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# Multifragmentation of nuclei by photons: new approaches and results

**V. Nedorezov**
*Institute for Nuclear Research RAS*
*Prospect 60-let Octabra, 7A, 117312 Moscow, Russia*

***E-mail:*** vladimir@cpc.inr.ac.ru

A review on multifragmentation of nuclei at intermediate energies is given. Main attention is paid on new experimental photonuclear data obtained in the GRAAL experiment. It is shown on example of the $^{12}C$ nucleus how separated partial meson photoproduction reactions lead to nuclear decay with different multiplicity up to the total disintegration of nucleus on separated nucleons. Some experimental features of the GRAAL facility are discussed which allow measurement of partial meson photoproduction channels in coincidence with the cascade evaporation particles. Perspective experiments on photodisintegration of heavy nuclei are proposed.

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## Introduction

The multifragmentation phenomenon considered as a phase transition between nuclear matter and gas of nucleons and fragments was studied until now with strongly interacting projectiles, mainly protons and relativistic ions [1-3]. Theoretically it was explained by the cascade evaporation models [4,5] which allows evaluation of the process probability as function of the nuclear excitation energy. It was shown that an explosive decay of an exited nucleus can be observed when the excitation energy of the nucleus is comparable to its total binding energy.

First photonuclear experiment on this subject was performed recently at the GRAAL facility [6]. New information was obtained due to new experimental possibilities, namely simultaneous measurement of partial meson photoproduction reactions was done in coincidences with the complementary decay products emitted in a large solid angle. Usually, unstable mesons ($\pi^0$, $\eta$, $\omega$ etc) have a large mean free path which exceeds the nuclear size. They can interact with quasi-free intra-nuclear nucleons, so the kinematics variables (energies, angles) can be vary from the free proton ones. This indicates a way to study interaction of unstable mesons with nuclear media. Also, the recoil nucleons, especially their missing masses, can give information on the excitation process.

The most interesting results in this direction can be obtained for heavy nuclei where the universal behavior of nuclear photoabsorption [7] was found to be not valid [8,9]. For example, we can expect the noticeable probability for coherent photoproduction of pseudo scalar and vector mesons by the Coulomb field of the nucleus. This "Primakoff effect" was evaluated recently for the peripheral Coulomb interactions of relativistic ions [10]. It would be interesting to compare the virtual and real photon photonuclear interaction from this point of view. Also other rare processes as photon splitting [11] or Delbruck scattering [12] can be studied using the modern photonuclear facilities.

### Multifragmentation data obtained with strongly interaction particles

Examples of multifragmentation events measured with 1 GeV protons on Pb target [1] and relativistic 1 GeV/a.m.u Au ions (nuclear emulsion target) [2] are shown in fig 1.

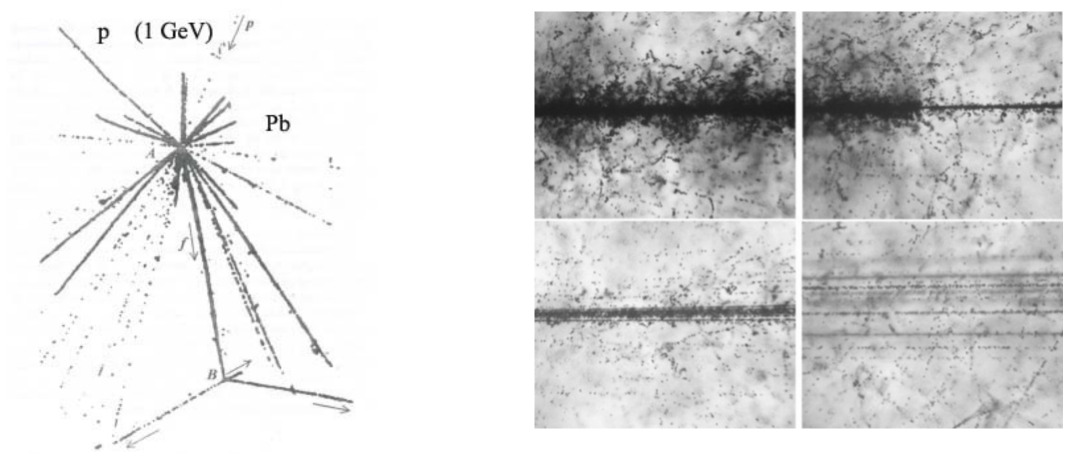


*Fig.1 : Nuclear explosion reaction events measured with relativistic protons [1] ( left) and relativistic Au ions [2 ](right figure).*

