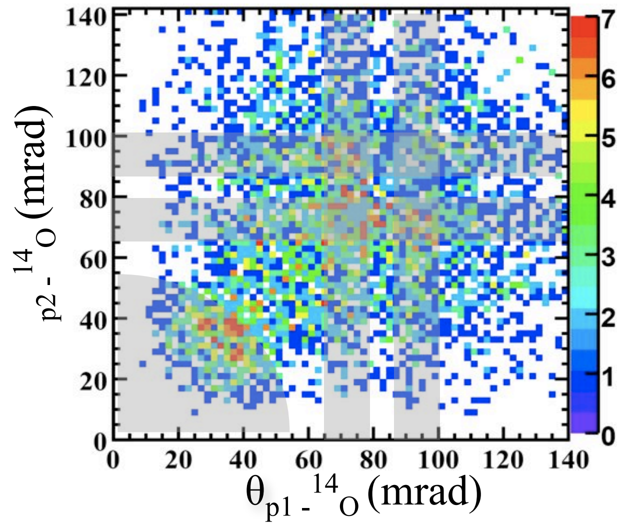
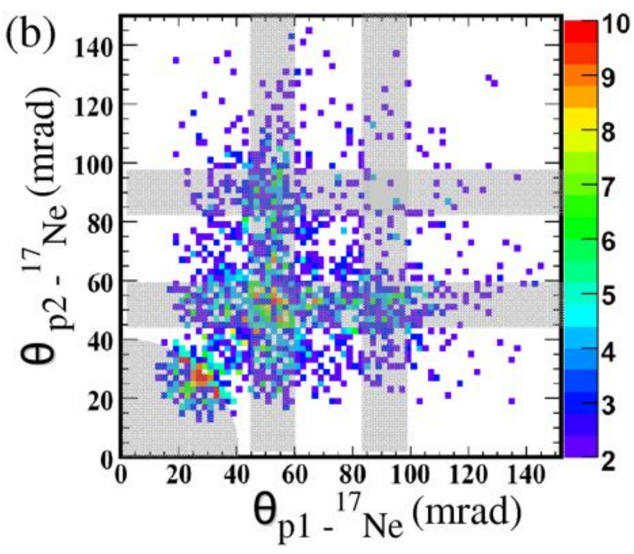
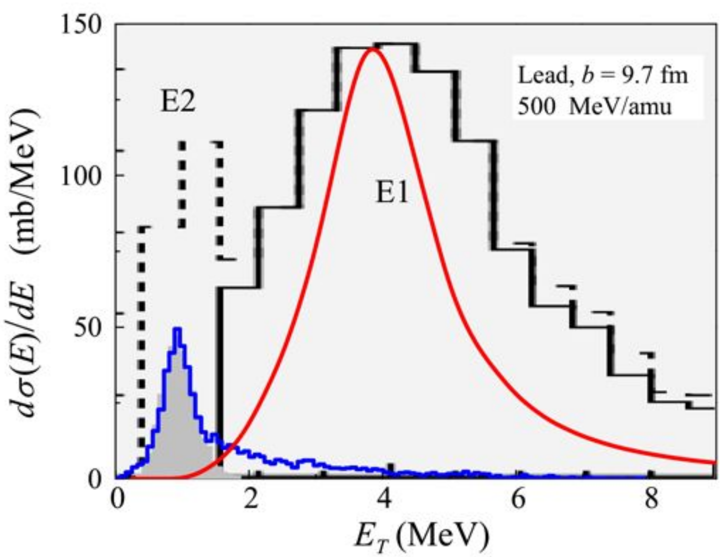


p2 - 14O (mrad)
θp1 - 14O (mrad)

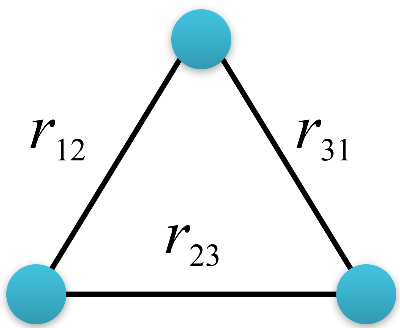


(b)
θp2 - 17Ne (mrad)
θp1 - 17Ne (mrad)



Lead, b = 9.7 fm
500 MeV/amu
E2
E1
dσ(E)/dE (mb/MeV)
ET (MeV)

	Two-body	Three-body
Discrete	$\sim A\, e^{-kr}/r$	$\sim A_3\, e^{-\kappa\rho}/\rho^{5/2} + \sum_{i>j} A_{ij}\, e^{-k_{ij} r_{ij}}/r_{ij}\; e^{-k_k r_k}/r_k$
Continuum	$\sim A(\theta) e^{ikr}/r$	$\sim A_3\, e^{i\kappa\rho}/\rho^{5/2} + \sum_{i>j} A_{ij}\, e^{i k_{ij} r_{ij}}/r_{ij}\; e^{i k_k r_k}/r_k$



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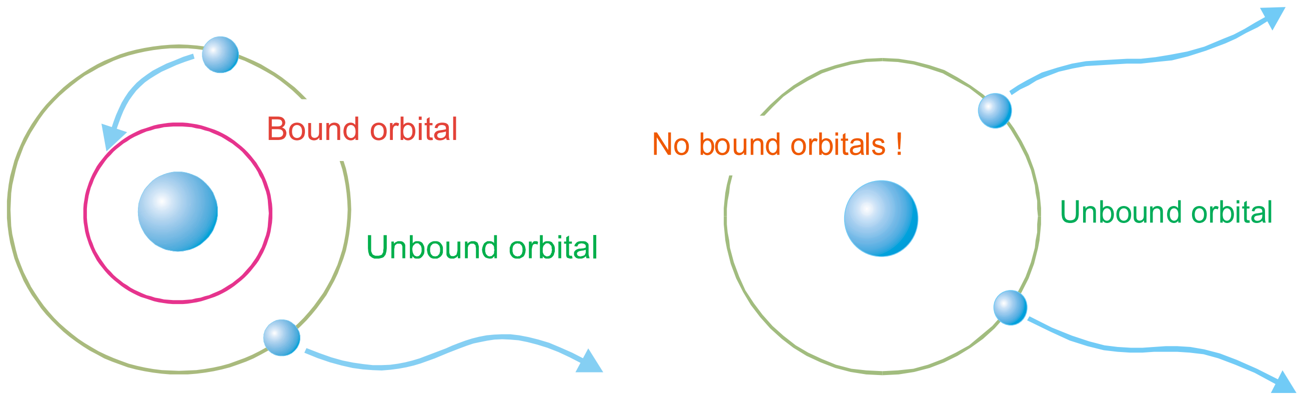
$$\rho^2 = (M M_n)^{-1} \sum_{i>j} M_i M_j r_{ij}^{\,2}$$

- A_{ij} - s
- **True three-body** system - if all A_{ij}
- A_3 -

Dynamics of the processes can not be reduced to the two-body dynamics and studies should be done using methods of the few-body theory

