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Emission of d, t, ^{3}He and α-particles from ^{12}C nuclei excited by intermediate energy photons

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Abstract. New GRAAL data on the fragmentation of carbon nuclei by photons at 800 - 1500 MeV are discussed. In addition to previously published results for the proton and neutron emission probabilities at different multiplicities, preliminary results on the yields of heavier fragments as d, t, ^{3}He and α-particles are presented. The obtained results are compared with theoretical predictions and other fragmentation data measured in different reactions induced by photons, electrons and relativistic ions.

1 Introduction

Motivation to study the nuclear fragmentation by photons at intermediate energies is caused by several reasons. At first, that is a way to investigate the nuclear dynamics leading to the creation of nuclear clusters in the final state of interaction. Such projectiles as photons allow to describe the process qualitatively and to test the theoretical predictions [1] with high accuracy. The positive feature of modern photonuclear experiments like the GRAAL is the possibility to use a monochromatic photon beam and large aperture detector with high enough spatial and energy resolution. To create a beam of monochromatic photons within 800 - 1500 MeV energy range, the backward Compton scattering method was used at the ESRF storage ring [2].

In this work, we continue an analysis of the GRAAL data [3] devoted to the nucleon fragmentation of ^{12}C nuclei to study nuclear fragments heavier than nucleons. New information is analyzed in terms of the dynamics of nuclear excitations and correlations of nucleons in nuclei. A comparison of present results with literature data available for different projectiles is done.

In frame of the RELDIS model the time scale for creation of nuclear products is shown in figure 1, taking from [1].

The time scale is presented in fm/c, where fm is equal to 10^{-13} cm, c is the light velocity. Time of flight for the photon through the carbon nucleus is about 10^{-23} sec, 100 fm/s correspond to $3{\cdot}10^{-22}$ s. One can see that all the fragments are created in the final state of interaction when a nucleus undergoes the transfer from the liquid to gas state.

1.1 The experimental procedure and results

The experiment was performed at the GRAIL facility [2] using a beam of tagged photons, produced by backward Compton scattering of laser photons on the electron storage ring ESRF. The detector

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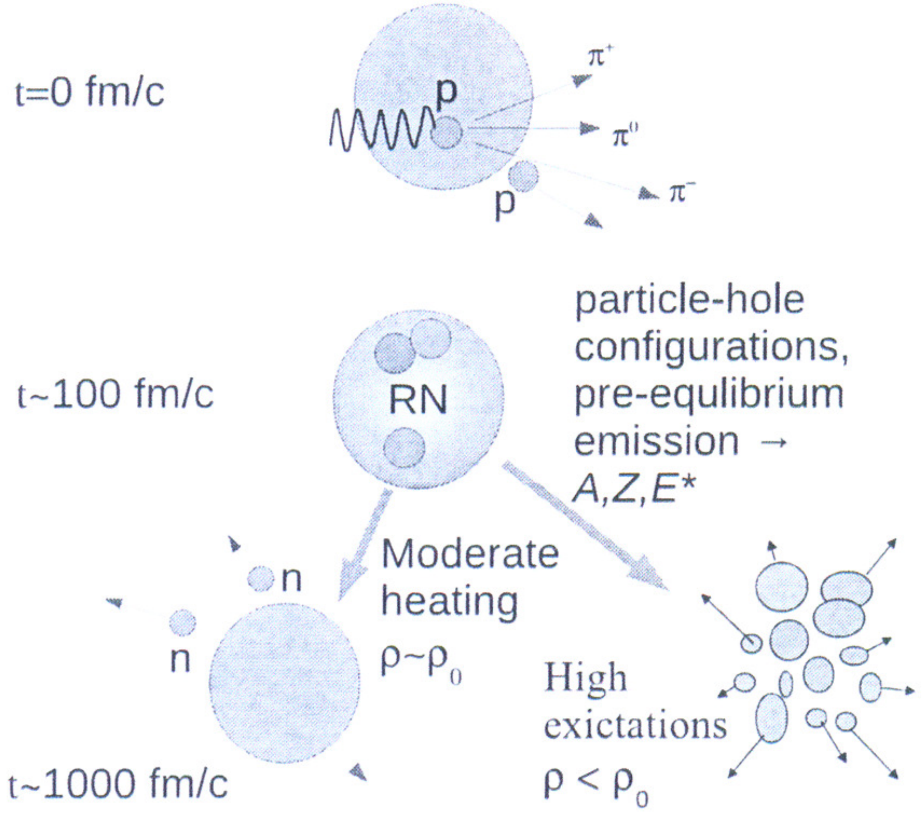

