → **consistently strong amplitude** and **<u>regular spacing</u>**. The class-I states have nearest neighbour spacing ($D^{I}_{J\pi}$) for same J^{π} that follows a Wigner distribution.

State coupling schematic



- (Deformed) alpha cluster states fragment due to coupling with mean-field states.
- The structure can be modelled using a double-humped fission barrier.

Adapted from Fp97-98 of R. Vandenbosch and J.R. Huizenga, Nuclear Fission, Academic Press (1973).

Parameters for simulating data

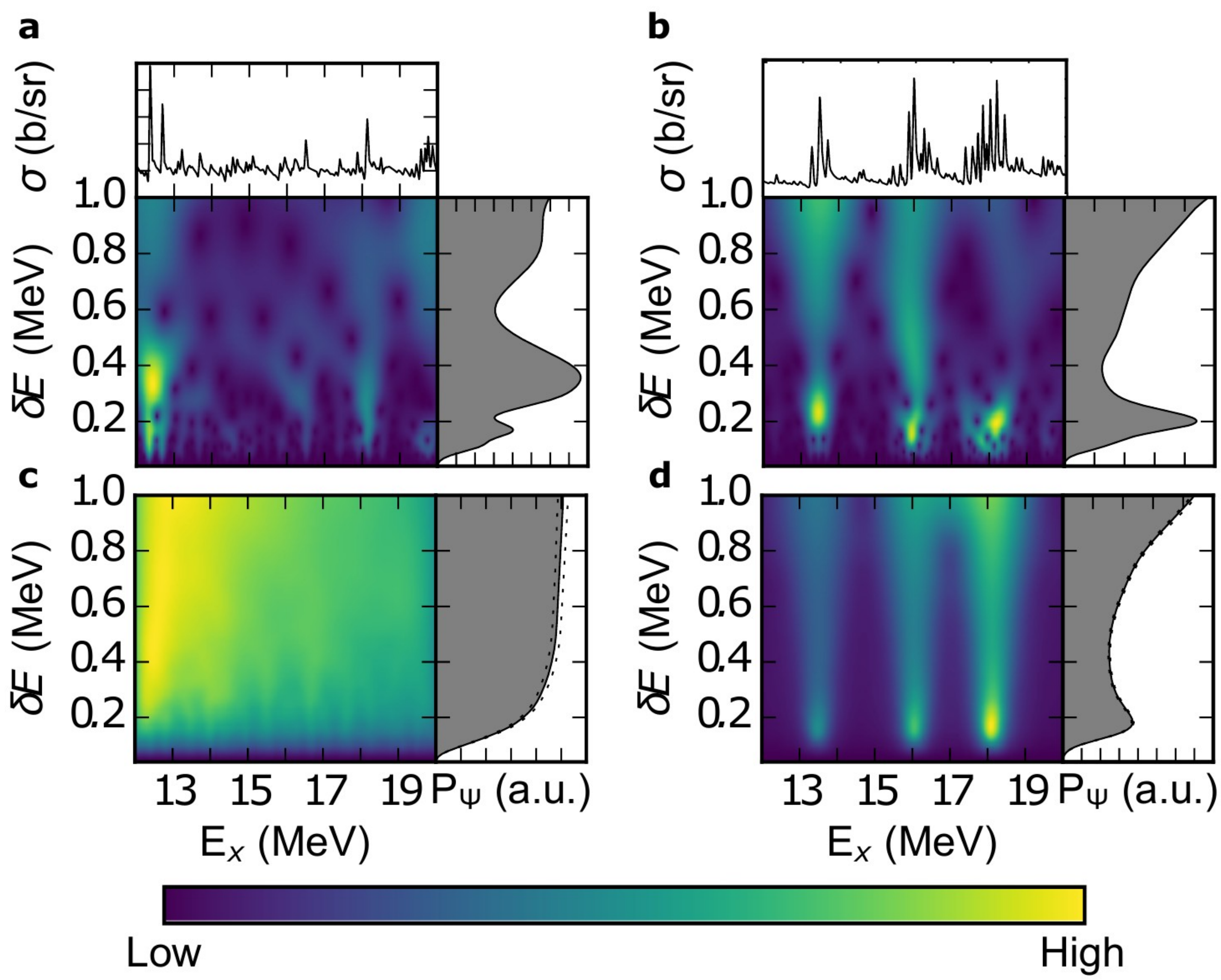
Class-I

$<D_{J\pi}{}^{I}>$	0.15 MeV	Expectation value for the class-I state nearest neighbour state spacing for states of the same spin and parity.
$<\gamma_{\alpha}{}^{I}>$	0.005 $MeV^{1/2}$	Alpha strength for class-I states.
$<\gamma_{\mu\neq\alpha}{}^{I}>$	0.01 $MeV^{1/2}$	Strength of other decay channels for class-I states.

Additionally for class-II