Predicted by V.I. Goldansky in 1960
Discovered at GSI in 2002

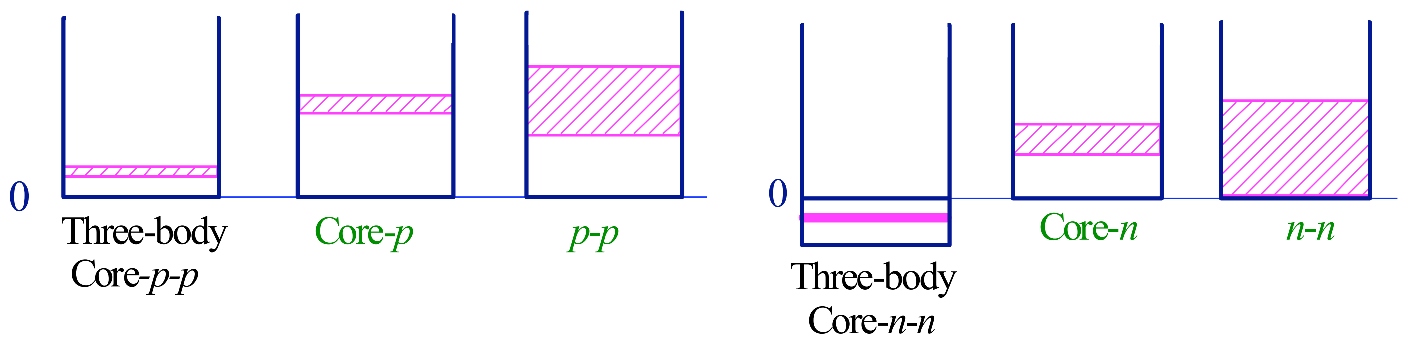


Classical case: one particle emission is always possible

Quantum mechanical case: it could be that both particles should be emitted simultaneously

True three-body decay

Borromean three-body ground state



- **True 2p decay** has different energy systematic compared to 1p
- Specific correlations among decay products
- True two-proton radioactivity is a "substitute" for Borromean halo nuclei when we move from neutron to proton dripline:

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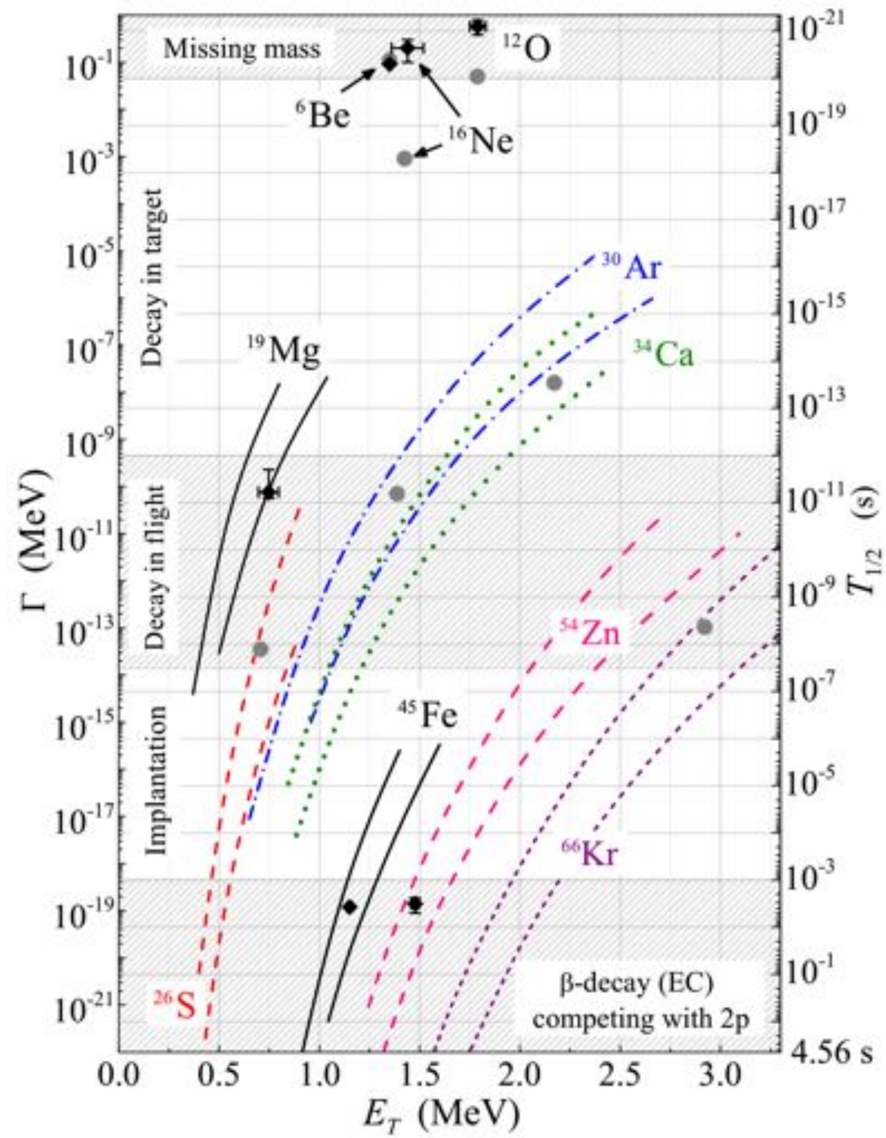
L.V. Grigorenko, R.C. Johnson, I.G. Mukha, I.J. Thompson, M.V. Zhukov, PRL 85 (2000) 22.

$$\left(\hat{H} - E_T + i\Gamma/2\right)\Psi^{(+)}(\rho,\Omega_\rho) = 0$$

Coulomb three-body problem is not tractable in general case: the exact analytical boundary conditions are not known

$$\Gamma = \frac{j(\rho_{\max})}{N(\rho_{box})} = \frac{\mathrm{Im}\int d\Omega_\rho\, \Psi^{(+)\dagger}\rho^{5/2}\frac{d}{d\rho}\rho^{5/2}\Psi^{(+)}\Big|_{\rho_{\max}}}{M\int d\Omega_\rho \int_0^{\rho_{box}} d\rho\, \rho^5 \left|\Psi^{(+)}\right|^2}$$

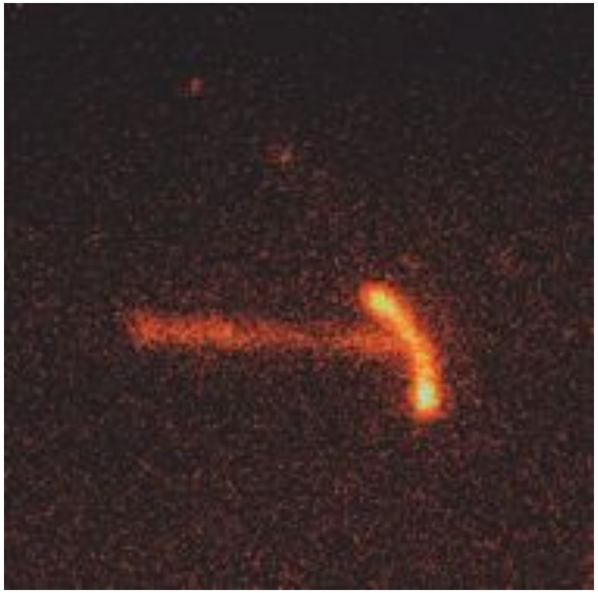
Typical precision: stable solution for $\Gamma/E_T > 10^{-30}$

