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Astrophysical aspects of multiple fragmentation of nuclei in nuclear emulsion

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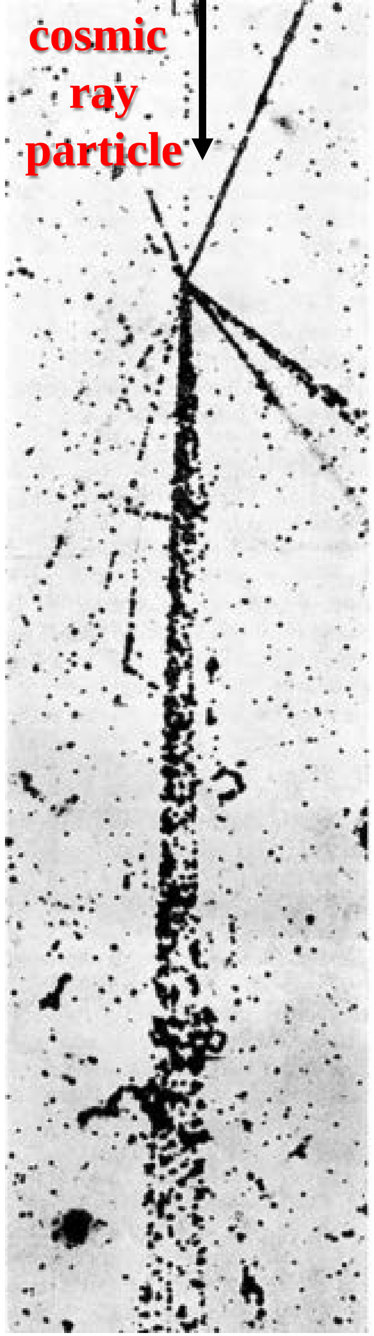
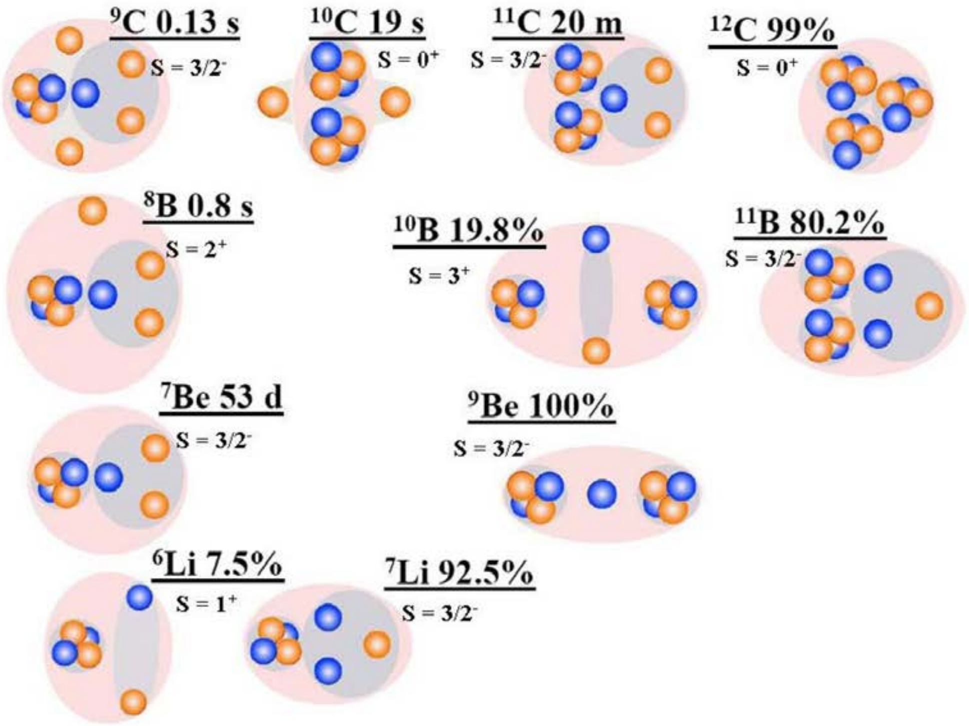
BEQUEREL Website

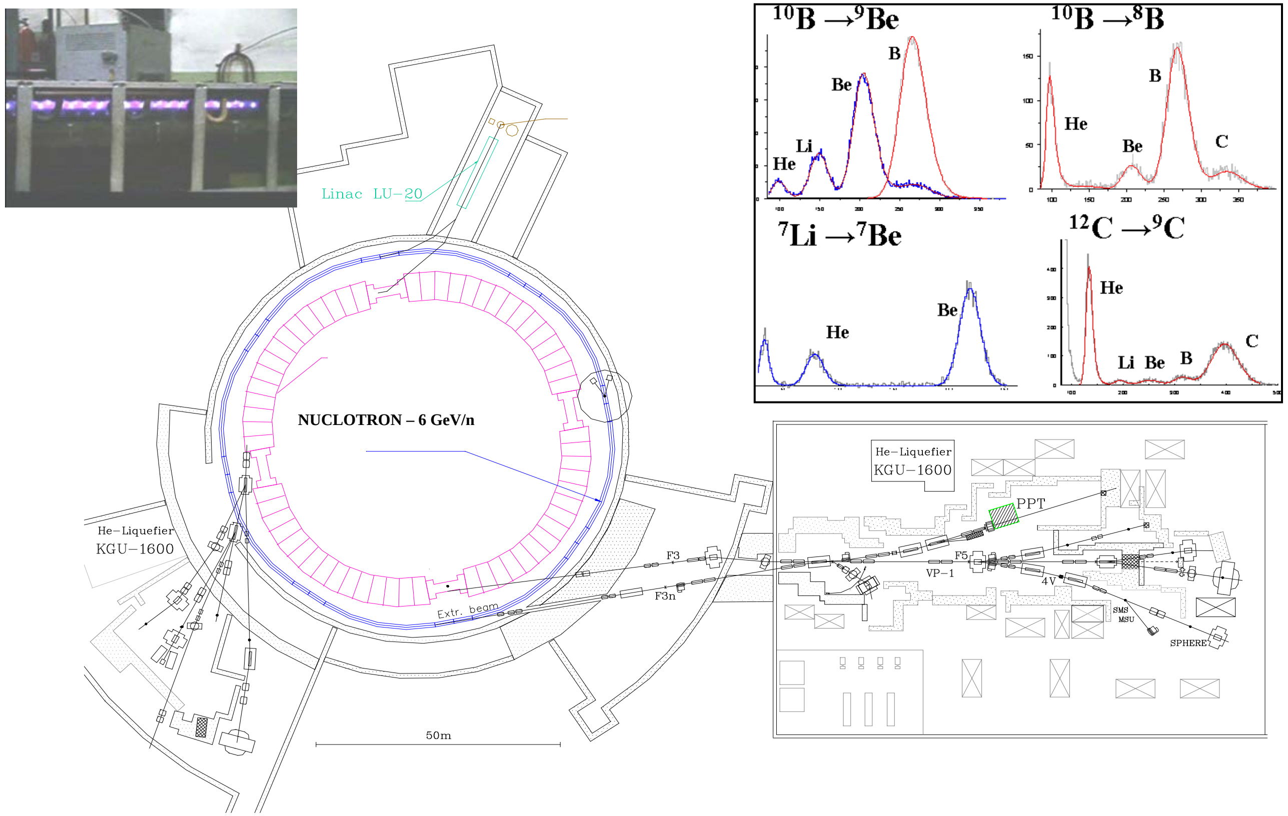
Outline

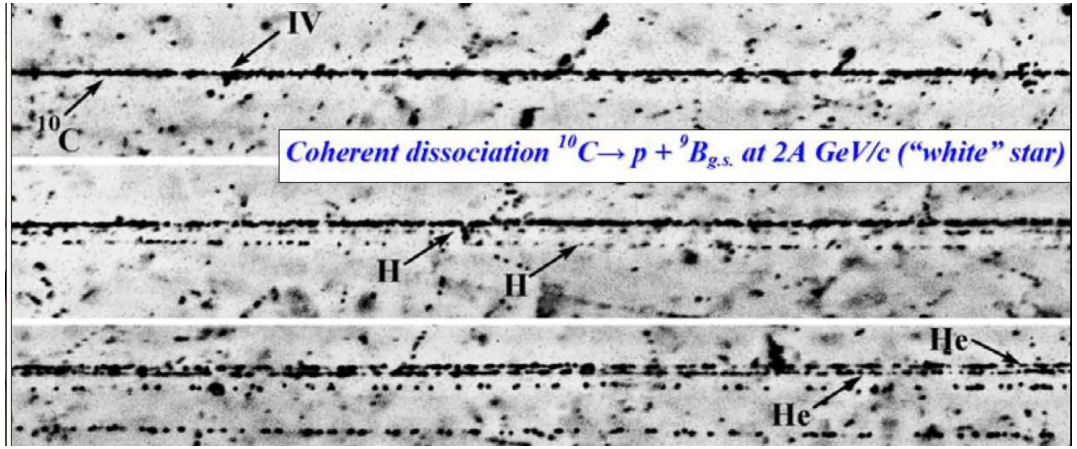
- Multifragmentation features of relativistic nuclei;
- Alpha fragmentation of heavy relativistic nuclei;
- Observation of the events induced by projectile neutrons.