E^{II}	13.5, 16 &18 MeV	Energies of clustered states (class II).
$\gamma_{\alpha}{}^{II}$	0.1 $MeV^{1/2}$	Alpha strength of the cluster states.
H_c	0.1 MeV	Coupling constant between class I and class II states.

Mixing, fragmentation and simulations



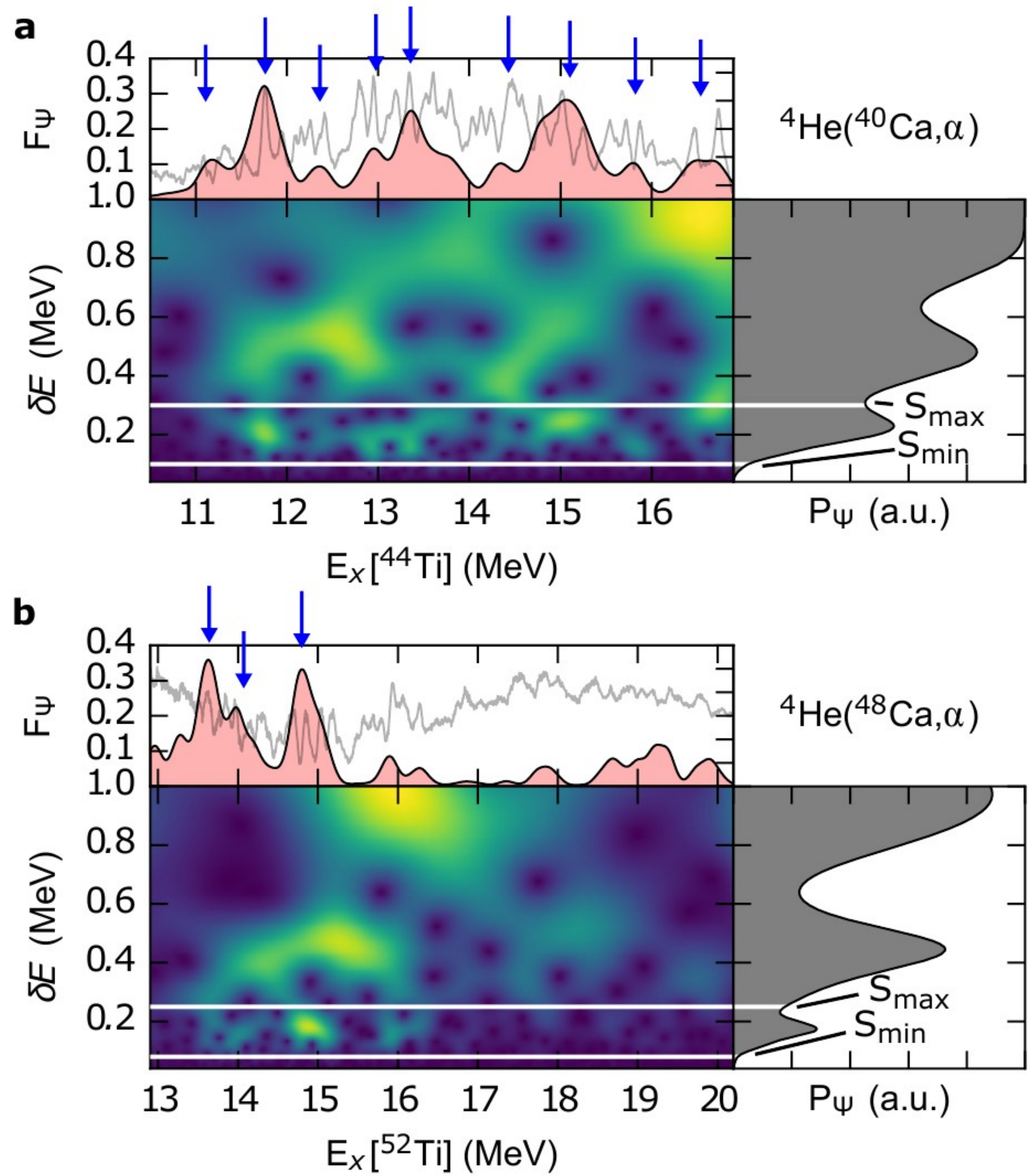
- Simulated spectrograms were created without (**a,c**) and with **(b,d)** coupling to class-II (alpha) states.
- Top: one iteration. Bottom: average over 500 spectrograms.