Figure 1. Dynamics of the multifragmentation process at intermediate energies [1].

LAGRANγE is described in detail in [4]. It consists of two main parts (see figure 2). The central part is organized to measure neutral and charged particles in a large solid angle close to 4π. Second part, situated at forward direction, allows measurement of particles using time of flight method with resolution about 0.6 ns, which corresponds to the energy resolution of $\approx$ 10% on the flight path of 3 m.

As seen in figure 1, the forward detector consists of the proportional chambers, two scintillation walls of plastic strips 10 cm wide and 3 cm thick, and showers calorimeter of five layers of plastic 5 cm thick and 5 mm thick lead. In previous work [3] to select the nucleons by shower calorimeter because the heavier fragments are absorbed by a plastic walls. In this paper, scintillation walls are included in the data analysis. Each scintillation strip, as well as shower calorimeter module was viewed from both ends by the photomultiplier tubes, what allowed determining the coordinates of the particles on the detector. So, the correction on the flight length for different emission angles of particles was done. The trigger for the data set served as a signal from the central part of LAGRANγE (BGO ball) in coincidence with the tagging system signal.

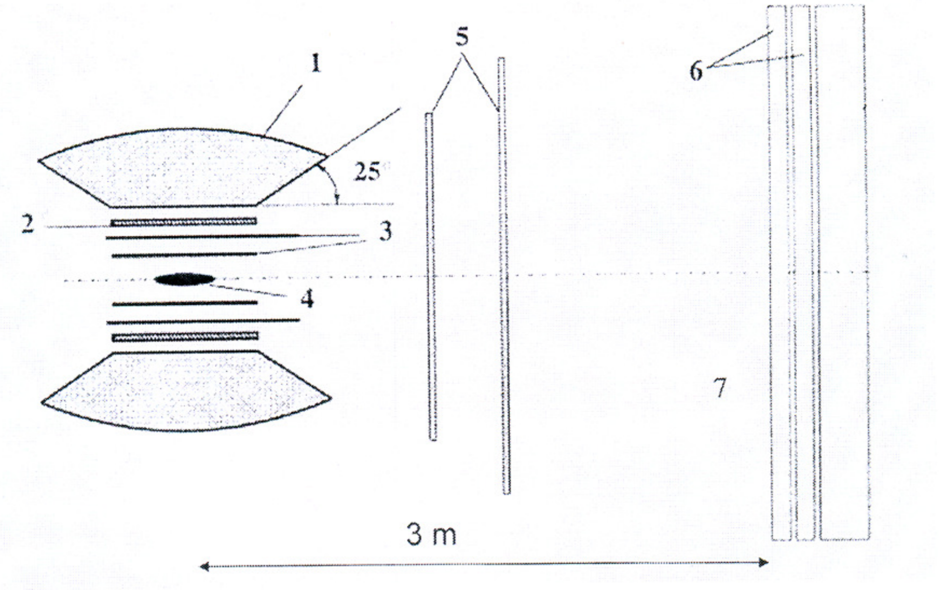

Figure 2. The detector LAGRANγE [6] of the experiment GRAAL [4]: BGO calorimeter (1), a plastic scintillation detector ring (2) is proportional to the cylindrical chamber (3), a target (4), flat proportional chamber (5), hodoscope of plastic scintillation detectors (6), shower detector (7).