Investigation of nucleus multifragmentation in the BECQUEREL project



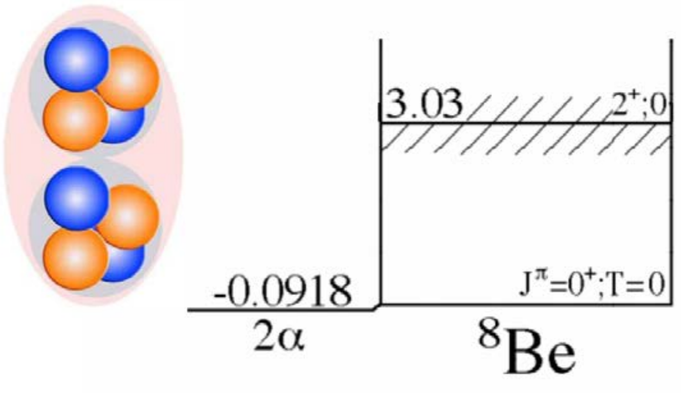


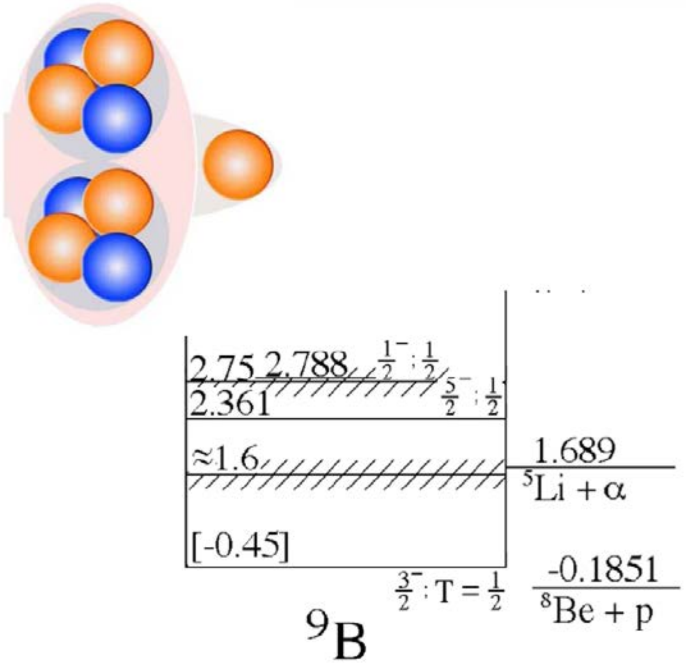


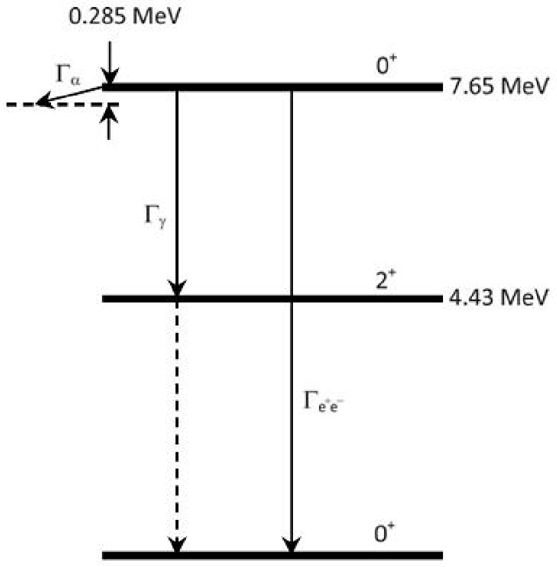
The cluster structure of light stable isotopes and the light radioactive ones, is studied in the BECQUEREL experiment at the JINR Nuclotron. According to the invariant mass of relativistic pairs and triplets of He and H the unstable nuclei ^{8}Be and ^{9}B are identified during dissociation of the ^{9}Be, ^{10}B, ^{10}C, and ^{11}C isotopes and the Hoyle state while dissociating of ^{12}C and ^{16}O.

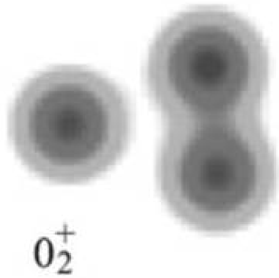
Investigation of nucleus multifragmentation in the BECQUEREL project

The decay energy of ^{8}Be $\rightarrow$ 2α is only $E_{th}(^{8}Be)$ = 91.8 keV, and the width $\Gamma(^{8}Be)$ = 5.57 ± 0.25 eV. The ^{8}Be nucleus is an indispensable decay product of ^{9}B and HS. The ^{9}B ground state is above the ^{8}Be*p* threshold at $E_{th}(^{9}B)$ = 185.1 keV at $\Gamma(^{9}B)$ = 0.54 ± 0.21 keV. The HS state is the second (and the first α-unbound) excitation of the ^{12}C nucleus at E_{th}(HS) = 378 keV above the 3α threshold. The value Γ(HS) = 9.3 ± 0.9 eV corresponds to the decay width $\pi^{0} \rightarrow 2\gamma$ on the order of the magnitude.