The results presented in fig.1 were obtained by help of the photo emulsion method. Such method demonstrates well that there is no doubt in the explosion mechanism of reaction, as seen on the figures. But the details of this process are not specified here. For example, the energy and momentum distributions of fragments as well the angular distributions are not evaluated. Moreover, looking on the right panel of fig.1 we can assume that the projectile (Au ion) is stopped in emulsion in the direct collision. So, all its energy is transferred to the lighter nucleus. Then, this light nucleus undergoes decay onto separated protons and fragments. But also the peripheral interaction can not be excluded because the momentum transfer is not measured here.

More detailed information on nuclear multifragmentation process was obtained with relativistic deuterons and $\alpha$ – particles in the FAZA experiment [3]. For example, the mass spectra of fragments were measured for $\alpha$ (3.65 GeV) + Au at different multiplicities. It was shown that fragment mass distribution of high multiplicity is described by a power function indicating the heating mechanism of nuclear excitation. Nevertheless, new experimental data were required and they appeared in the GRAAL experiment.

**GRAAL experiment**

The GRAAL apparatus has been described in several papers, see for example [13-15]. Principal GRAAL goal was to measure polarization effects in photoproduction of mesons at 500 – 1500 MeV using the polarized photons; the liquid proton and deuteron target were applied for this purpose. Here we discuss the complementary features of the GRAAL facility to measure the multifragmentation off nuclei [13]. The principal part of the GRAAL facility is the LAGRAN$\gamma$E detector (see fig.2). It is located approximately 30 meters downstream of the Compton interaction region (6 meter straight section of the 6.04 GeV electron storage ring ESRF). An argon laser of 514 nm (green line) or 351 nm (UV line) gives rise to the maximal energies for back scattered photons E = 1.1 GeV and 1.5 GeV, respectively.

The central LAGRAN$\gamma$E part is organized around the cryogenic Liquid Hydrogen (LH) or Liquid Deuterium (LD) target (8 cm length, 5 cm diameter). Solid Carbon (SC) target has a thickness of 3 mm which is, equivalent to 4 cm of LD. Central The central detector part is composed of a tracking system based on two cylindrical MWPCs, a barrel of 32 $\Delta$E plastic scintillators and a high energy resolution BGO ball.

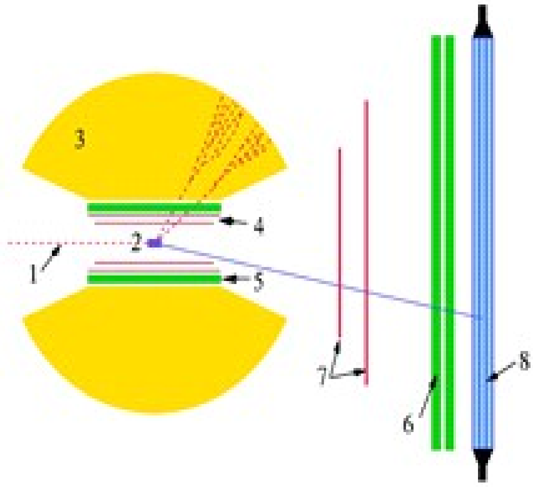


*Figure 2 : Experimental scheme of the detector LAGRAN$\gamma$E . 1 - Compton $\gamma$ – beam, 2 - target, 3 - BGO calorimeter, 4 - Cylindrical MWPCs, 5 - Plastic barrel, 6 - Plastic wall, 7 - Plane MWPCs, 8 - Shower wall*

The idea of the present experiment is demonstrated by Fig.3, where the yield of different multiplicity events is shown for the liquid deuteron target in comparison with the yield from the target mylar ($C_{10}H_8O_4$) windows. Here the 700 – 1500 MeV gamma beam was used. One can see that for low multiplicity (n=2,3) the distribution of events along the beam axis Z is flat correspondingly to the target length of 8 cm. For higher multiplicity the yield from the deuterium is decreasing but the yield from the windows is increasing, in contrary. This means that we can study the multifragmentation process in details using this facility.