The experimental results for the carbon target obtained with scintillation walls and shower calorimeter are shown in figure 3 and table 1 in comparison with simulations.

The simulation results for protons and fragments of different types are indicated by different colors. Such simulations take into account the intranuclear effects described by the RELDIS code [1], and the response function of the detector using the program LAGDIG [2].

Simulation and experiments show that fragments heavier than nucleons (^{2}D, ^{3}H, ^{4}He) are seen in the first scintillation wall clearly. The protons are separated in the calorimeter; heavier particles are absorbed in the walls.

Let us note some features of figure 3. Most of the fragments are concentrated within a band of (ΔE-TOF). The break in the slope of this band at the time of flight of about 18 ns means that the particle range exceeds the thickness of the detector, excepting the α - particles which have a high flight time (up to 100 ns) and consequently the small energy losses. The sharp peak at 12 ns, in the calorimeter corresponds to fast mesons and photons coming from the target to the wall with the speed of light. Scintillation walls do not indicate such peak because of low measurement efficiency for neutral particles. The significant background in all figures (black dots) is seen. This background corresponds to the scattered particles, probably neutrons.

As it is seen from figure 3, stripes of fragments of different types are overlapping. The main reason for that is the limited energy and ΔE resolution of the detectors. To extract the experimental values the same cuts as used in simulation were applied.

As simulations show, the energy resolution about 1% is required for a more reliable separation of the different observed fragments. Such resolution can be achieved using a magnetic spectrometer. This available facility is functioning at present in the collaboration BGO-OD in Bonn [5].