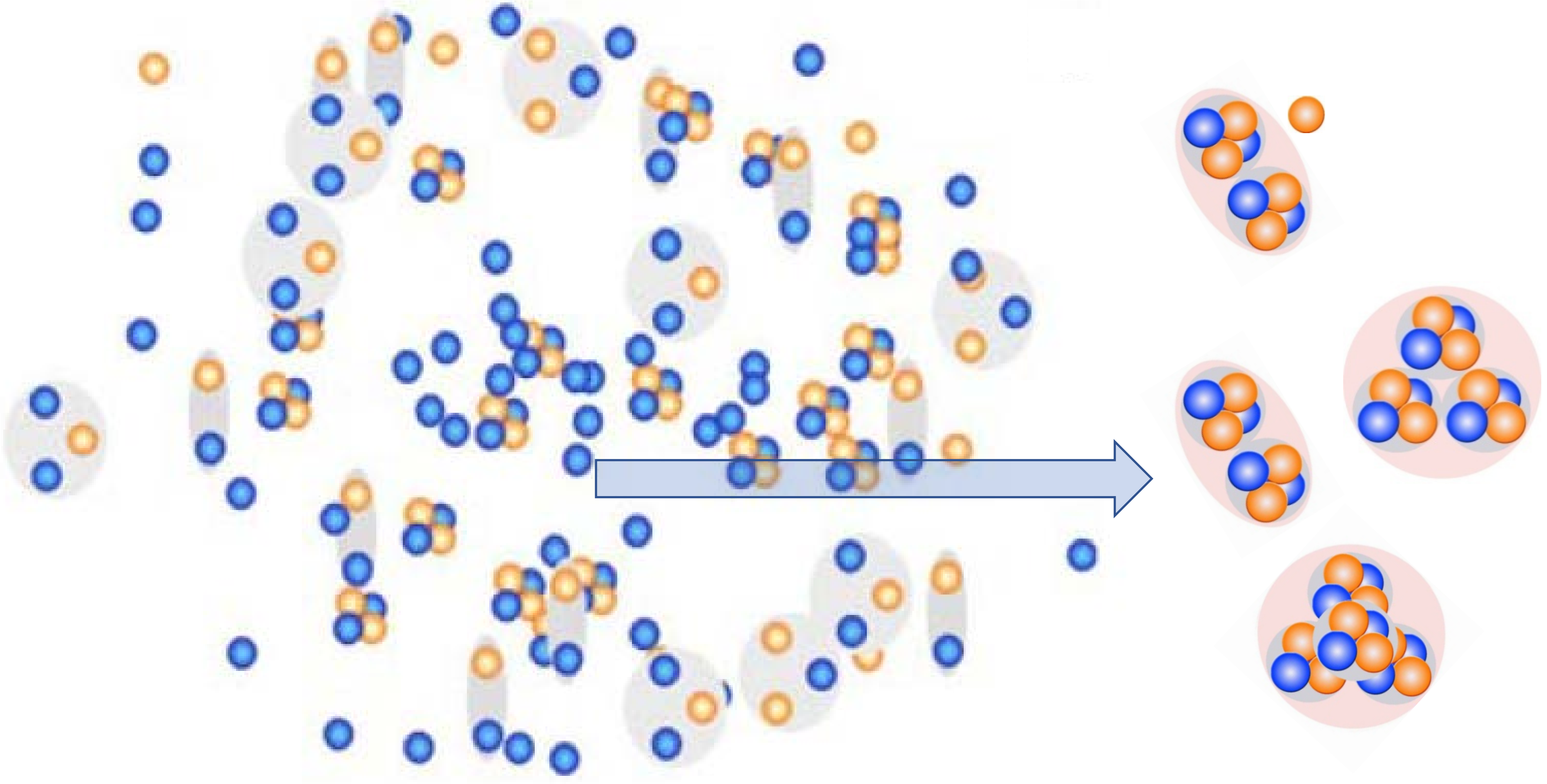








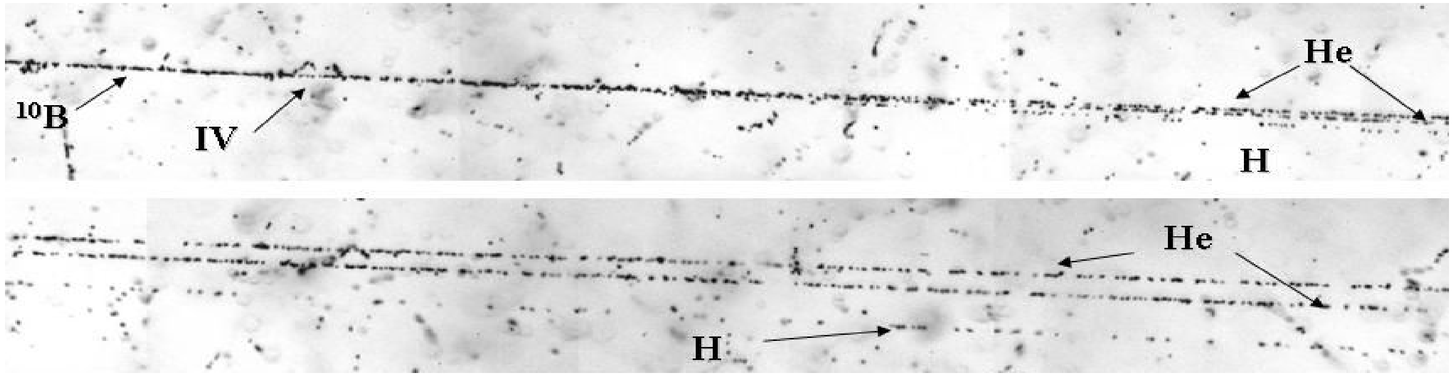
The Hoyle state

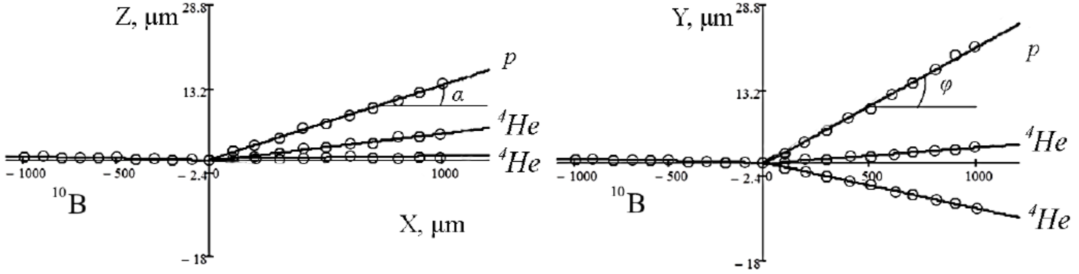


Having been tested, this approach was used to identify ^{8}Be and HS and search for more complex states of α-particles in fragmentation of medium and heavy nuclei. Recently, based on the statistics of dozens of ^{8}Be decays, we have found the enhancement of the probability to detect ^{8}Be in the event while increasing the number of relativistic α-particles. A preliminary conclusion has been made that contributions of ^{9}B and HS decays also increase. The exotically large sizes and lifetimes of ^{8}Be and HS allow us to assume an opportunity of synthesizing αBEC by means of successively connected emerging α-particles.

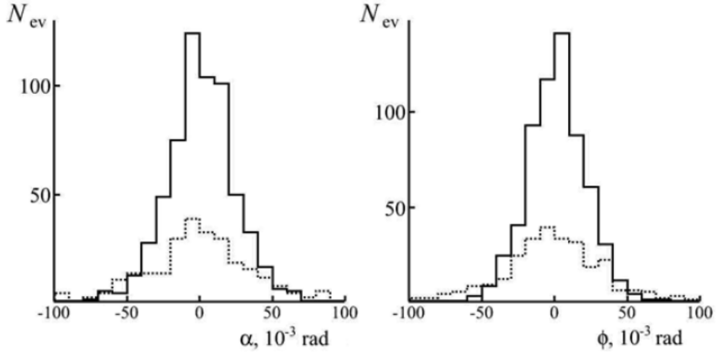
Investigation of nucleus multifragmentation in the BECQUEREL project

In the study of interactions at high energies, a significant role belongs to the method of nuclear photo emulsion which has unique features. In the nuclear emulsion, depending on the primary nucleus momentum, the angular resolution for tracks of relativistic fragments up to 10^{-5} rad can be obtained due to the best spatial resolution (0.5 μm). This ensures complete observability of all possible decays of relativistic nuclei into charged fragments. In addition, the emulsion technique makes it possible to measure particle momentum and identify the type of particles. Therefore, because of the high resolution of emulsions and the opportunity to observe reactions in 4π geometry, this method seems to be an efficient way to study the processes of relativistic fragmentation.



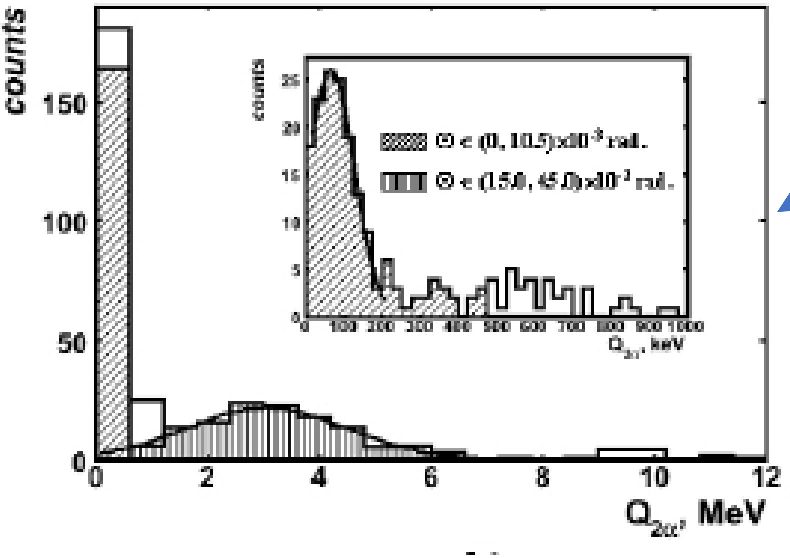


Example of restored directions in event $^{10}B \to 2He + H$ @ 1.2 *A* GeV over vertical and planar planes.

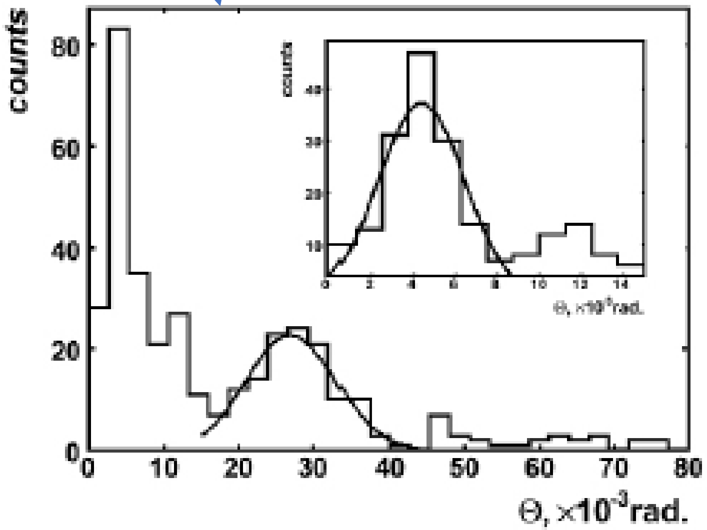


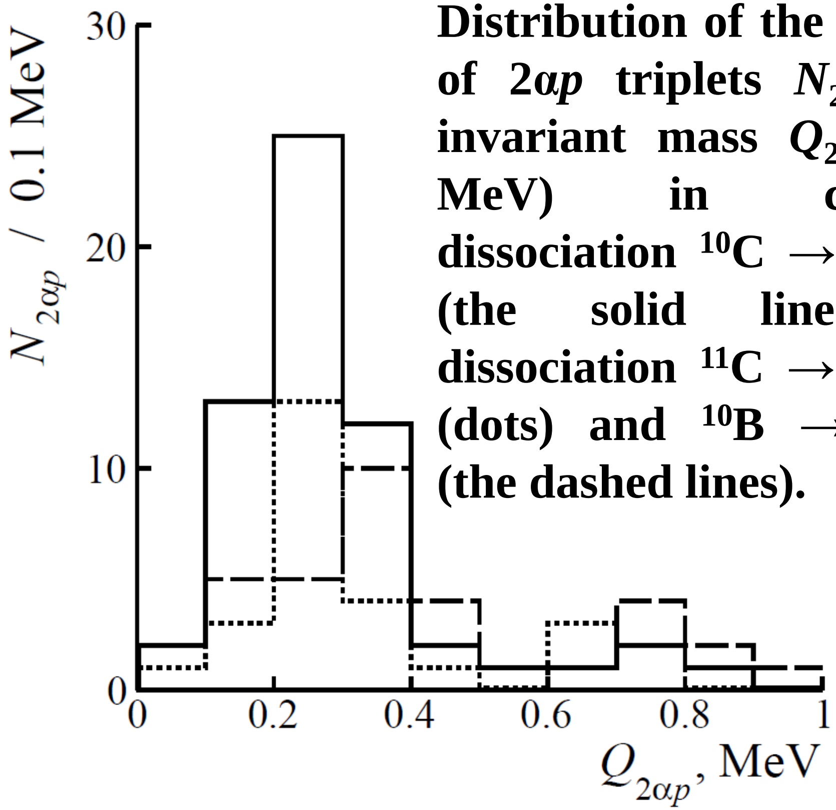
Distributions of fragments He (solid) and H (dotted) over dip and planar angles α and φ in events $^{10}B \to 2He + H$ @ 1.2 *A* GeV.