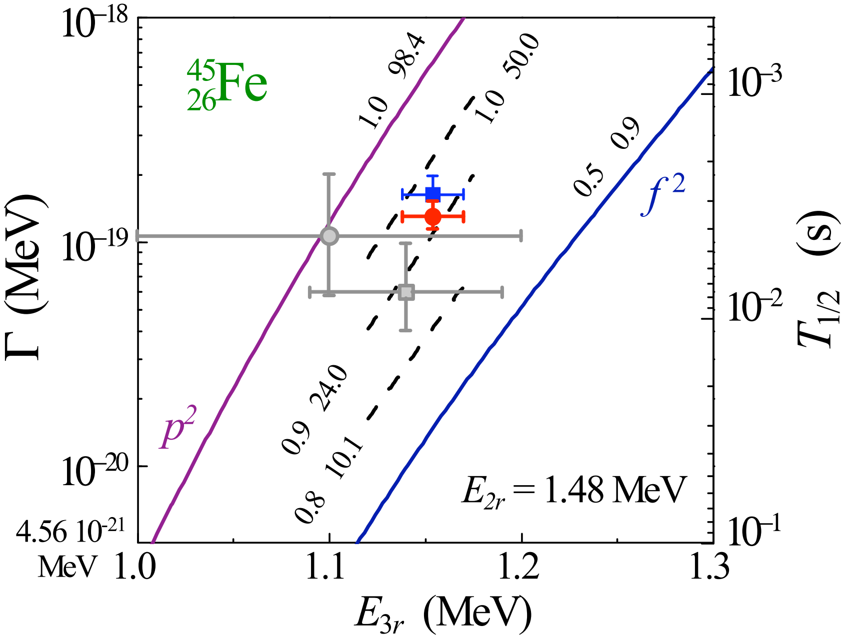


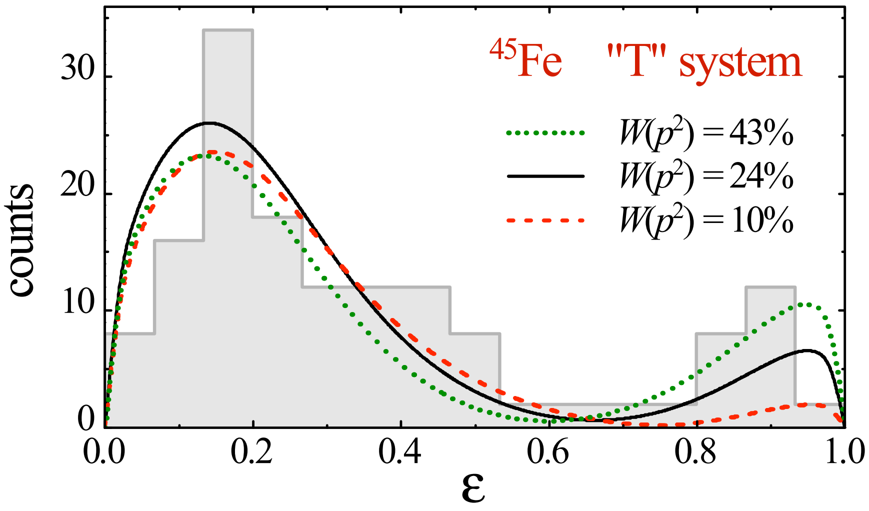
- Best studied case of 2p radioactivity
- Rapid improvement of data in the recent years
- Special design Optical TPC → nuclear physics "live video" Miernik et al., PRL 99 (2007) 192501

$$\Gamma_{2p} = 1.3^{+0.22}_{-0.16} \times 10^{-19} \quad \text{MeV} \quad T_{1/2}(2p) = 3.5(5) \quad \text{ms}$$

- Complete kinematics reconstructed, both lifetime and correlations available from experiment
- L.Grigorenko et al., PLB 677 (2009) 30
- Both lifetime and correlations provide $W(p^2) \sim 30\%$







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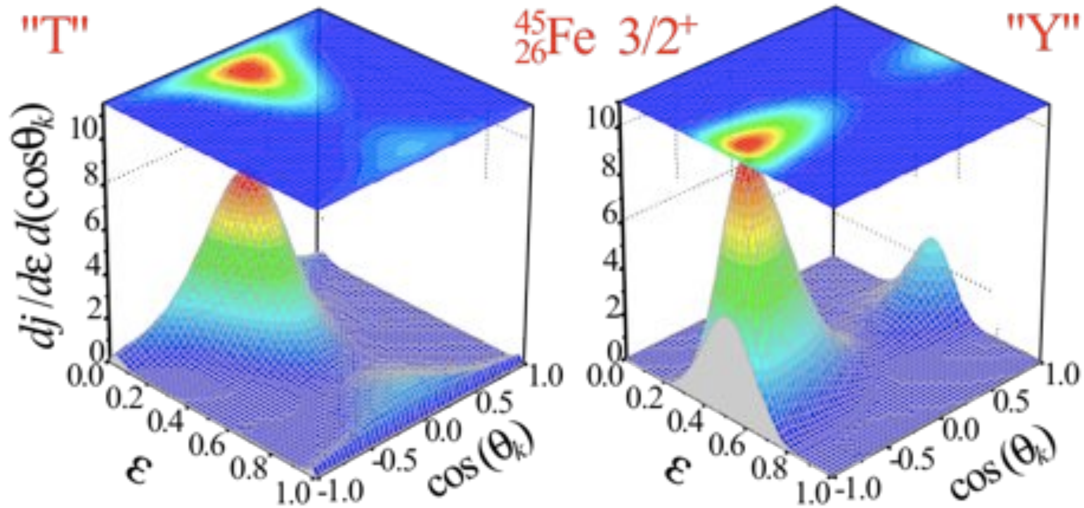
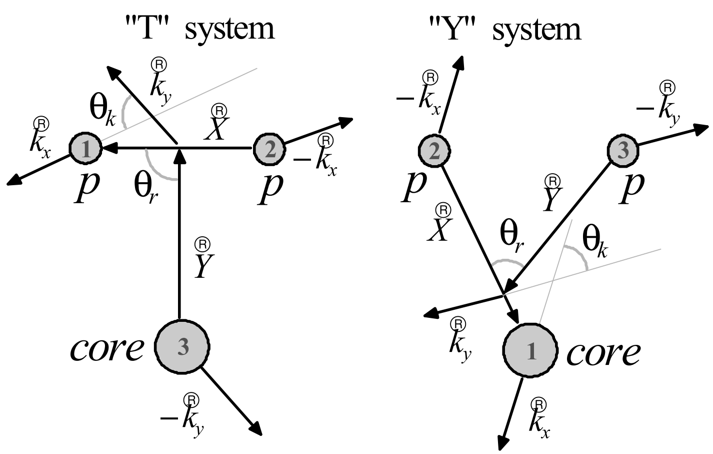
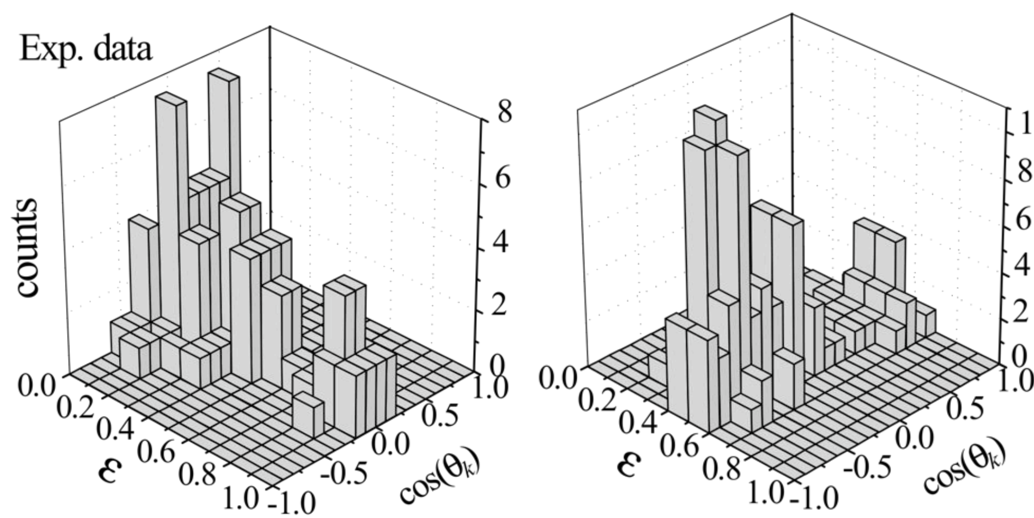
$J < 1$ –