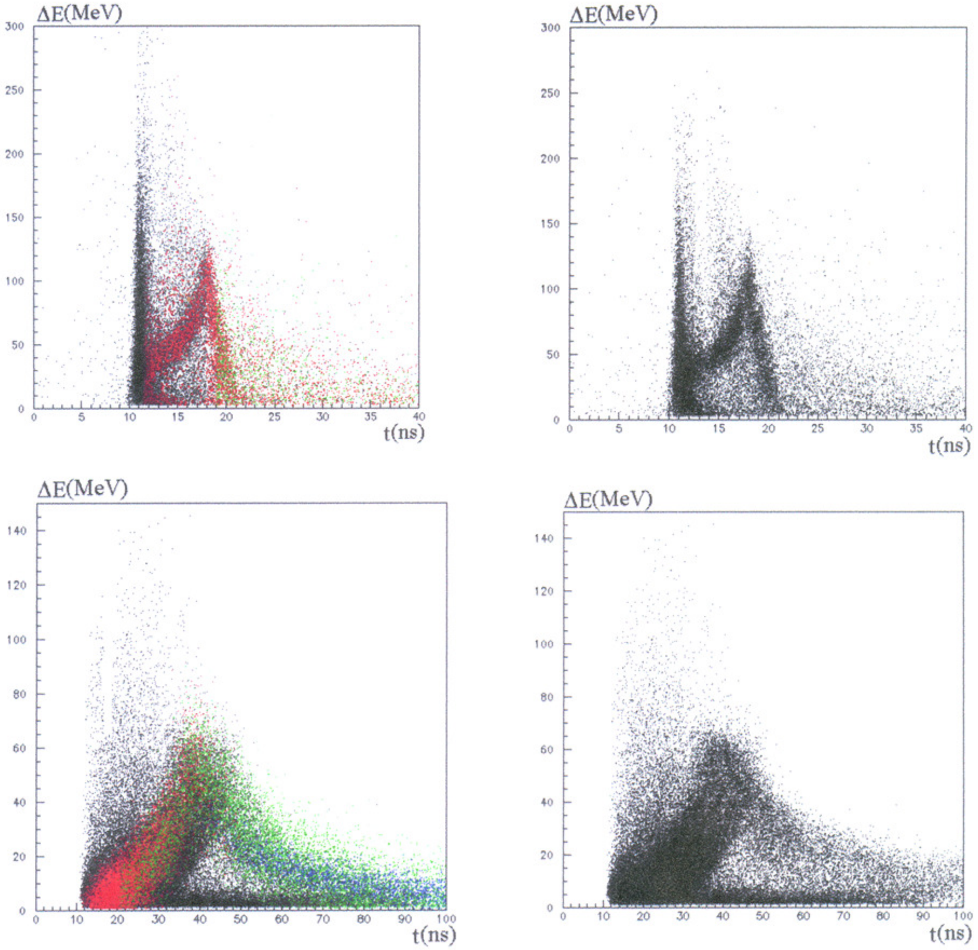

Figure 3. The dependence of the energy loss on the time of flight of the particles in the shower calorimeter (top) and scintillation wall (bottom). On the left: the results of simulations using the equal program RELDIS [5], on the right: the experimental data.

On the basis of the obtained data we can conclude that the experimental results for emission probabilities of deuterons, α- particles and tritium nuclei do not contradict the theoretical predictions [1]. The main feature is that the probability of fragmentation decreases with increasing mass of emitted fragments. This feature can be compared with another experimental results obtained with different projectiles.

1.2 Comparison of the nuclear fragmentation processes induced by real and virtual photons.

In accordance with the theoretical model [1], the mechanism of nuclear fragmentation depends primarily on their excitation energy. Below the meson production threshold, when the wavelength of the

Table 1. Relative probabilities of nuclear fragmentation evaluated from figure 3. Experimental values correspond to the yields from different detectors (two scintillation walls and shower calorimeter).

	First scintillation wall	First and second scintillation walls in coincidence	Shower calorimeter	Simulation
Protons	(53 ± 21)%	(73 ± 24)%	(91 ± 27)%	52%
Deuterons	(20 ± 11)%	(18 ± 12)%	(9 ± 6)%	18%
α-particles	(18 ± 11)%	(4 ± 3)%	-	18%
^{3}He	(5 ± 3)%	(2 ± 3)%	-	7%
^{3}H	(4 ± 3)%	(3 ± 3)%	-	5%

photon is comparable to the size of the nucleus, the most important role play the collective excitations, namely, giant resonances. Considering from this point of view, the data were obtained with beams of real and virtual photons (electrons and relativistic ions), when the excitation energy does not exceed 100 MeV.

So far, most of the experimental results on nuclear fragmentation by electrons and bremsstrahlung photons were obtained about 30 years ago (see for example the review [6]). The measured integrated yields were analyzed in term of real and virtual spectrum as seen in formula (1) :

$$\sigma_{e(q)}(E_e) = \frac{E_e \int\limits_0^{E_e} N^{\lambda L}(E_e, E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma/E_\gamma}{\int\limits_0^{E_e} N_V^{\lambda L}(E_e, E_\gamma)dE_\gamma} \quad . \tag{1}$$

In this formula, the symbols q and e correspond to real bremsstrahlung and virtual photons, respectively. So, the only difference is related to the photon spectra which are quite different for different projectiles, especially taking into account that λ means electrical or magnetic transition, L - multipolarity of interaction. In contrast to real photons having only transverse polarization, the virtual photons can have an admixture of the longitudinal components.

Qualitatively, in first approximation, the spectra of real and virtual photons are proportional to 1/E$_\gamma$. Therefore, we would expect the similar behavior of fragmentation probabilities for different projectiles. In fact, it is not so. Figure 4 shows the output of light fragments from ^{27}Al, irradiated by electrons with an energy of 800 MeV [7]. In the same figure the spectrum of virtual photons calculated by the model Weizscker - Williams [8] is shown. One can see that this spectrum strongly depends on the multipole interaction, where E1 transition dominates. Experimentally, the role of high multipole interactions in nuclei photo - fragmentation is not studied yet.