Investigation of nucleus multifragmentation in the BECQUEREL project



^{9}**Be→2α**

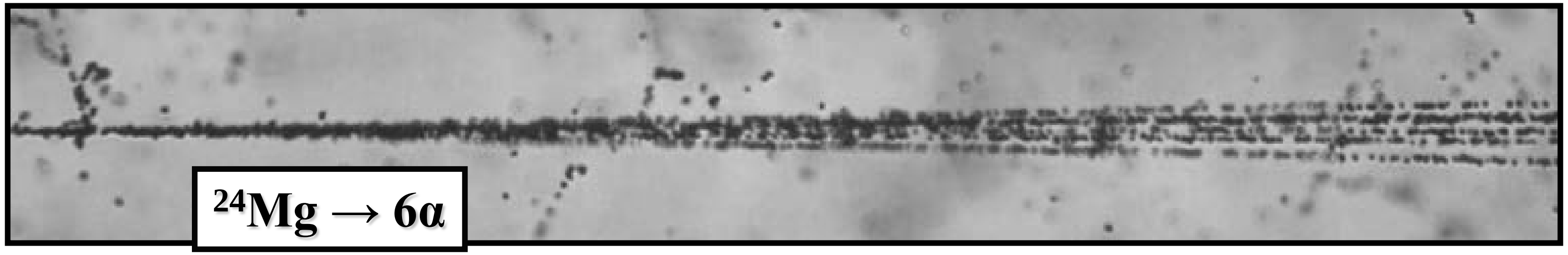


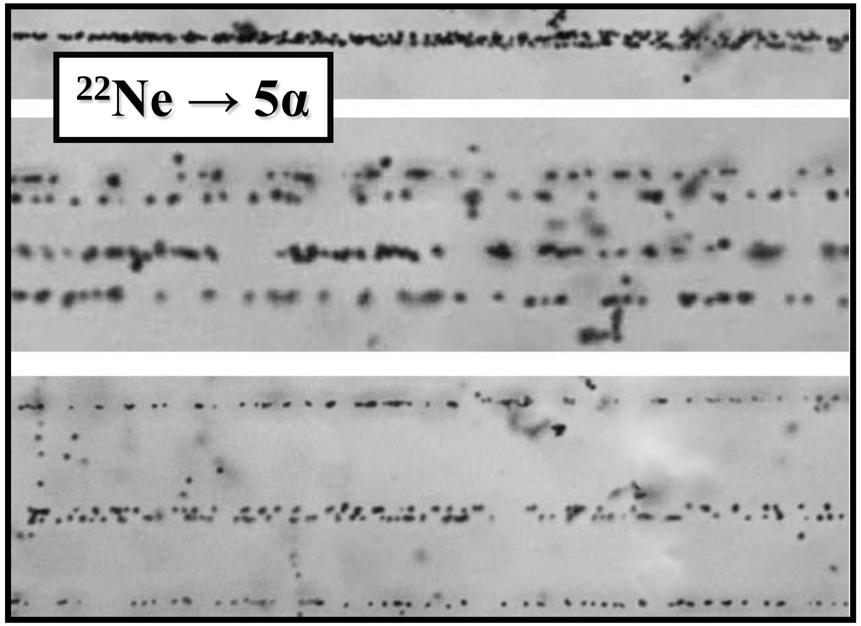


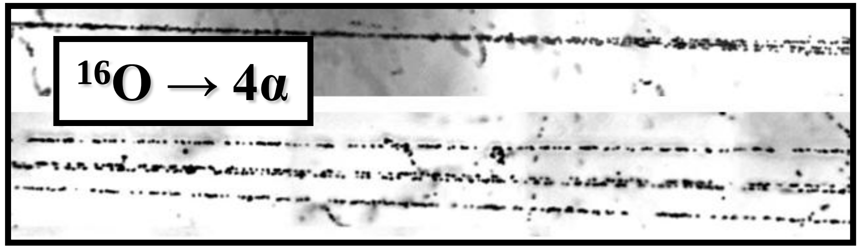
Distribution of the number of $2\alpha p$ triplets $N_{2\alpha p}$ over invariant mass $Q_{2\alpha p}$ (< 1 MeV) in coherent dissociation $^{10}C \rightarrow 2He2H$ (the solid line) and dissociation $^{11}C \rightarrow 2He2H$ (dots) and $^{10}B \rightarrow 2HeH$ (the dashed lines).

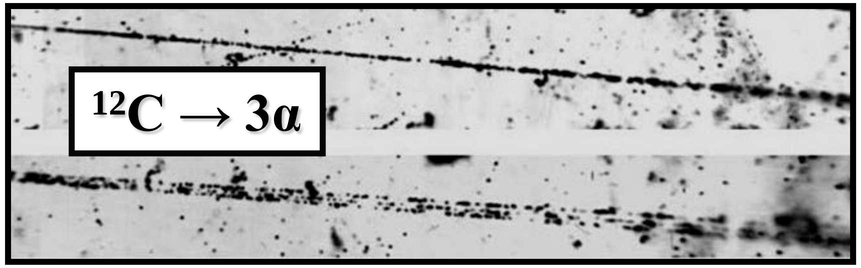
In general, the energy Q of a few-particle system is $Q = M^* - M$. M^* is the invariant mass defined by the sum of all products of 4-momenta $P_{i,k}$ fragments $M^{*2} = \sum(P_i \cdot P_k)$. Subtraction of mass M is a matter of convenience. The 4-momenta $P_{i,k}$ are determined in the approximation of conservation of the initial momentum per nucleon. Then, the definition of Q comes down to determine the angles between the fragment emission directions.

α-fragmentation of relativistic nuclei







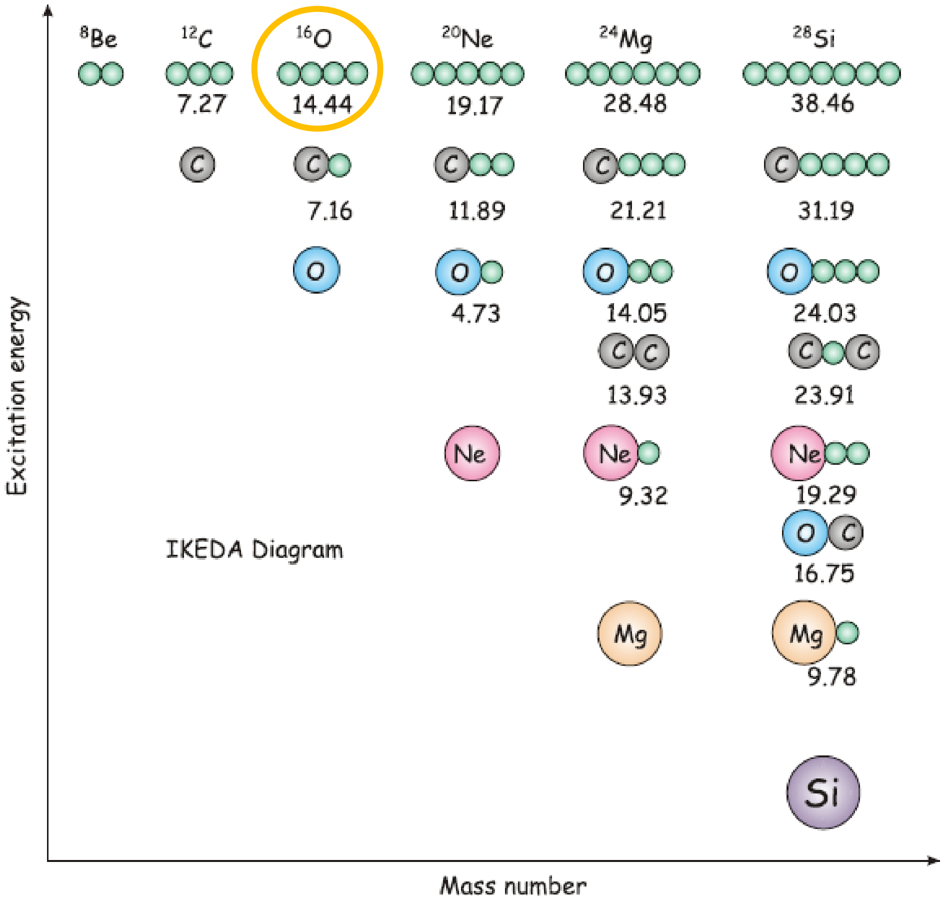


The study of the nuclear structure in the relativistic approach under conditions of very small energy-momentum transfers, has important advantages, since the structure of the initial states of nuclei should be most fully reflected in the final states of the fragments.

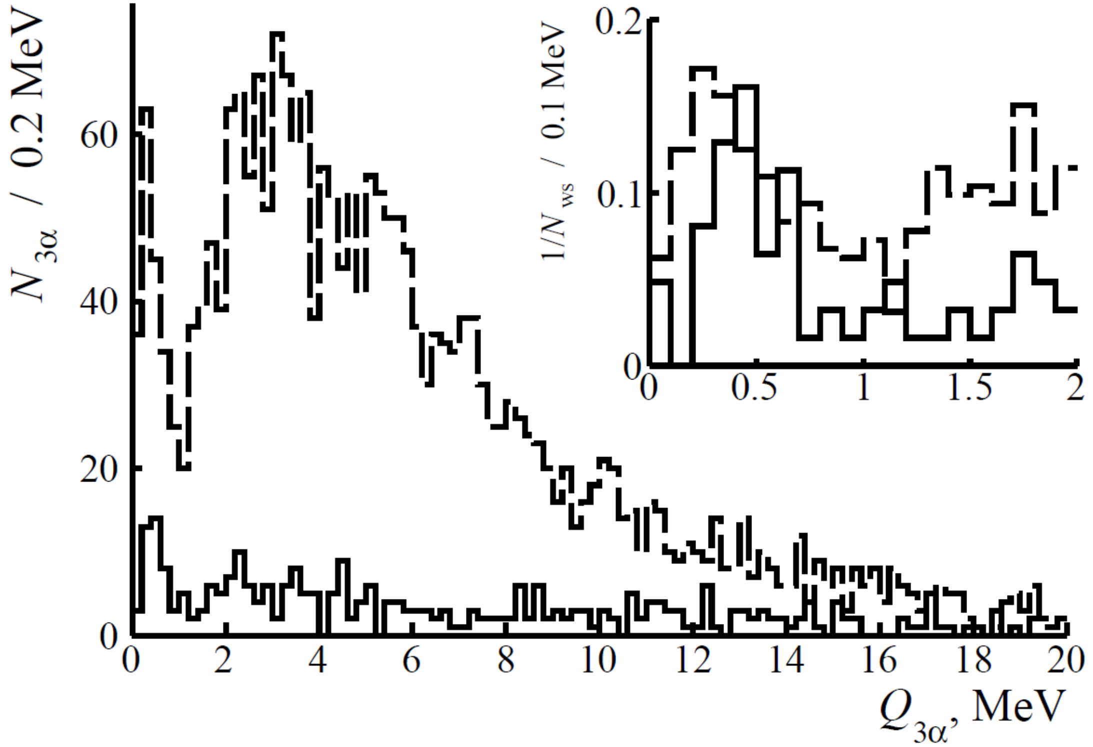
Modern experiments are carried out with relativistic radioactive nuclei having a large excess of neutrons on magnetic spectrometers. They are focused on detecting the fragments with the initial charge similar to that of the nucleus under study or close to it.