$\varepsilon = E_x / E_T \qquad \cos(\theta_k) = (\mathbf{k}_x, \mathbf{k}_y)/k_x k_y$





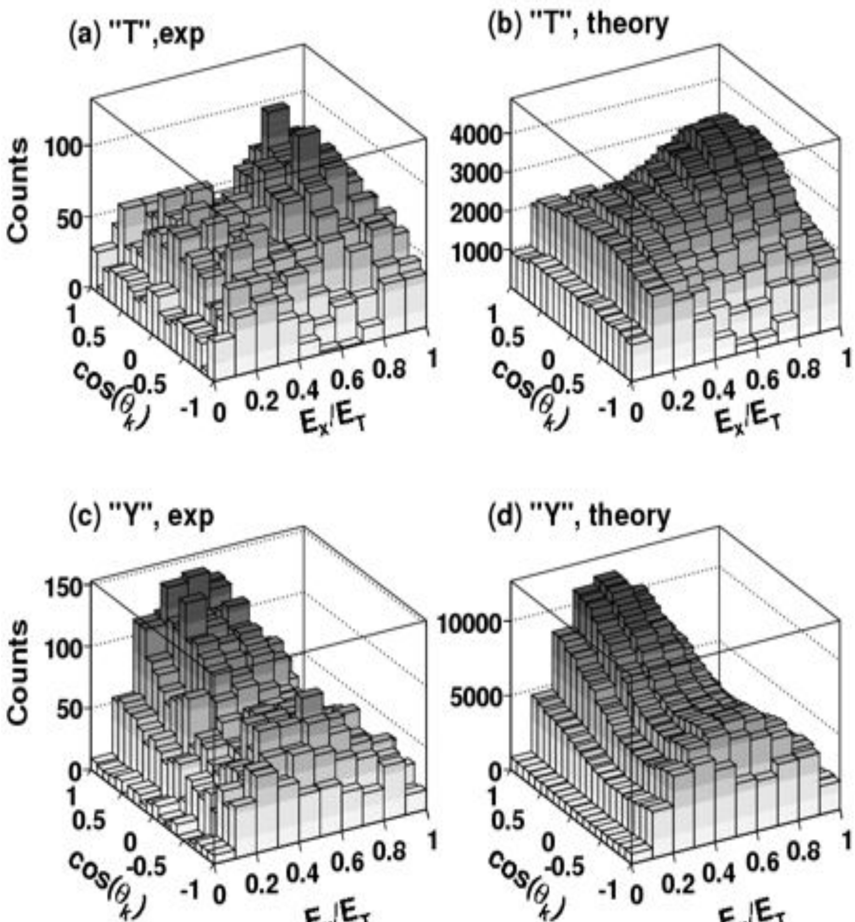


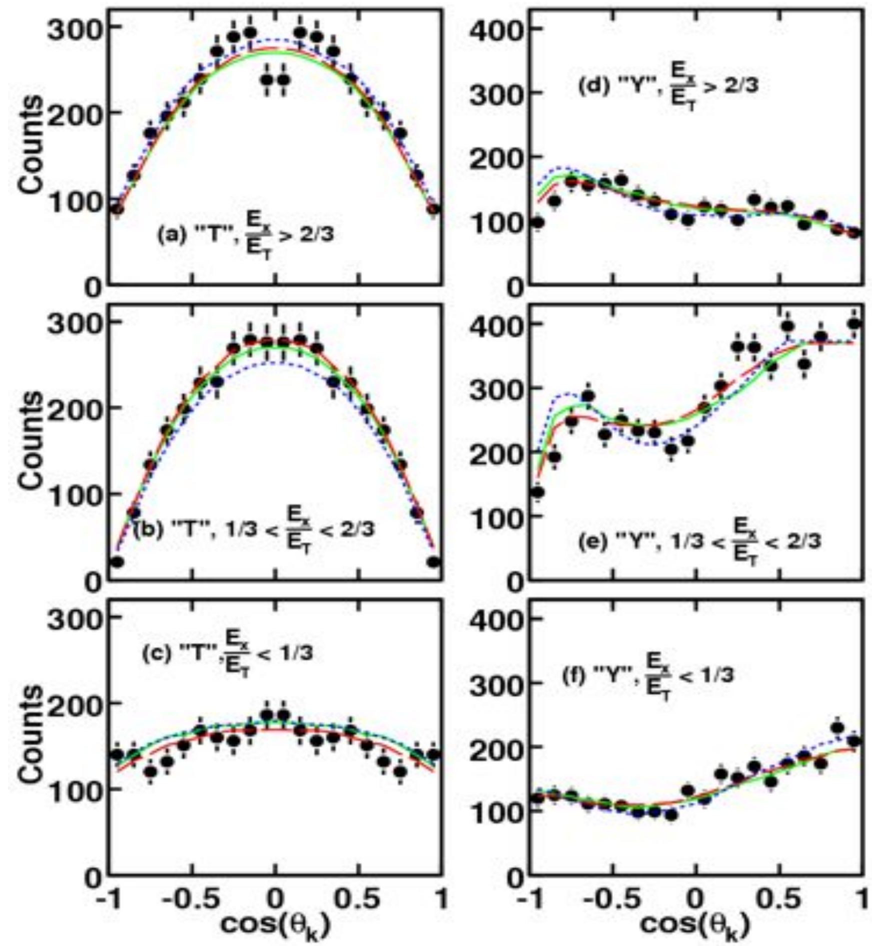
Experiment: R. Charity and coworkers,

Texas A&M $^{10}Be(p,n)^{10}C^*$ $^{10}C^* \rightarrow \alpha + {}^6Be$

L.Grigorenko et al., PLB 677 (2009) 30.

L.Grigorenko et al., PRC 80 (2009) 034602.





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Two-proton radioactivity and three-body decay

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Dynamics of the processes can not be reduced to the two-body dynamics and studies should be done using methods of the few-body theory

Theoretical dreams. What about reality?