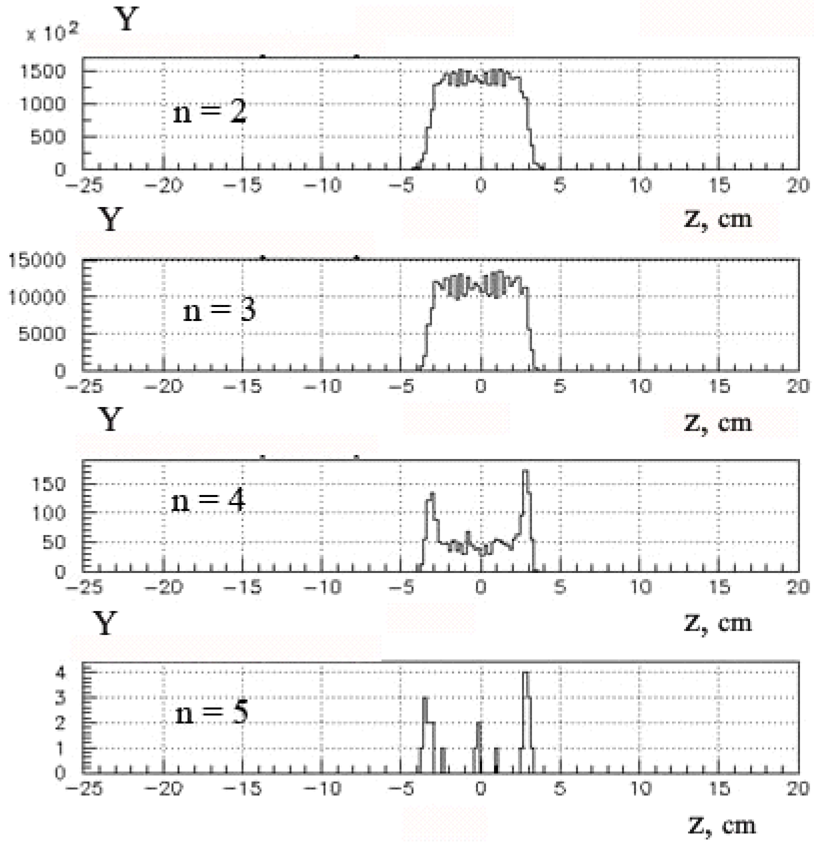


*Fig.3: Yield of charged particles of different multiplicity ( n =2,3,4,5) from deuterium target and mylar windows*

Naturally the LAGRANγE detector is advantageous for detecting fragmentation decays of nuclei. The first nuclear target was the $^{12}C$ one of 3 mm thickness and 3 cm diameter. The choice of the carbon target was explained by several considerations. At first, this nucleus is heavy enough to study the nuclear media effects in photoproduction of mesons. From the other side it is light enough from the point of view of model calculations to describe the mechanism of its decay.

Nucleons and nuclear fragments were disentangled from pions and photons emitted at various angles with respect to the photon beam. In forward direction charged and neutral particles are discriminated by the time-of-flight method, as seen in Fig. 4 (upper figures). The velocity of protons and recoil light nuclei created in meson photoproduction on $^{12}C$ was less than 82% of the speed of light. This makes possible to disentangle them from pions and photons. Particles emitted at larger angles above $25^0$ are successfully identified by taking into account the relation between the energy loss $\Delta E$ in the barrel and BGO calorimeter, as seen in Fig. 4 (down figures).