Extraction of alpha-clustered states

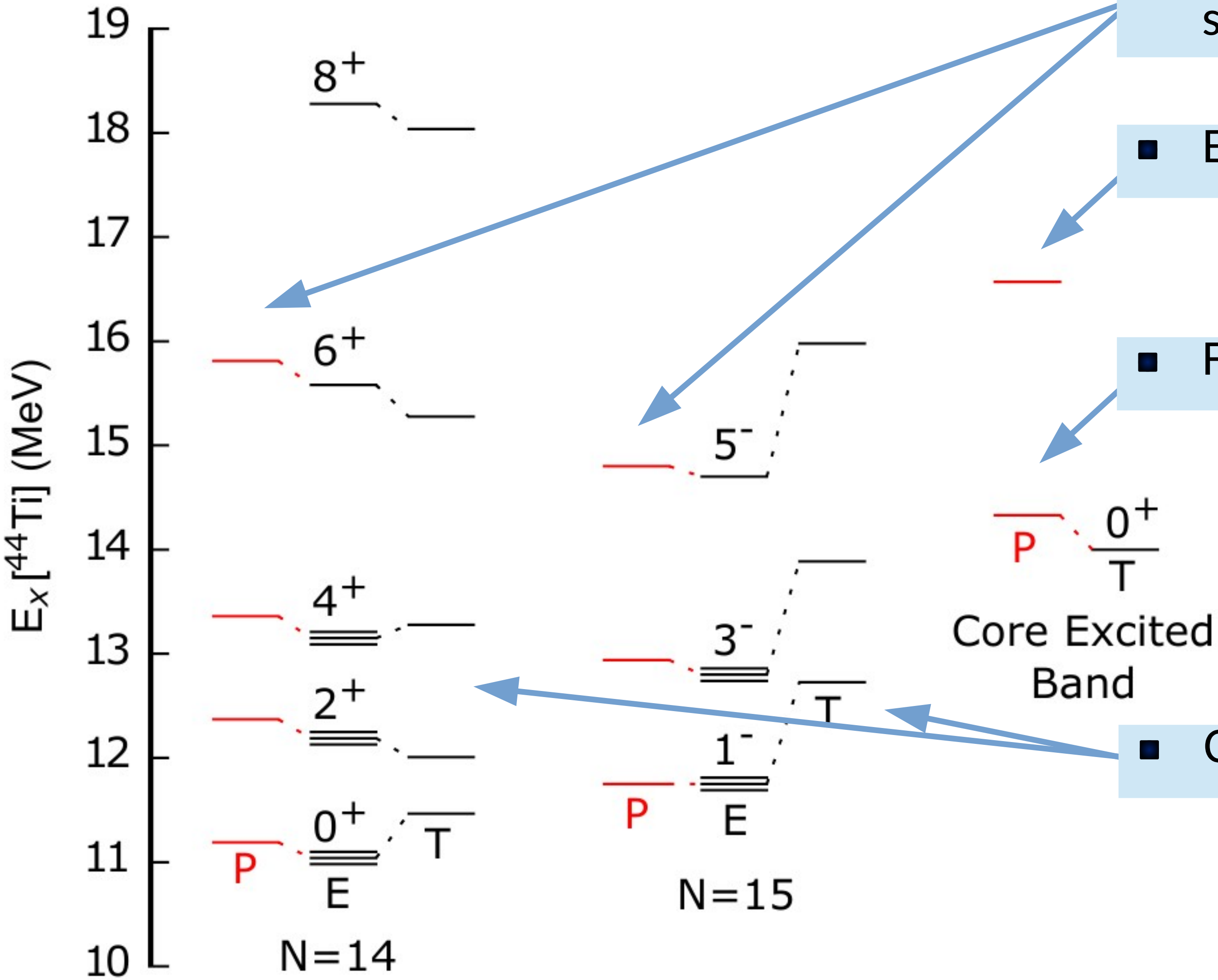
- How to extract the original class-II, alpha cluster state energies?
- Can use the 'hot-spots' to extract the alpha-cluster energies, for example, by the fraction of W_Ψ that originates from within the boundaries of the signature peak:

$$F_\Psi(E) = \frac{\int_{S_{min}}^{S_{max}} |W_\Psi(E,\delta E)|^2 d\,\delta E}{\int_0^\infty |W_\Psi(E,\delta E)|^2 d\,\delta E}\ .$$

- This is shown in the light red filled spectra opposite.



Cluster structure



- First observation of fragmented states.
- Experimental 'suggestion'!
- First observation.
- Confirmed.

Publication Phys. Rev. C Rapid Communication → appearing shortly.

P: present work, **T**: Theoretically predicted,
E: experimentally observed (fragmented if multiple lines)

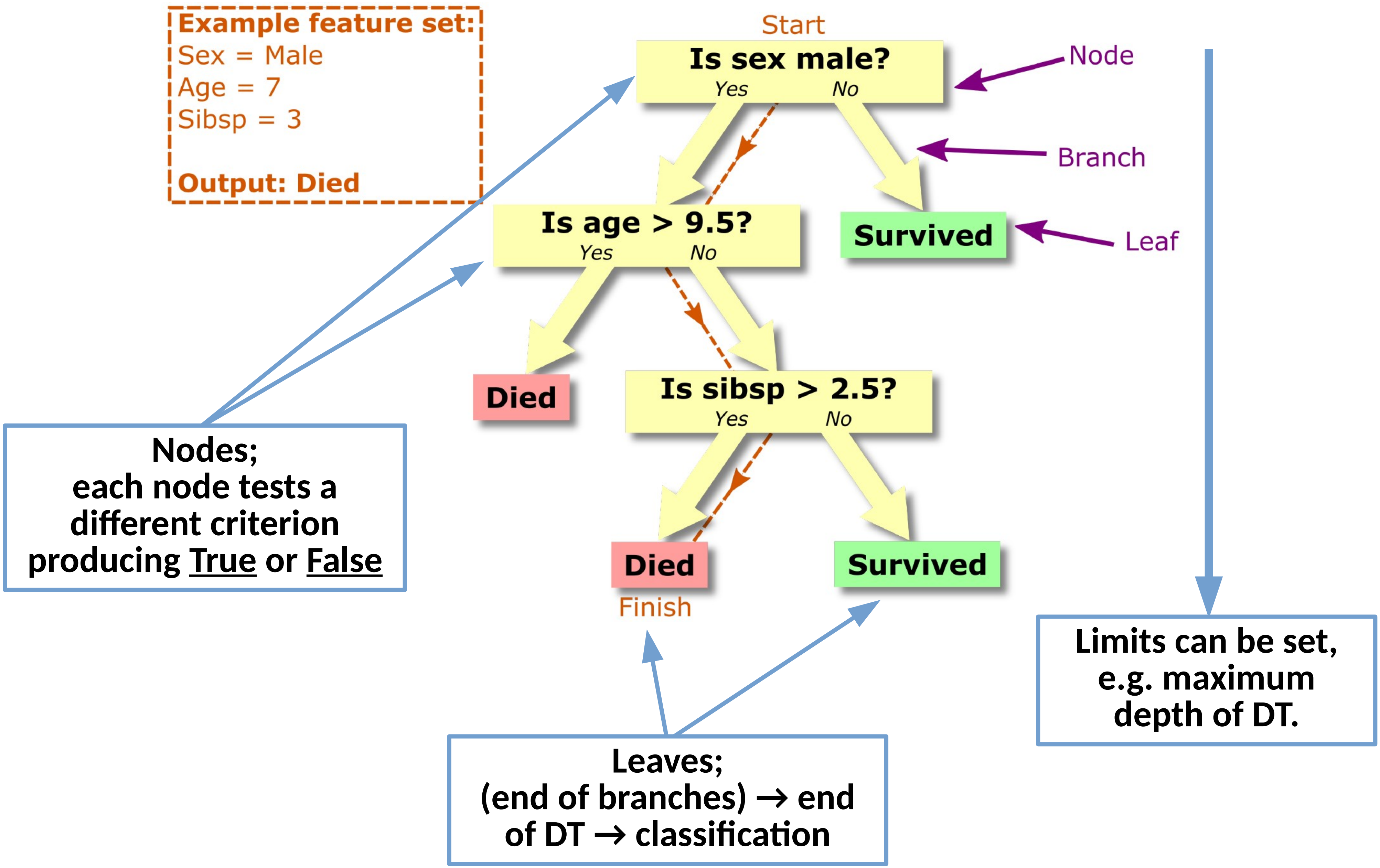
Figure based on Fig. 29 from : S. Ohkubo, *et al.*, Chapter 1 - Introduction, Progress of Theoretical Physics Supplement 132, 1 (1999) and T. Sakuda and S. Ohkubo, Chapter 4, Progress of Theoretical Physics Supplement 132, 103 (1999).

Uninteresting or interesting?

To answer the 'interesting' questions in physics it is often necessary to spend (a lot of) time answering many 'uninteresting' question, e.g. about the detector resolution, calibration *etc*. Such uninteresting questions often take most of the researcher's effort or time.

So, are we interested in the overall structure physics of a given nucleus or the detailed properties of every state?