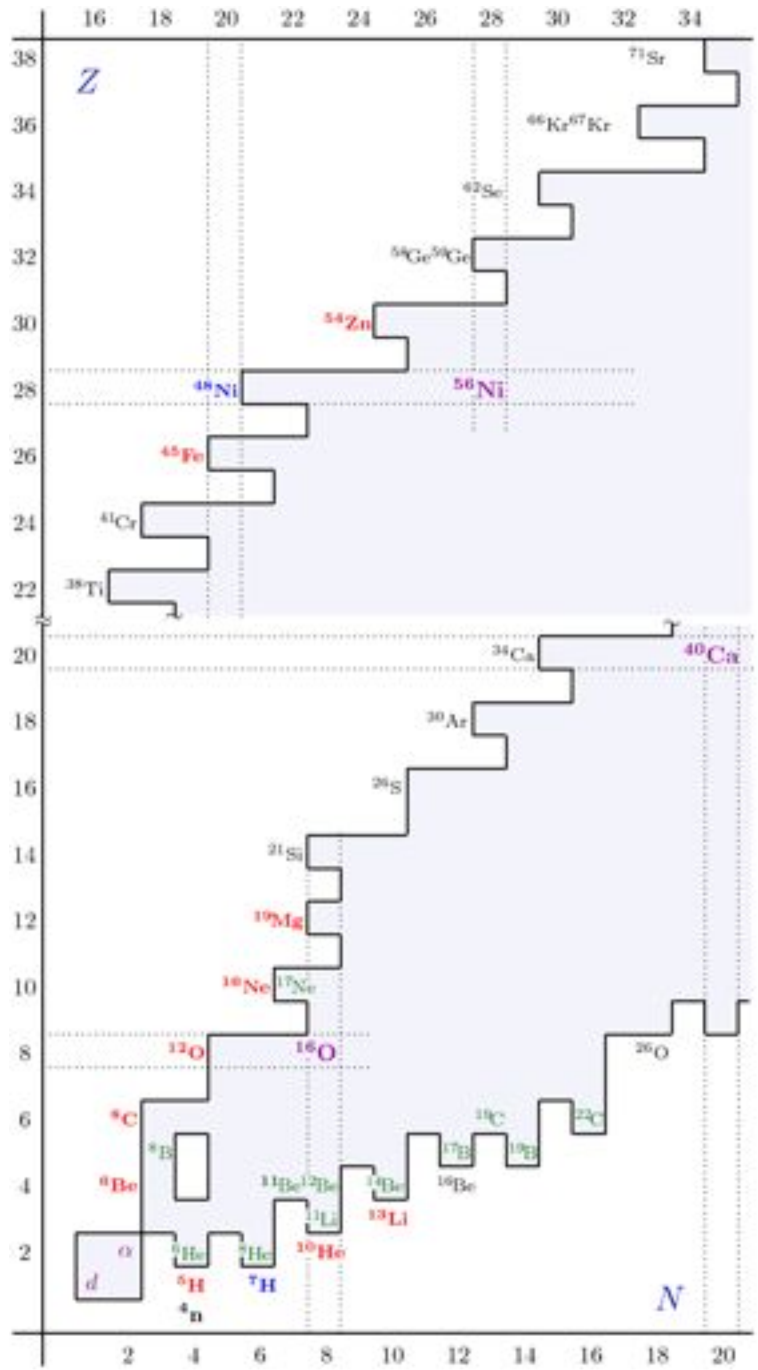
- Red – true 2p/2n emitters studied
- Green – halo systems
- Black – **nothing** is known

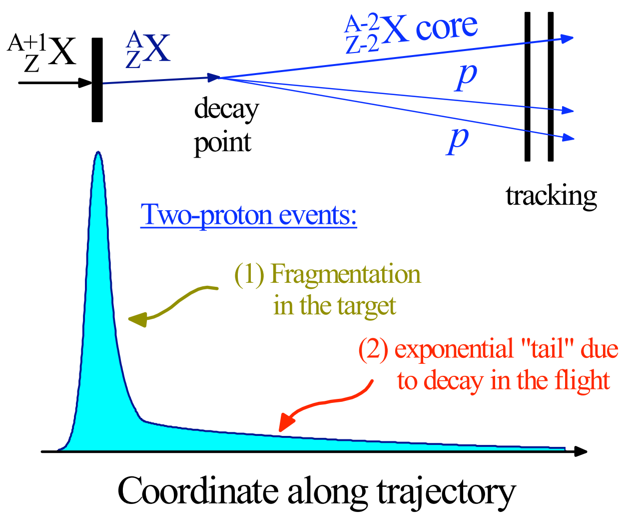
- Every second nucleus beyond the proton dripline is true 2p emitter

- ^{7}H and ^{8}C are four neutron emitters. The candidates are ^{28}O and ^{29}Si.
- Two-neutron g.s. emission in ^{10}He and ^{13}Li studied recently at GSI
- True 2p emitters: ^{6}Be, ^{12}O, ^{16}Ne, ^{19}Mg, ^{45}Fe, ^{54}Zn.
- Discovery of ^{19}Mg and most recent data on ^{16}Ne are from GSI

Experiment S388 “Two-proton decay of ^{30}Ar and one-proton decays of ^{69}Br, ^{73}Rb” is preliminary scheduled for May 2011

- It is probable that in the first instance the 2p decays of ^{26}S, ^{30}Ar and maybe ^{34}Ca will be studied

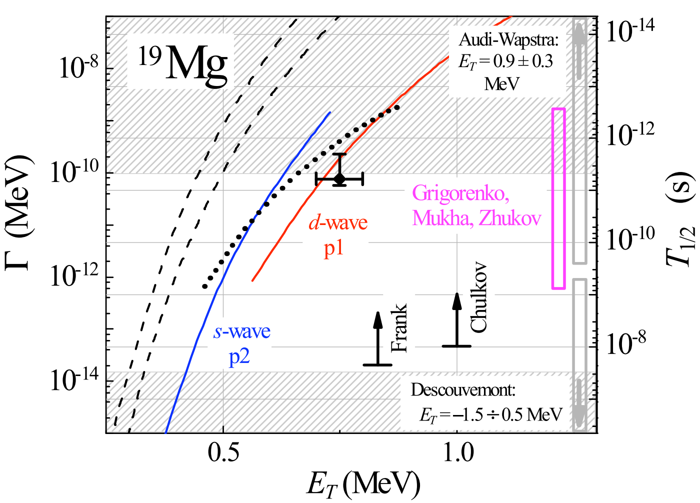


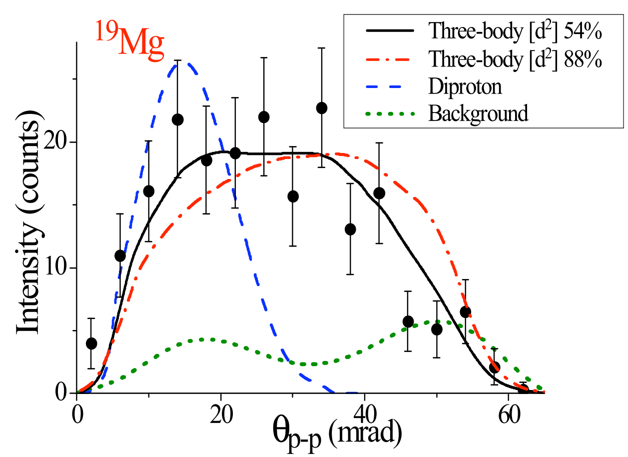


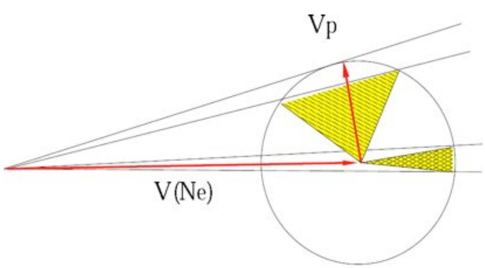
Lifetime, decay energy, projected correlations are obtained all in one run for several systems!