As already noted, for light nuclei including the beryllium and carbon, the main mechanism of absorption of photons in this energy range is associated with the excitation of the giant dipole resonance. In such case the main decay channel is the neutron emission one.

We now consider the fragmentation of relativistic nuclei by virtual photons of relativistic nuclei. The yield also can be described by formula (1) but the spectrum of photons does not depend on the multipolarity of interaction.

Data for splitting fragments heavier than nucleons were obtained primarily in emulsions experiments. Table 1 shows the results of the collaboration BECQUEREL [9] in comparison with our data.

Table 2 shows that the probability of proton emission at Coulomb dissociation close to 50%, as well as for a bundle of real photons. The main difference is that in the real beam of photons, a signifi-

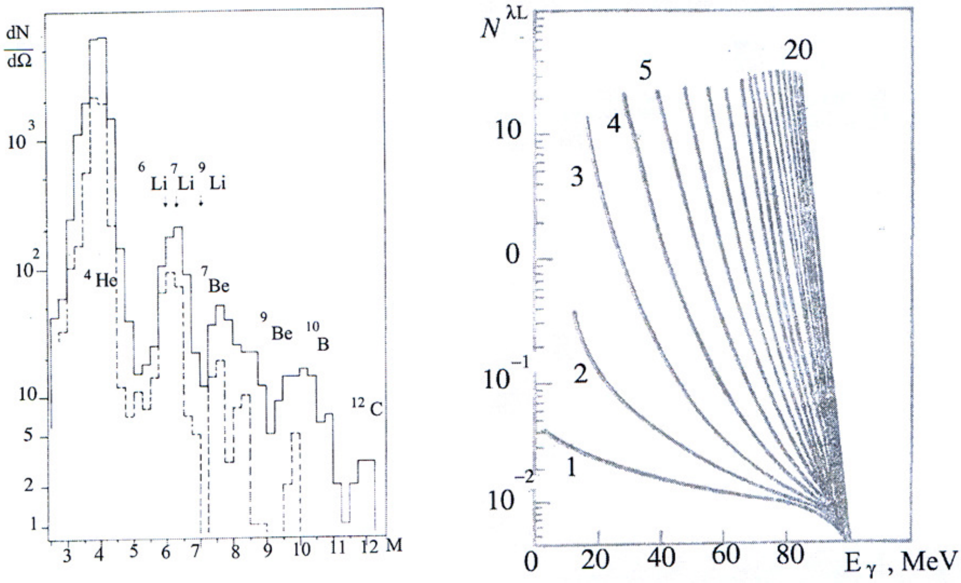

Figure 4. The yield of light fragments from the nucleus ^{27}Al by 800 MeV electrons [7]. Solid lines and dotted lines correspond to different methods of etching track detectors (experimental details see [7]). On the right, the spectrum of virtual photons for the uranium nucleus (Z = 92), is shown as the result of calculation in the long-wave Born approximation [8]. The numbers on the curves correspond to the multipole order of interactions.

Table 2. Distinguishing the probability of formation of light fragments in the Coulomb dissociation of relativistic nuclei ^{12}N and ^{11}C [9] at an energy of 1.2 GeV / nucleon in comparison with the data of the present work.

	^{12}C [simulation]	^{12}C Experiment (present work)	^{12}N Experiment[9]	^{11}C Experiment[9]
Proton	52%	53%	184 (68%)	204 (48%)
Deutron	18%	20%	0	0
^{3}H	5%	18%	0	0
^{3}He	7%	5%	0	0
^{4}He	18%	4%	75 (32%)	221 (52%)

cant contribution to output fragments comprise deuterons and tritium nuclei. In the case of relativistic nuclei are absent, while the departure α - particles of residual large and reaches approximately 20% relative to the total output. Obviously, this points to the fact that the dynamics of the processes of fragmentation under the influence of real and virtual photons in the Coulomb dissociation is different.