Decision Tree (DT) example

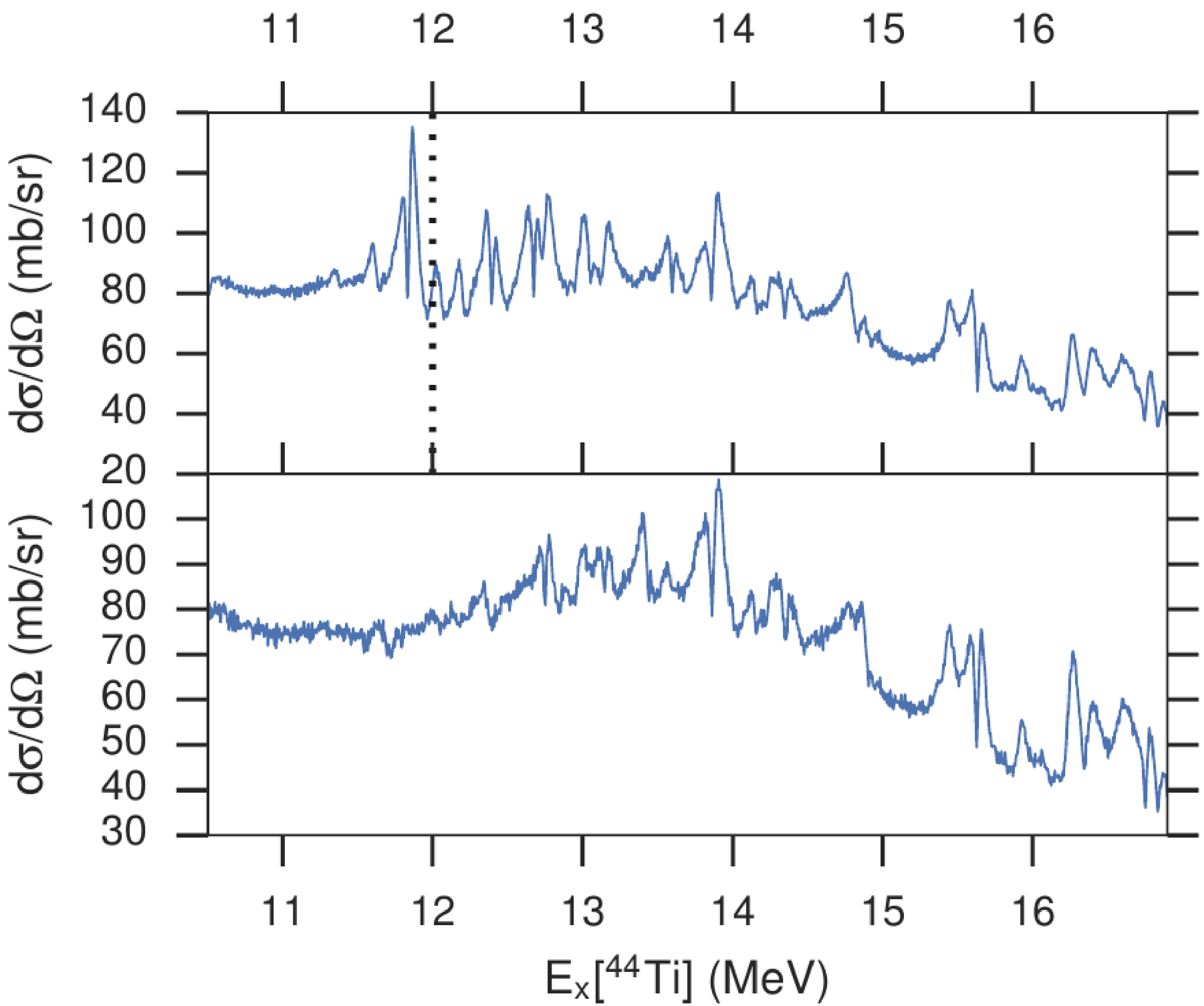


Random Forest (RF) machine learning

- Need to produce a Decision Tree that correctly classifies spectra.
- Maximum depth prevents over fitting the training data.
- Generate Decision Tree using a training data set comprising many ‘events’ for which the true classification is known, (e.g. clustered state is present or not).
- Random Forest technique trains many DTs on a random subset of the training data.
- Also, at each node the available features on which to make a decision are chosen randomly.
- Each DT makes an independent decision.
- The final classification is calculated from the fraction of all Decision Trees that give a particular classification.
- A predication threshold is used to make a definitive classification.
- A likelihood is returned (how likely the classification is to be correct).