However, this approach loses fundamentally important channels containing He and H fragments and, accordingly, ^{8}Be and ^{9}B decays. The BECQUEREL experiment at the JINR Nuclotron/NICA facility is also motivated by the opportunity of solving this problem with the nuclear emulsion method.

α-fragmentation of relativistic nuclei

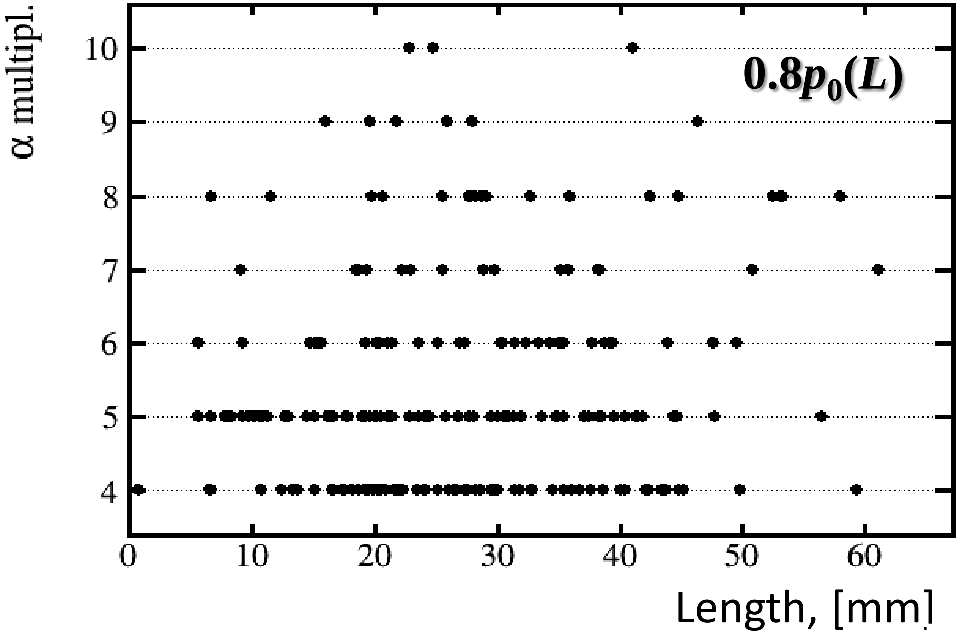


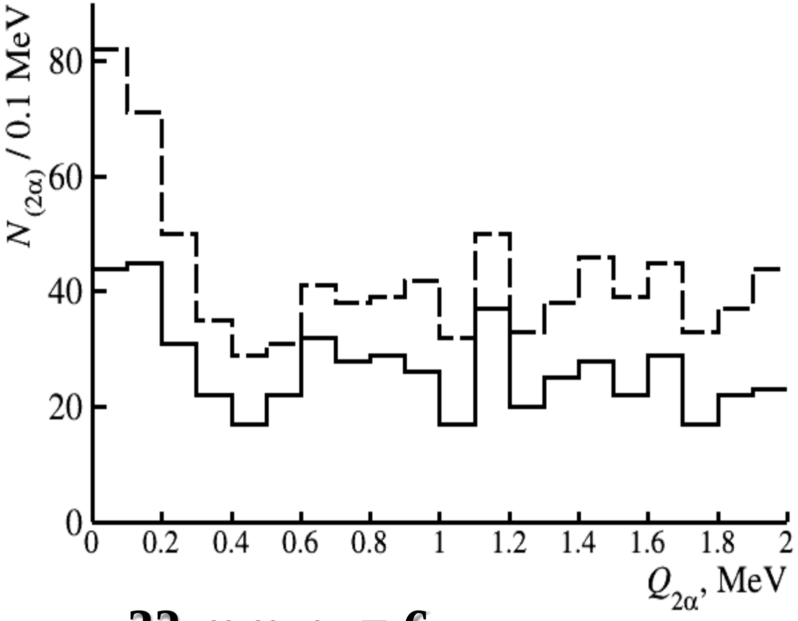
The "Ikeda diagram", showing the development of the cluster structure in α-conjugate nuclei when the excitation energy is increased.

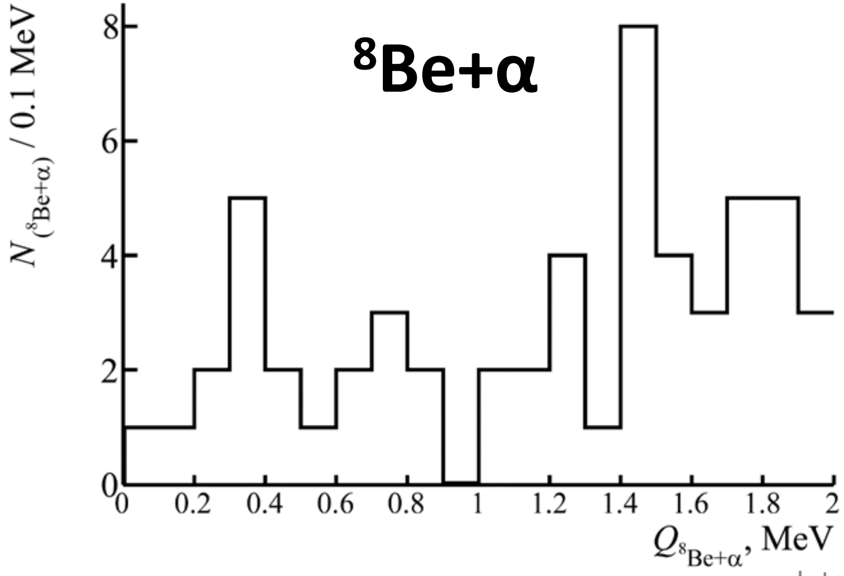


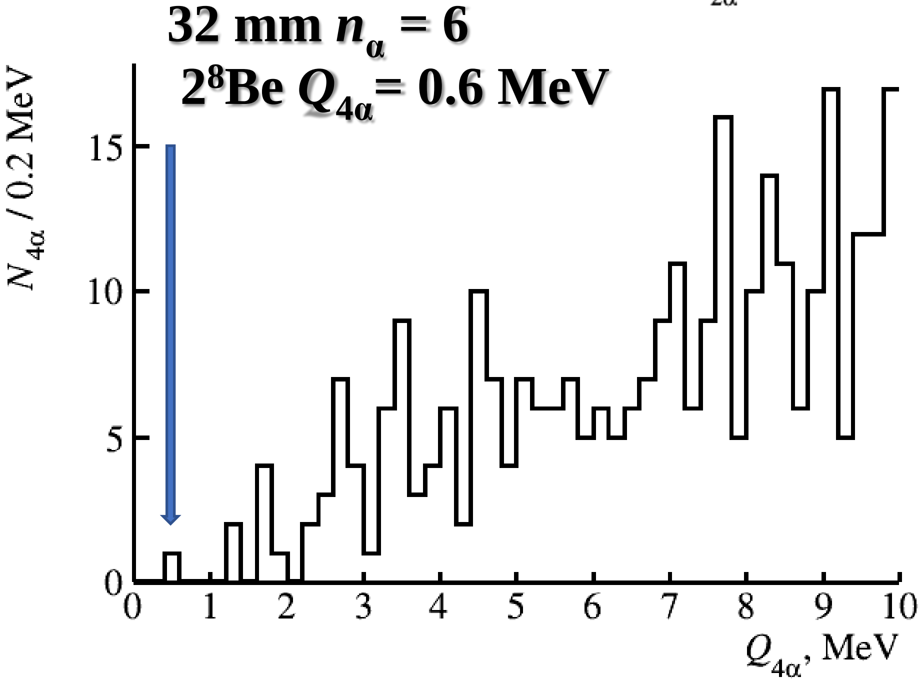
The analysis of "white" stars ^{12}C → 3α and ^{16}O → 4α has made it possible to establish that the fraction of events containing ^{8}Be (HS) decays is 45 ± 4% (11 ± 3%) for ^{12}C and 62 ± 3% (22 ± 2%) for ^{16}O. It can be seen that the growth of 2α- and 3α-combinations enhances the contribution of ^{8}Be and HS. This observation is worth being verified for heavier nuclei.