Moreover, the detailed analysis of events [16] shows possibility to distinguish the primary recoil nucleons corresponding to definite partial meson photoproduction reaction from cascade evaporation particles. This can be done basing on the energy and angular distributions of recoils because such distribution are noticeably different.

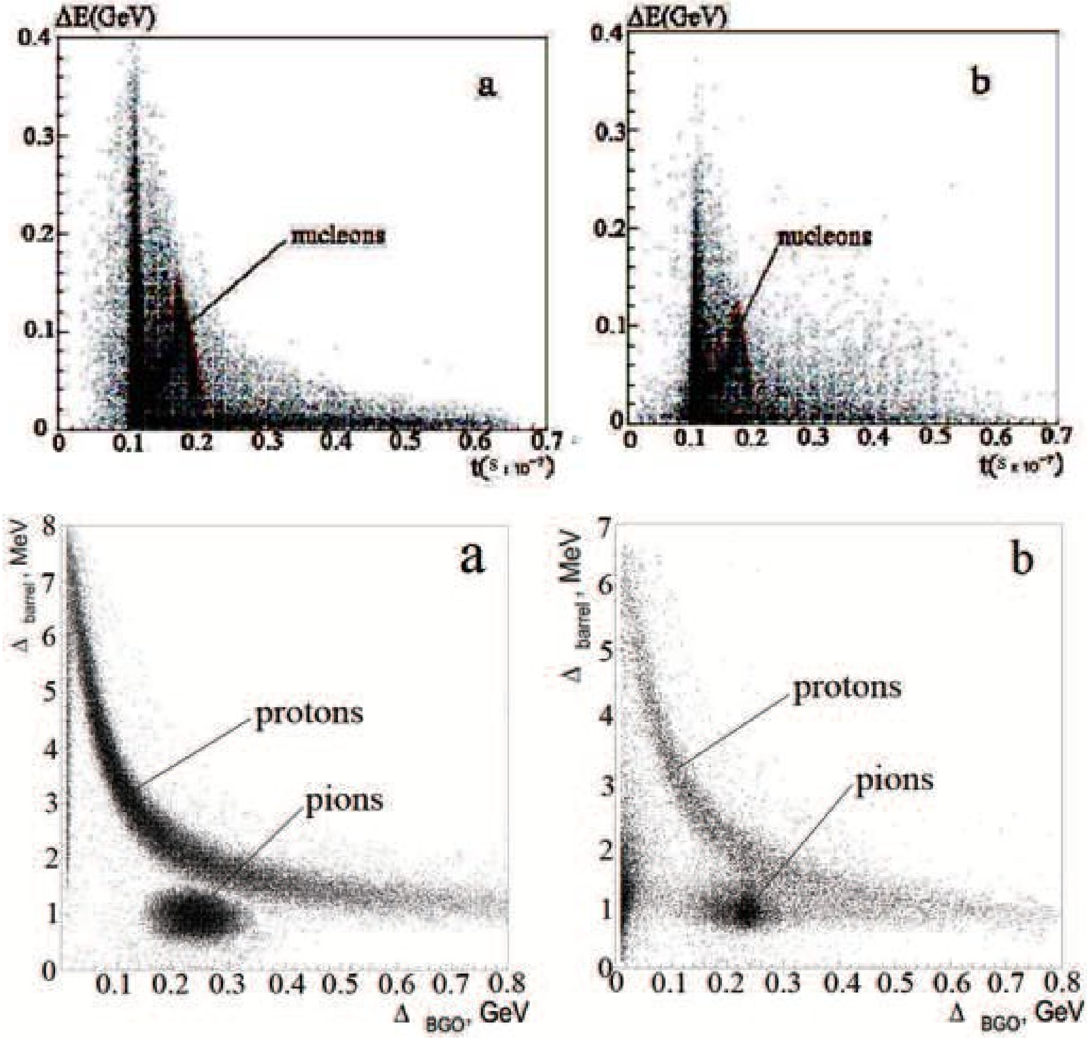


*Figure 4: Dimensional distributions for nucleons and pions measured in the forward detector (top) and BGO calorimeter (bottom). Simulated (a) and detected (b) events are shown for both cases.*

One can see a reasonable separation between relativistic mesons and recoil nucleons in this figure. Unfortunately, the energy and TOF resolution was not enough to separate the light fragments as deuterons and $\alpha$ – particles. A magnetic spectrometer combined with the TOF detector would be very favorable for this purpose.