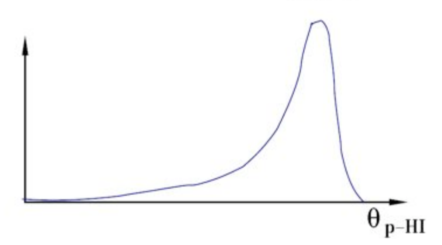
Ideal for RIB experiments with short-living products:

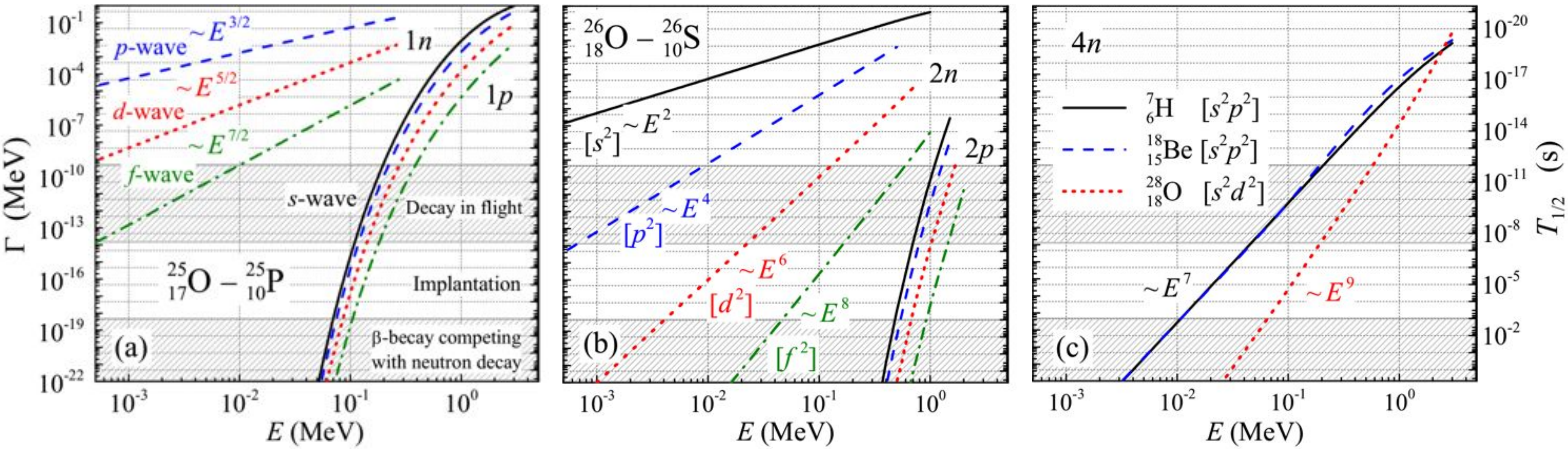
- Very thick target
- Low intensity and cocktail beams
- Several experiments in one run
- Very precise resonance parameters





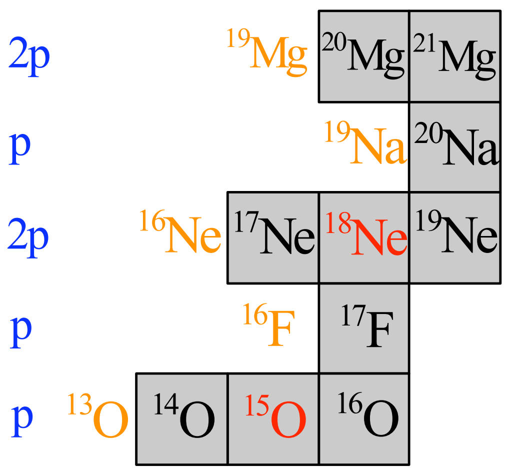


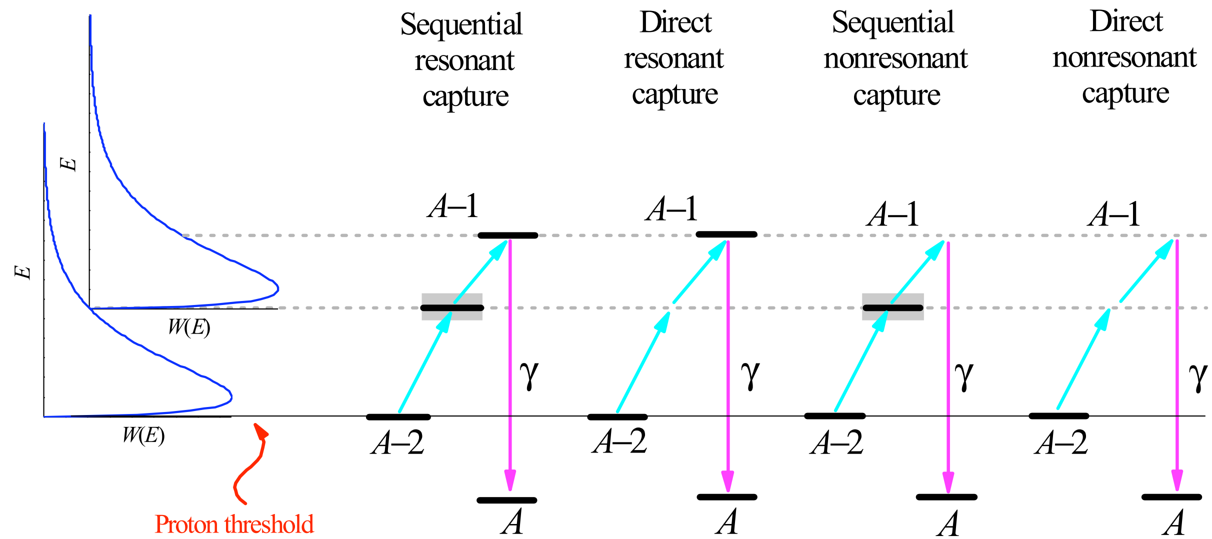




- Two-proton radioactivity is the long awaited and the most recently found mode of the radioactive decay. Can neutron radioactivity exist?
- Estimates: **one-neutron** radioactivity is highly unlikely.
- There are additional effective few-body “centrifugal” barriers making few-body emission relatively slower.
- Long-living **Two-neutron** decay and moreover **four-neutron** decay states are reasonably probable.