Nα fragmentation of ^{84}Kr→(4-10)α at 950*A* MeV

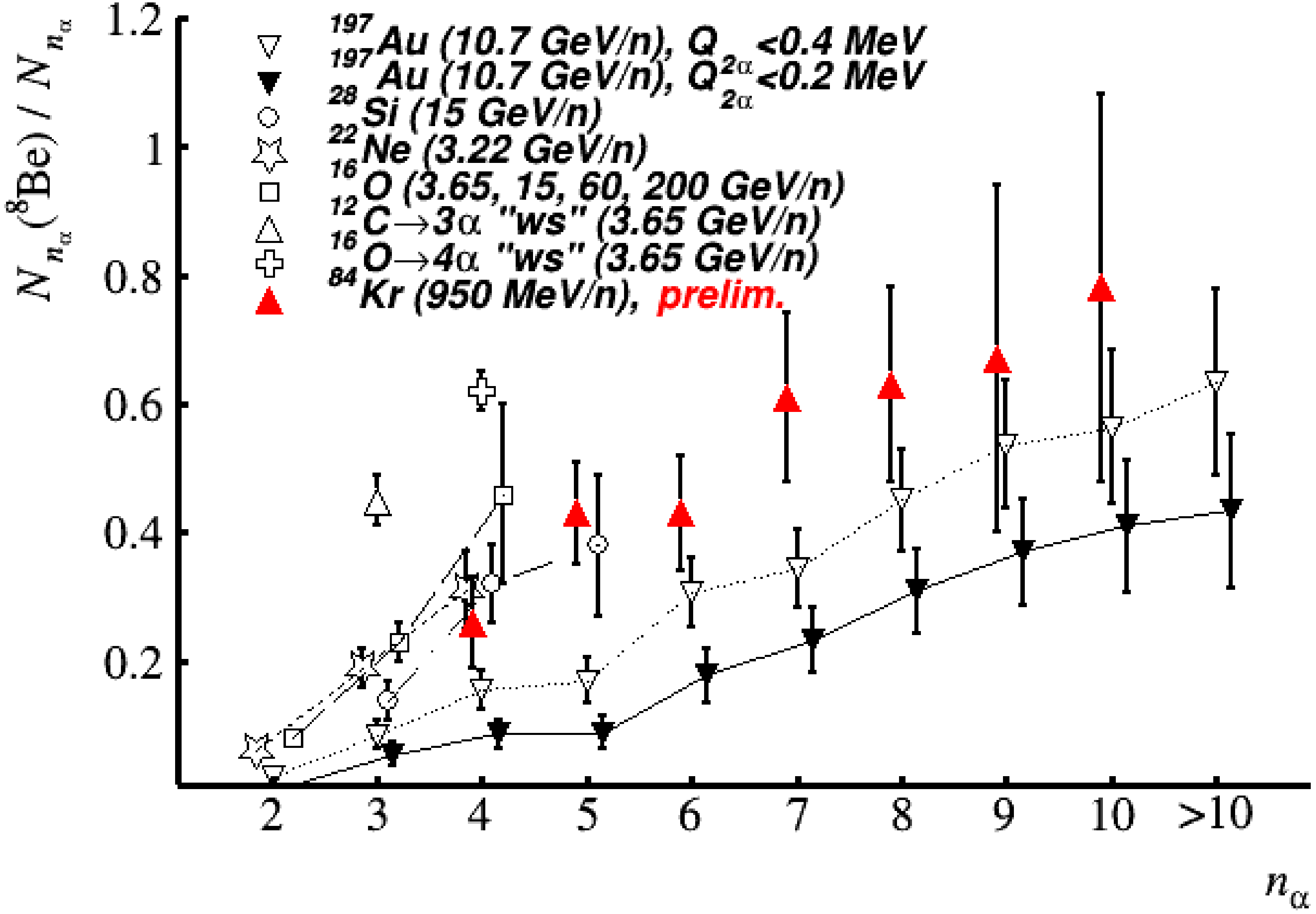




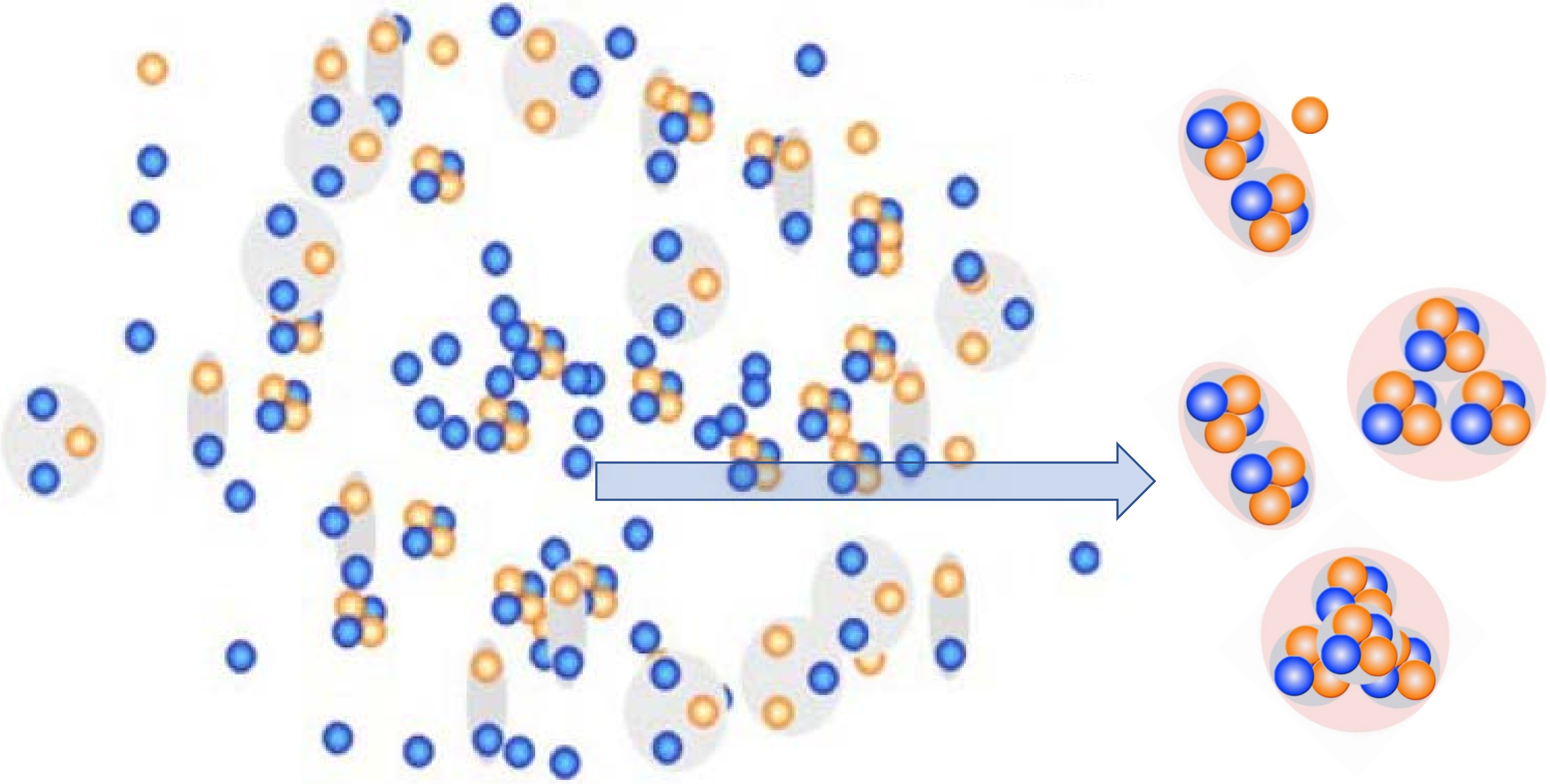




Correlation in formation of ^{8}Be nuclei and α-particles in fragmentation of relativistic nuclei



Dependence of relative contribution of $N_{n\alpha}(^8\mathrm{Be})$ decays on statistics of $N_{n\alpha}$ events with α-particle multiplicity nα in relativistic fragmentation of C, O, Ne, Si, and Au nuclei. The marked "white" stars ^{12}C → 3α and ^{16}O → 4α (WS). The points are slightly shifted from the values of n_α and are connected with the dotted line.