The main results of the GRAAL experiment [6] on multifragmentation of $^{12}$C nuclei are presented in Fig. 5 - 7. Measured and calculated probabilities of events with a given number of fragments (from 5 to 12) are plotted in this figure. As seen, in all three intervals of photon energy, 0.7–1. GeV, 1.–1.25 GeV and 1.25–1.5 GeV, 0, 1% of all photoabsoprtion events lead to the production of eight nuclear fragments. This probability drops down for events with nine and, especially, with 10, 11 and 12 fragments. The probability of a full disintegration of $^{12}$C into 12 nucleons is very small, 0.05%, i.e. ones per 2000 events on average. This feature is caused by a low probability to deliver high excitation energy to the nuclear residue created after the cascade stage of the photonuclear reaction. One can see a good agreement between the experiment and the model RELDIS predictions.

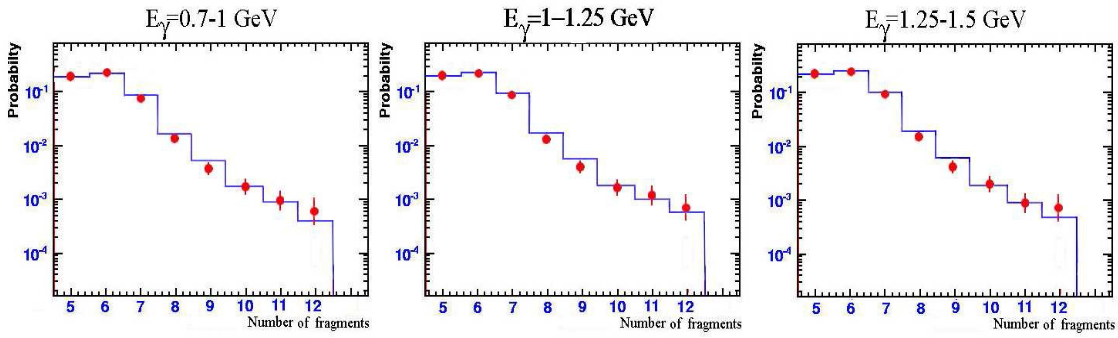


*Figure 5: Measured and calculated probabilities of photodisintegration events of $^{12}C$ nucleus with a given number of fragments for three photon energy bins.*

As was mentioned above, the GRAAL setup makes possible to measure the coincidences of mesons and nucleons . Experimental data for $\pi+n$ and $\pi^0p$ photoproduction on $^{12}$C are presented in Fig. 6. In order to demonstrate the validity of particle identification procedure, the respective probabilities for photoabsoprtion on a hydrogen target are also shown in Fig. 6. Since there are no protons in the final state of $\pi^+n$ reaction, and there is only a single proton in $\pi^0p$ reaction, any deviations from this count reveal a deficiency of proton identification. As seen from Fig. 6, about of 10% of $\pi^+n$ events are misidentified as events of proton emission, and 20% of $\pi^0p$ ones as events with two protons. One can also conclude from Fig. 6 that there are no *p* events identified as events with more than two protons. This demonstrates that low- and high-multiplicity events are disentangled with confidence.