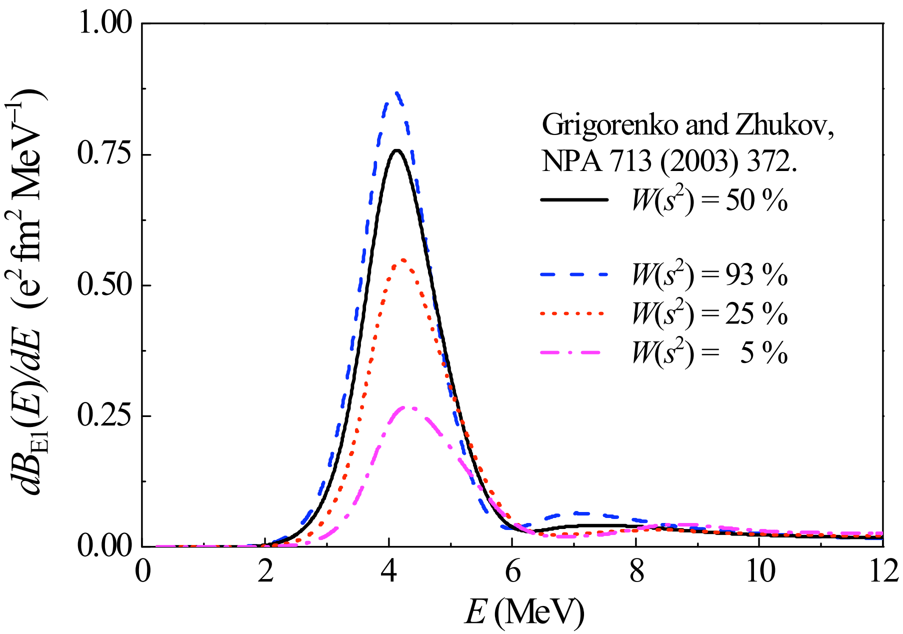
It is proposed at GSI to develop neutron tracking technique (in analogy with microstrip proton tracking) having in mind narrow neutron resonances and 2n radioactivity search.

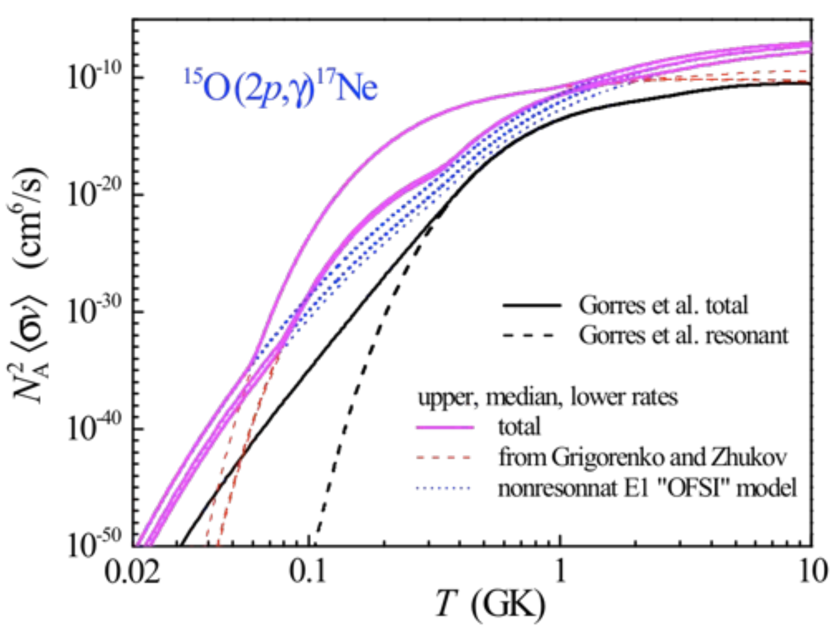




- rp-process at high temperature and density.
- Could be important in the regions of nuclear chart, where there are “ridges” connected with paring and intermediate system is not nuclear stable. Analogy with true 2p emission.
- ^{15}O, ^{18}Ne, ^{38}Ca : J.Gorres, M.Wiescher, and F.-K.Thielemann, PRC **51** (1995) 392.
- ^{68}Se, ^{72}Kr, … ,^{96}Cd : H.Schatz et al., Phys. Rep. **294** (1998) 167.
- Famous $\alpha+\alpha+\alpha \rightarrow {}^{12}\mathrm{C}+\gamma$ capture process belongs to this class also.

- Soft dipole mode: fragmentation of the GDR in systems with spatially extended density (haloes, skins).
- Existence of “soft E1” mode now established in neutron-rich nuclei (“pigmy” dipole resonance in heavy systems).
- L.V.Grigorenko, K.Langanke, N.B.Shul’gina, M.V.Zhukov, Phys. Lett. **B641** (2006) 254.
- Possibility of “soft E1” in proton-dripline nuclei: predict a strong and narrow E1 peak in ^{17}Ne.
- The 2p capture rate is dominated by the nonresonant E1 capture connected with SDM for T < 0.05-0.08 GK and T > 0.4-1.0 GK.