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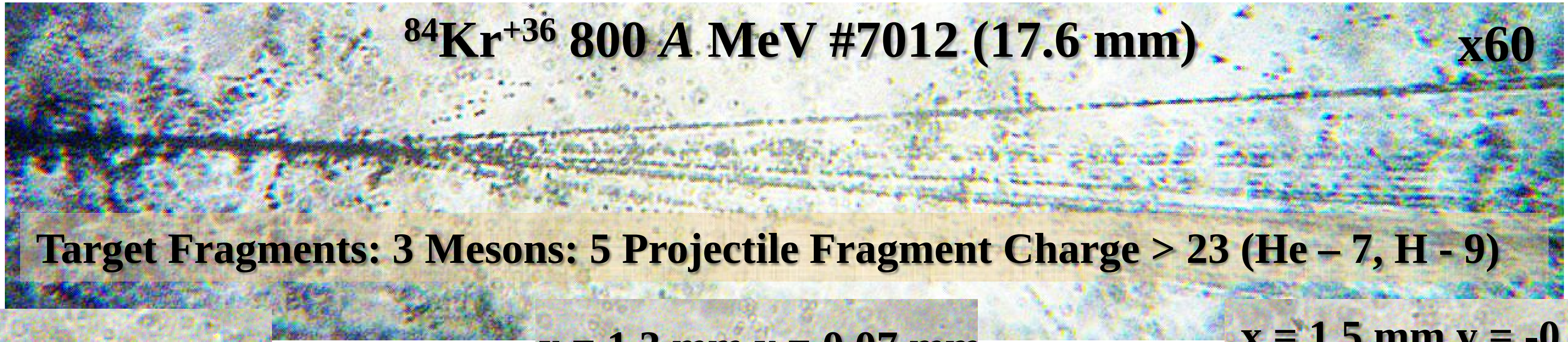
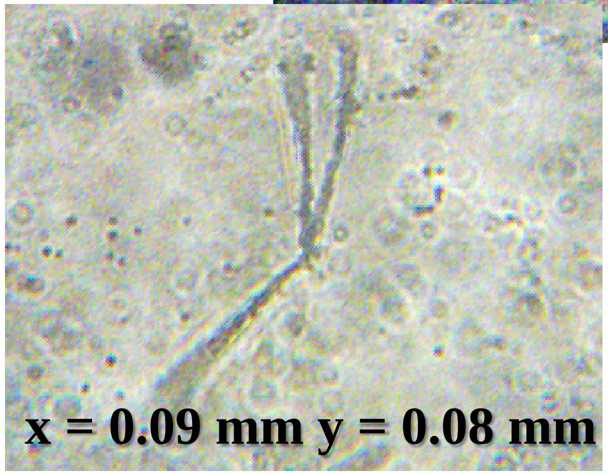
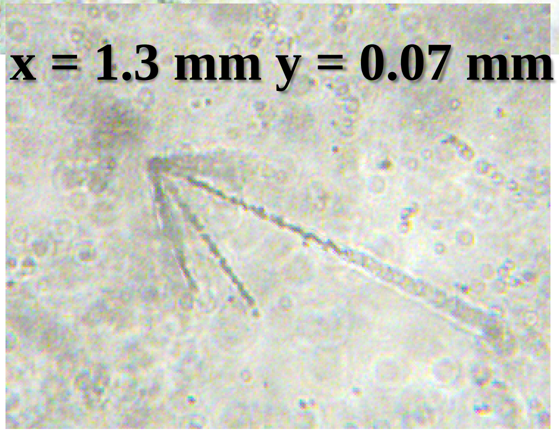
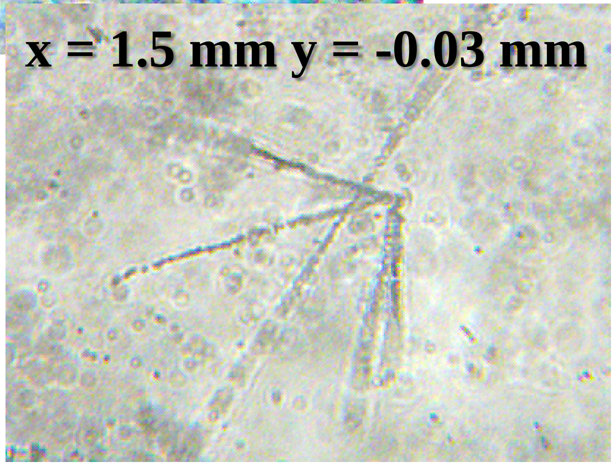
The events induced by projectile neutrons

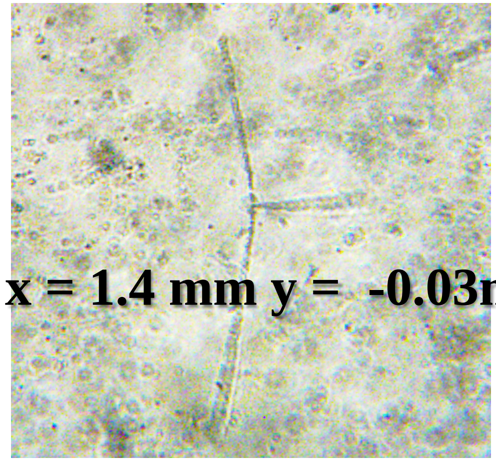


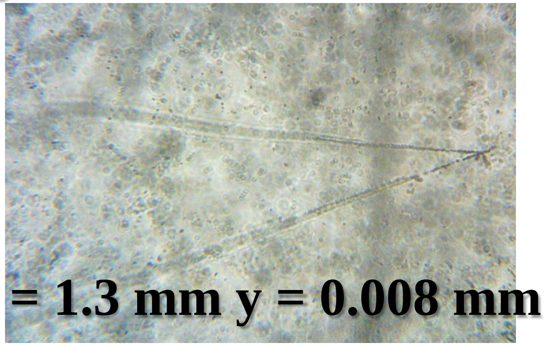


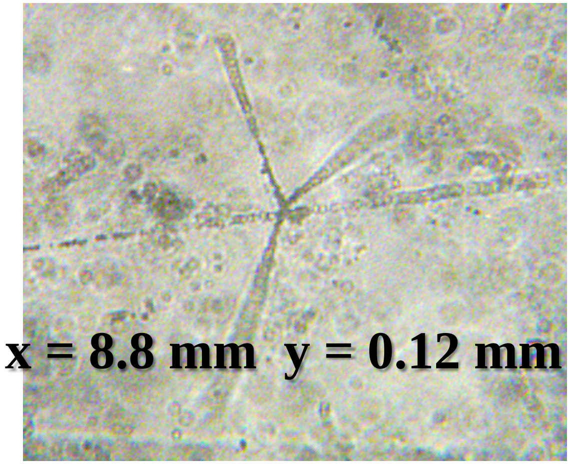




Projectile neutrons?







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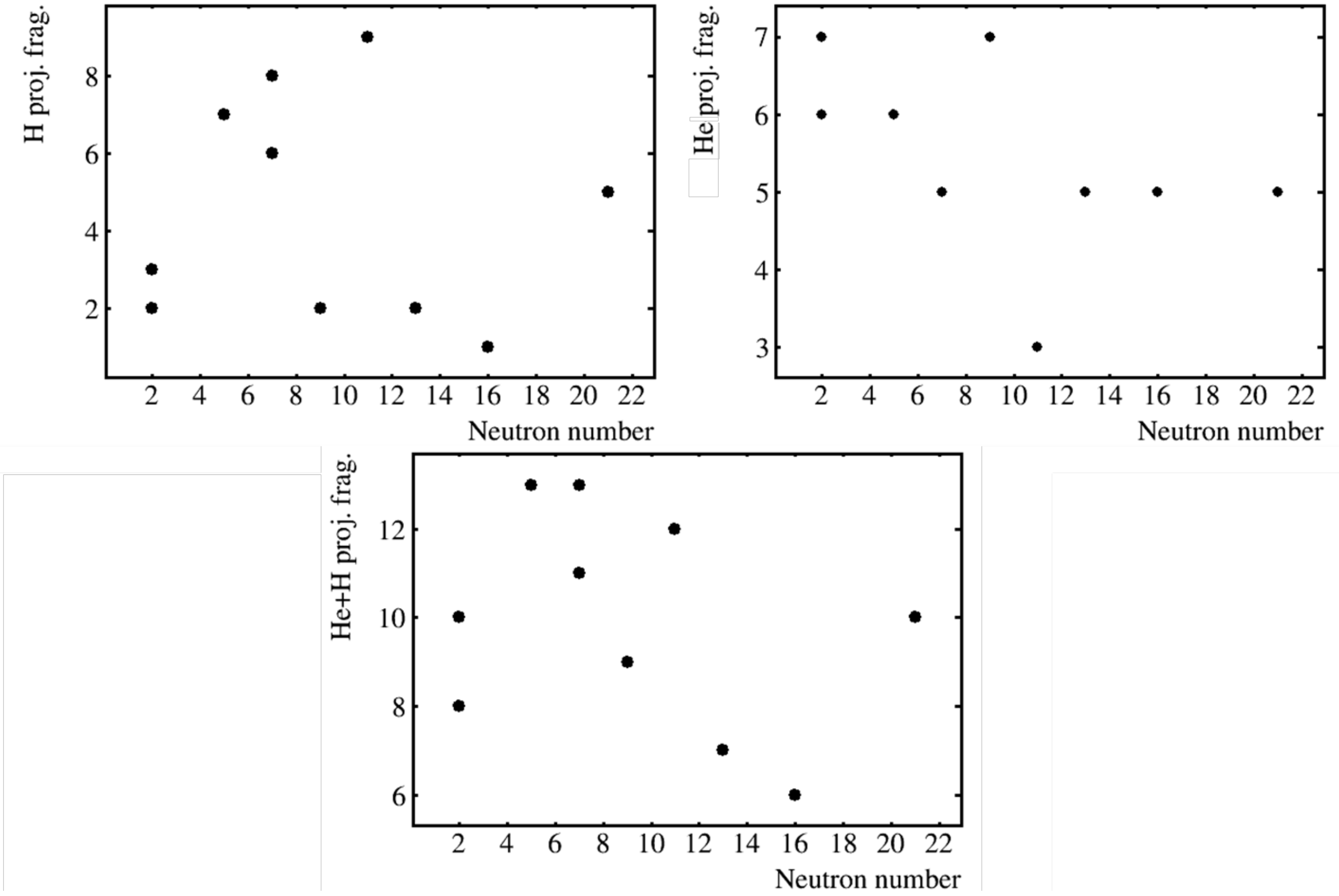