As it was already noted, the cause of the observed differences are likely to be found in the difference between the spectra of virtual and real photons, which have been shown in figure 4. However, this conclusion should be considered preliminary. For final output new experimental data and new theoretical assessment are required, primarily from the spectra of virtual photons.

The spectrum of virtual photons in the case of scattering of relativistic nuclei is usually expressed not dependent on the photon energy and the impact parameter b [10]:

$$N_{Z_1}(E_1, b) = \frac{\alpha Z_1^2}{\pi^2}\frac{x^2}{\beta^2 E_1 b^2}(K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)). \tag{2}$$

Here E_1 is the photon energy, Z - nuclear charge, γ- relativistic factor for the incident ion, K_0 and K_1 are the Bessel functions of the zero and first order, respectively. It can be seen that in all the above formulas, the photon energy is in the denominator. But the differences between the spectra of virtual photons to electrons and relativistic ions, as it is evident from the above formulas, very significant. It should be noted that they are all prepared using different model approximations and their accuracy is limited.

However, as it is already noted, even in light nuclei, such as beryllium or carbon basic mechanism of the Coulomb dissociation is associated with the excitation of the giant dipole resonance dominated photoneutron reaction. However, neutrons in the emulsion are not registered. The return target nuclei at these energies and momentum transfers of very small and also can not be registered. This casts doubt on the claims of orthodoxy coherence of the interaction of the incident photon with a nucleus. This raises also the question of why in the real photon coherent dissociation of sight.

Thus, since the conditions of experiments with real and virtual photons, which highlighted the "white star" essentially different, to compare them and make conclusions about the physical features of the mechanisms and dynamics of these reactions is difficult. This requires new experimental data carried out in the similar experimental conditions. This is even more needed more accurate theoretical evaluation of the spectra of virtual photons, or the results of their measurements, as proposed, for example, in [6].

2 Conclusion

In recent years, the level of photonuclear experiments at intermediate energies increased significantly. Firstly, this is due to the use of monochromatic photon beams, and secondly, with the creation of the detectors with a large solid angle and high energy and angular resolution. It is possible now to study photonuclear reactions with the formation of a large number of nucleons in the final state until the complete disintegration of the nucleus into separate nucleons. So, the new level to study the nucleon correlations in nuclei and cluster is available now. New developments are expected also with the help of a magnetic spectrometer in combination with a method of flight time.

An important motivation for these experiments is the presence of predictive framework based on modern theoretical models. In this study the dynamics of nuclear processes can be studied in photonuclear reactions for each of the partial meson photoproduction channel.

An additional incentive for the new experiments is possible to check the model calculations in the framework of quantum electrodynamics (the spectrum of virtual photons) to study the mechanisms of interaction of virtual photons with nuclei. Energy range of studies includes both the area of collective excitations of nuclei (giant resonances) and the region of nucleon resonances with photoproduction of mesons.

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References

[1] I. Pshenichnov et al., Phys. Rev. C **57**, 1920 (1998)
[2] J. P.Bocquet et al., Nucl.Phys. A **622**, 124 (1997)
[3] V. Nedorezov et al. (GRAAL collaboration), Nucl.Phys. A **940**, 264 (2015)
[4] M. Castoldi et al., NIM A **403**, 22 (2002)
[5] T. Zimmerman et al., JPS Conf.Proc. **10**, 032003 (2016)
[6] V. Nedorezov, Yu.N. Ranyuk, *Photofission above the giant resonance* (Naukova Dumka, Kiev, 1984)
[7] S. di Lierto, F. Merdi, G. Romqanio et al., Nucl.Phys. A **296**, 519 (1978)
[8] P. Durgapara, D.S. Onley, Phys.Rev. C **27(2)**, 523 (1983)
[9] P.I. Zarubin, Lect.Notes Phys. **875**, 51-93 (2014)
[10] I. Pshenichnov, Phys.Atom.Nucl. **78(6)**, 794-799 (2015)