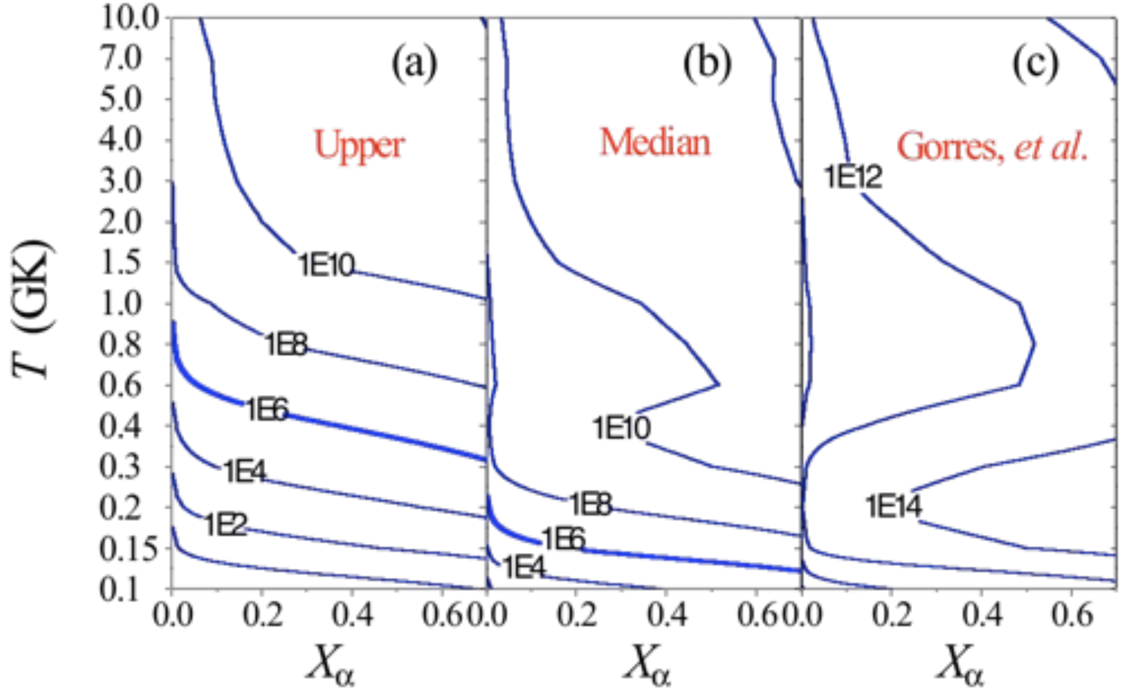




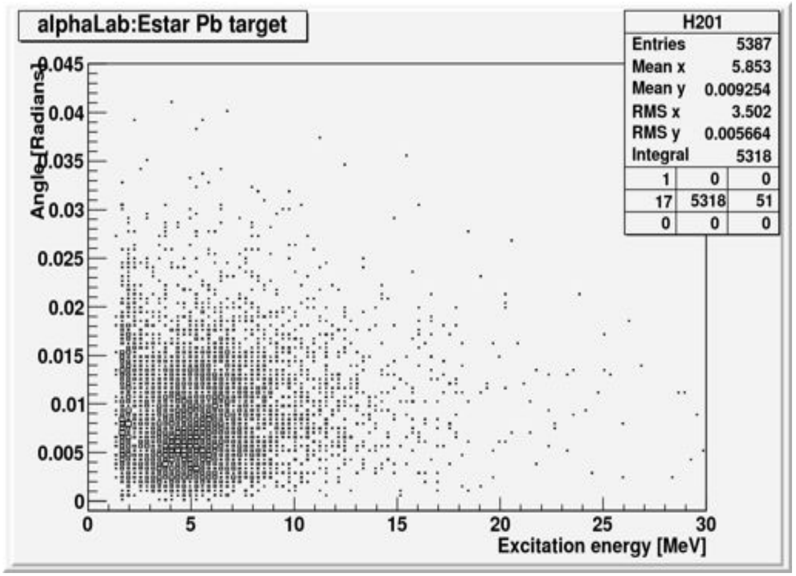
α

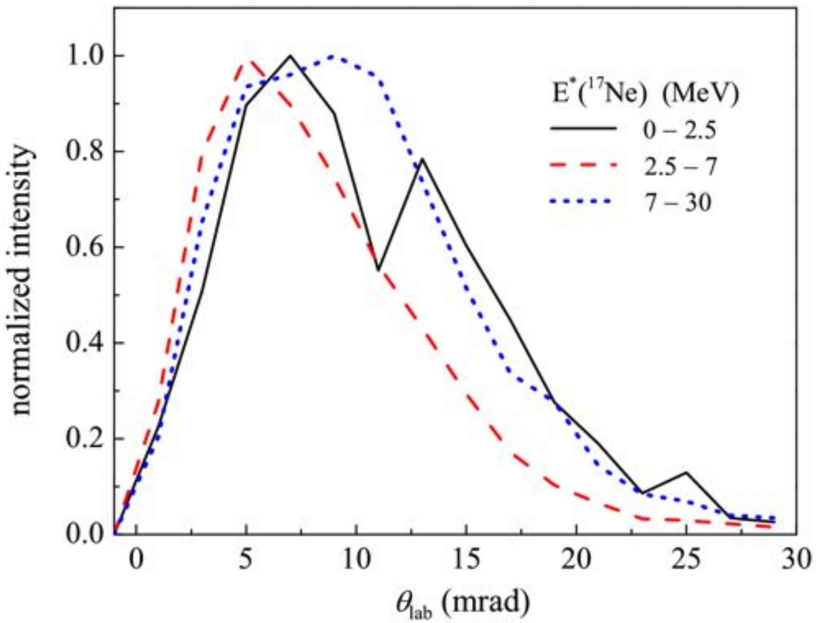
- $^{15}O(2p\ \gamma\quad Ne$ versus $^{15}O(\alpha\ \gamma)^{19}Ne$

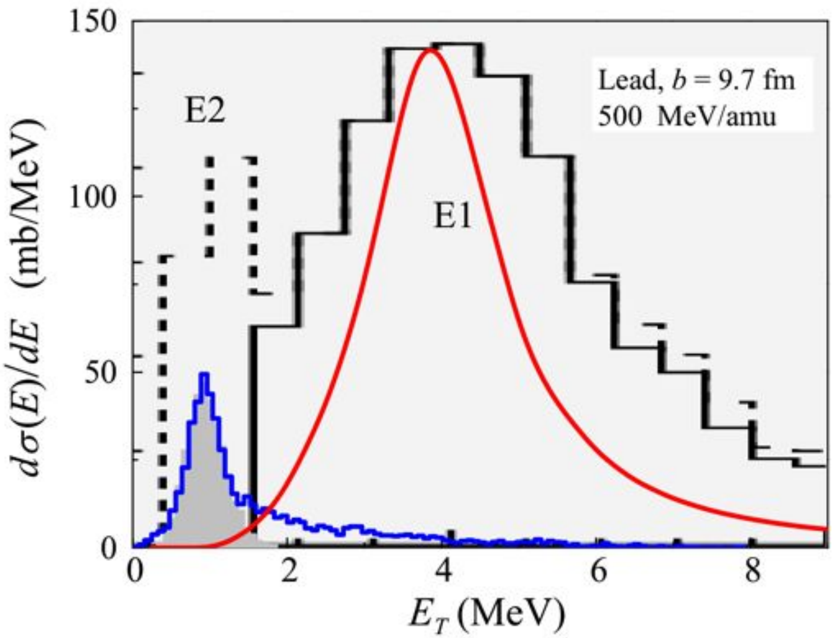
- Densities (in g/ccm) at which the production rate of ^{17}Ne by 2p-capture on ^{15}O equals the production rate of ^{19}Ne by α capture as function of temperature and α-particle mass abundance $X_\alpha \quad 4\ Y_\alpha$

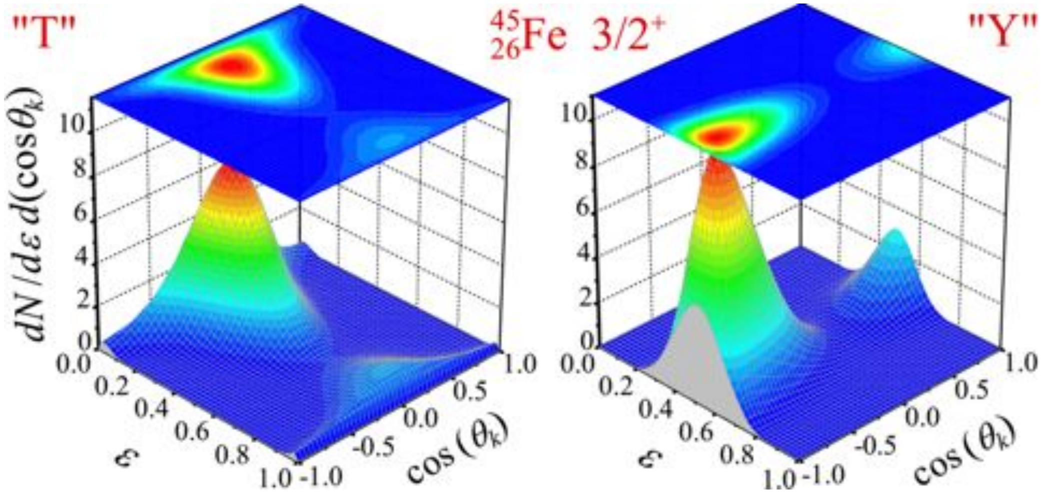


- “Study of the Borromean dripline nucleus ^{17}Ne”.
- ^{17}Ne beam, Pb/C/CH2 target.
- Very pronounced and narrow E1 peak in ^{17}Ne.
- NEW cluster sum rule exhausted by 10-13 MeV.
- Nice agreement with theoretical predictions.
- First observation of the soft dipole mode in 2p halo nucleus.
- Implementations for astrophysics.









We have exciting developing field in which fruitful, mutually beneficent interaction between theory and experiment exists