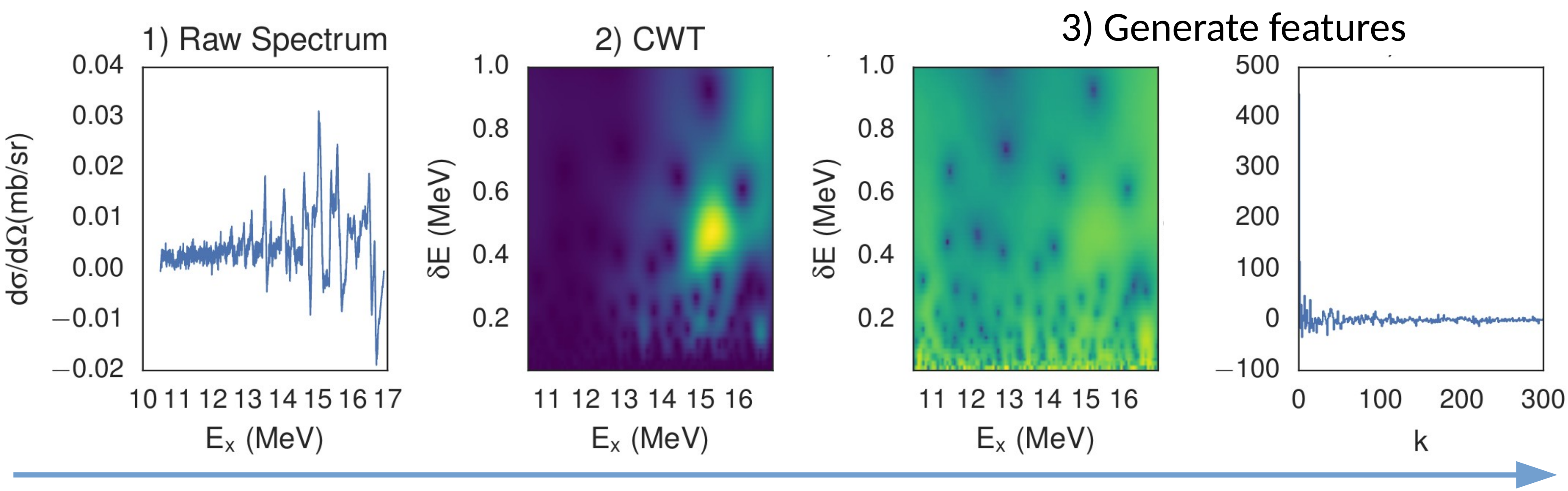
Machine learning – simulated training data

Simulation of a clustered spectrum and non-clustered spectrum.



Machine learning

- Use simulations to generate training data for a Random Forest Classifier (RFC) algorithm.
- Generate features (k) from wavelet spectrum.
- This approach uses many randomised decision trees to produce a more robust classification than is possible with a single tree.
- Each tree is randomised by training it on a random subset of the training data and at each node in the tree the optimal training criterion is chosen from a subset of the available features.
- After averaging over all the trees, this method gives a likelihood, once calibrated, that the spectrum is clustered, i.e. that the spectrum contains at least one alpha-clustered state.



Results

- Three RFCs produced, one each for ^{44}Ti, ^{48}Ti and ^{52}Ti.
- These were cross validated with classification accuracies of 76%, 77% and 79%.
- Sensitivities (True Positive Rates) of 77%, 76% and 79%.
- Dependence on chosen parameters explored.

RFC predicted clustering likelihoods using experimentally measured data (i.e. likelihood of containing at least 1 clustered state):

- $^{44}Ti \rightarrow 92\%$
- $^{48}Ti \rightarrow 41\%$
- $^{52}Ti \rightarrow 83\%$

The most important feature represents whether or not the average resonant amplitude increases or decreases throughout the spectrum. *In other words having large resonances at low excitation energies is indicative of alpha clustered doorway states.*

Back to the future

- Continuous Wavelet Transform use to identify the signature of (fragmented) alpha cluster states.
- Resonant scattering with TTIK spectra can be more easily analysed.
- Fragmented spectra can be generated using mixing parameters to mean-field states.
- Machine learning used to extract alpha-clustering.
- Technique is effective despite being relatively unsophisticated. Improvements might be obtained using convolutional neutral networks.