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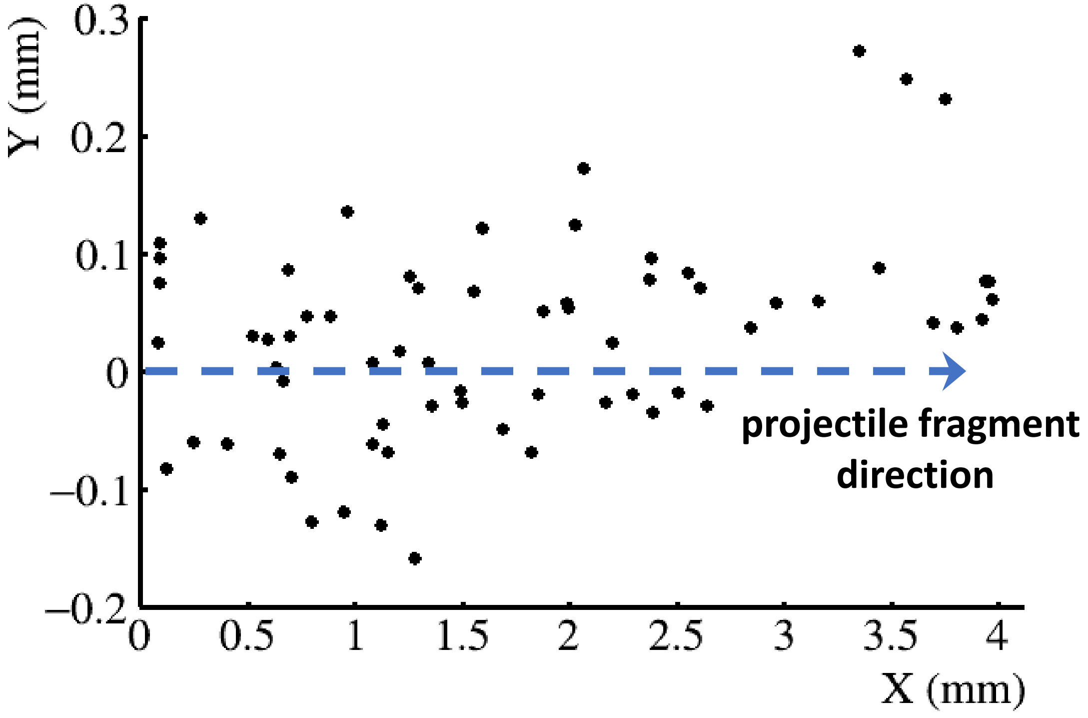
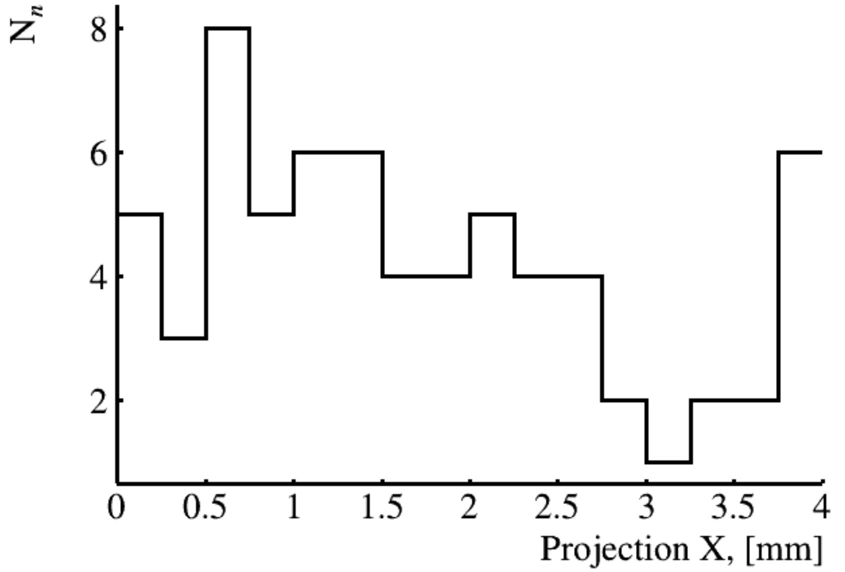
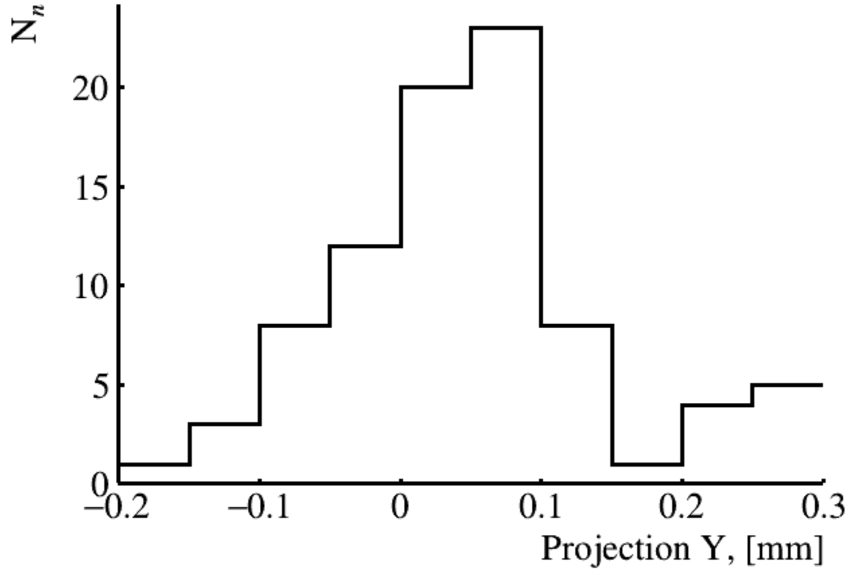
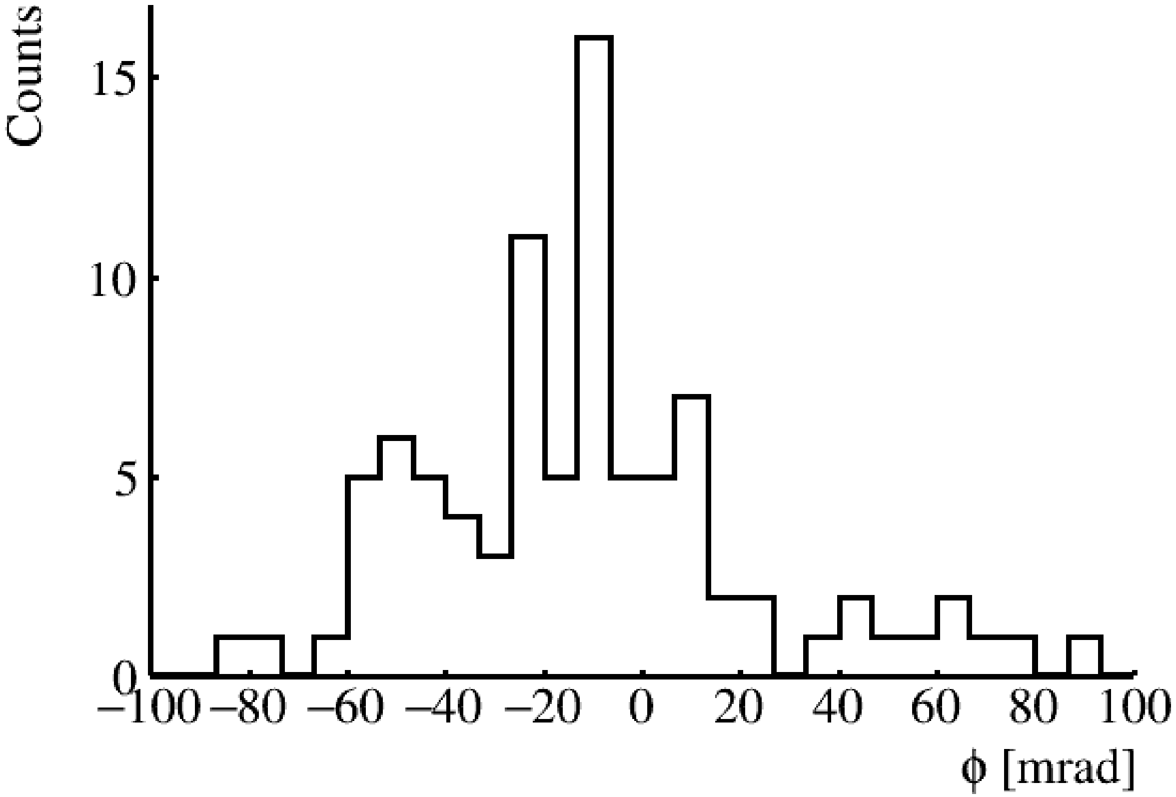






The search for neutron induced events was carried out in 10 events with big number of secondary He and H projectile fragments. The total number of observed neutron events is 93. The vertex positions of the observed events are shown in the figure above.

The events induced by projectile neutrons



Distribution over the planar angle φ between the direction of the observed neutron event relative to the direction of the Kr nucleus track.

Conclusion

- **Identification of decays ^{8}Be → 2α, ^{9}Be → 2α, and ^{12}C(0^{+}_{2}) → ^{8}Beα (the Hoyle state) was tested by the invariant mass for light nuclei, including the radioactive ones.**
- **We have discovered the trend of increasing ^{8}Be nucleus with the growing number of α-particles, as well as ^{9}B and ^{12}C(0^{+}_{2}) for medium and heavy nuclei.**
- **The analysis is aimed at analyzing the ^{84}Kr fragmentation at 950 MeV per nucleon to clarify the connection between ^{8}Be and the Hoyle state and the multiplicity of α-ensembles. On this basis it is possible to search for the decays of the ^{16}O(0^{+}_{6}) → ^{12}C(0^{+}_{2})α state and 2^{8}Be.**
- **The preliminary analysis is presented of the range and angular characteristics of the observed neutron induced events by the multiplicity of formed fragments.**

Thank you for your attention!

The events induced by projectile neutrons