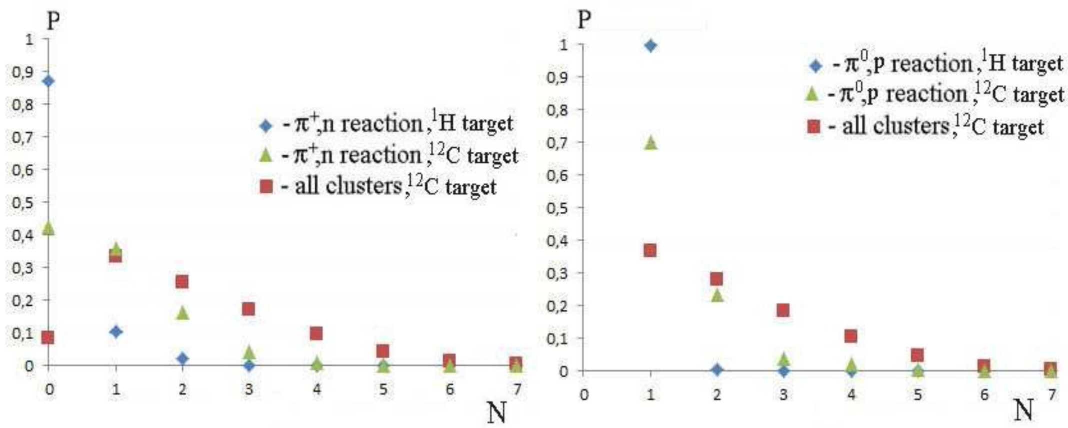


*Figure 6: Measured probabilities of proton emission together with $\pi+n$ (left panel) and $\pi^0p$ (right panel) emission in the photodisintegration of $^{12}C$. The data for probabilities to detect protons in $\pi+n$ and $\pi^0p$ reactions on the free proton are also shown to demonstrate the accuracy of particle identification procedure.*

Fig.7 show the angular distribution of high multiplicity events (n>7) in the laboratory system. We see that this distribution is isotropic in first approximation what demonstrates the cascade evaporation mechanisms of the process. Here it is averaged over the rather large number of nucleons (n > 7). As shown in [6], the most energetic primary recoils have the anisotropic distribution and can be separated from the cascade evaporation ones but the contribution is relatively small. More detailed analysis exceeds the frame of the present work.

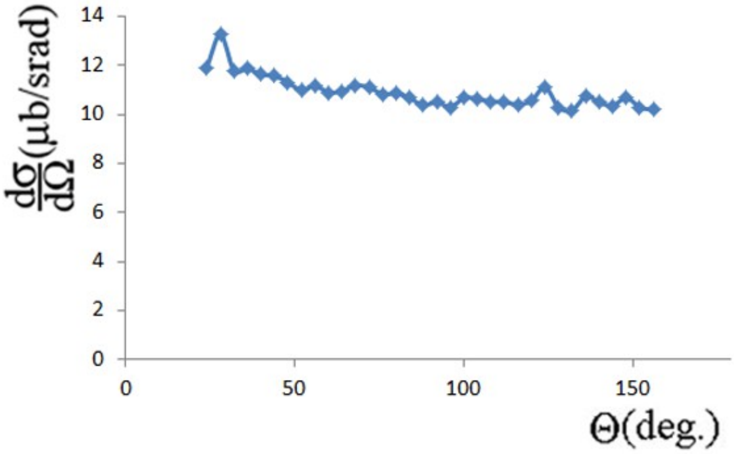


*Fig.7 : The angular distribution of nucleons in the laboratory system when their number is more than 7.*

**Conclusions**

First photonuclear experiment on the multifragmentation of light nuclei in the nucleon resonance energy region is sufficiently described by the cascade evaporation model RELDIS. An explosion mechanism of nuclear decay is available with small probability (≤ 0.1%). There is no difference between different projectiles (1 GeV photons, protons etc) reactions for the multifragmentation process.

What follows? What can give future photonuclear experiments? Evidently, the investigation program would be expanded to the region of heavier nuclei. One of new expected results can be related to the Primakoff effect, namely the coherent photoproduction of pseudo scalar and vector mesons by the Coulomb field of the nucleus. Contribution of such effect for heavy nuclei is not small in accordance with the preliminary results indicating the excess of 10% in the total photo absorption of heavy nuclei. That is the way to study the polarizabilities of $\pi$, $\eta$ – and other mesons. To realize this project a high resolution magnetic spectrometer in forward direction downstream of the target is required.

Also, it would be interesting to compare the experimental results on multifragmentation, obtained with real and virtual (Coulomb dissociation) photons.

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