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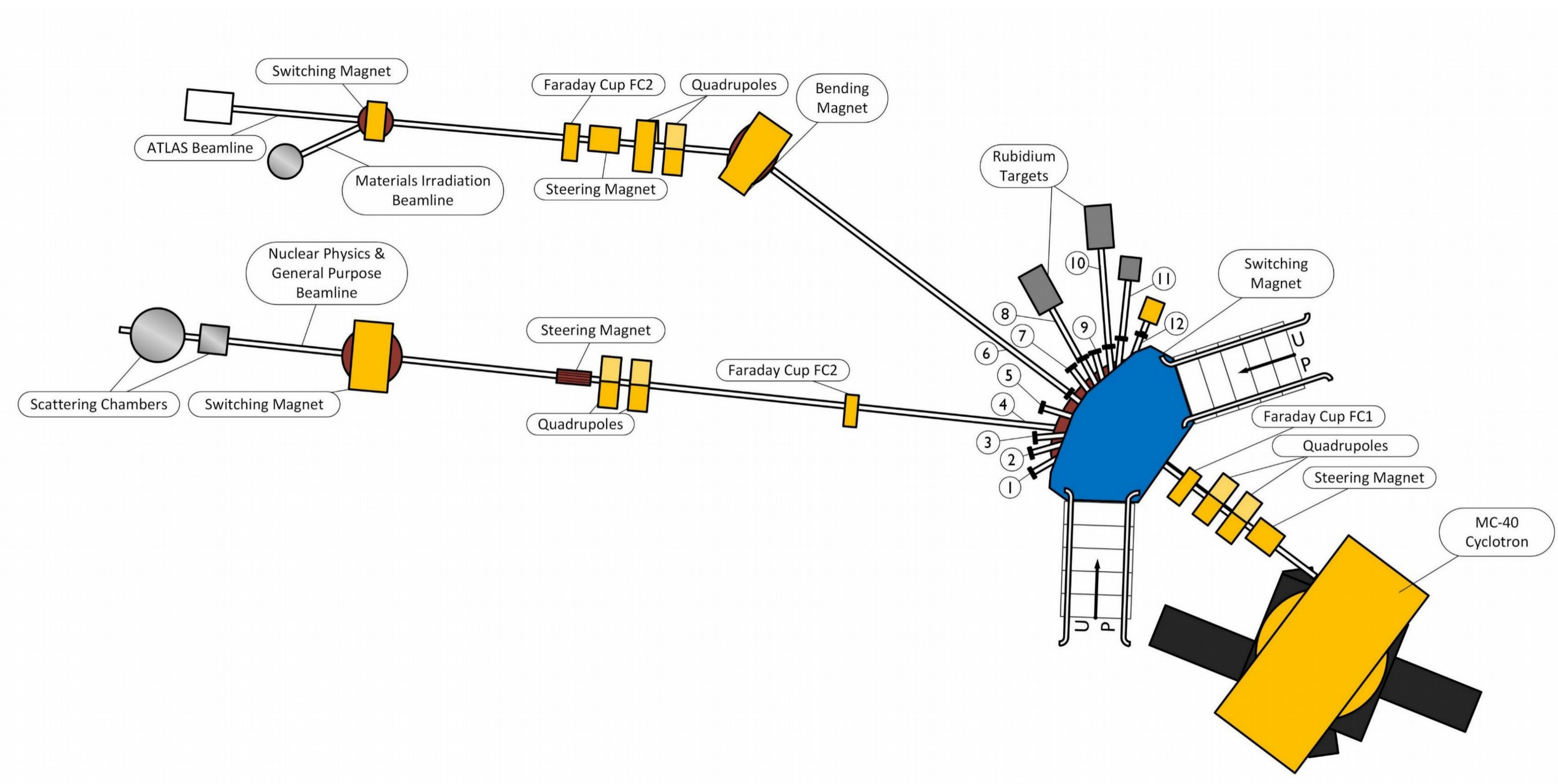
Thanks for your attention.

Birmingham in the sunshine

The tallest free-standing clock tower in the world.

Birmingham MC40 beam-line orientation



Birmingham MC40 beam lines

MC40 cyclotron (2004 -) In 2005 we added a 12-way switching magnet (blue) [ex Vivitron, Strasbourg, France]