2) the similar value $\Gamma_\alpha/\Gamma$ for the EQGR decay exceeds twenty percent, which is three times higher than the value of $\Gamma_\alpha^{st}/\Gamma$ calculated from the statistical theory of Hauser and Feshbach;

3) the experimental lowest value of the direct component $\Gamma_\alpha^\uparrow$ of the $\alpha$-decay of EQGR of $^{58}$Ni nuclei exceeds nearly by a factor of 2 the upper value $(\Gamma_\alpha^\uparrow)_{theor}$, calculated using the shell-model spectroscopic factors of $\alpha$-particles, and it is several times bigger than the result of estimation on the basis of the exciton model of excitation and decay of EQGR.

We would like to stress that many works mentioned above were carried out due to elaboration of the method of an internal thin target placed directly into the vacuum chamber of the synchrotron and allowing multiple crossing of the target by the accelerated electrons [11].

# References

[1] *V.P.Chizhov, V.P.Fominenko, G.A.Kolomensky, E.F.Lakovichev, E.D.Makhnovsky, A.V.Nadtochy, V.V.Popov, Yu.M.Volkov.* // Yad. Fiz., 1978. V.27. P.868.

[2] *V.P.Chizhov.* Doctor's Thesis, Leningrad, LNPI, 1990.

[3] *V.P.Chizhov, G.A.Kolomensky, E.D.Makhnovsky, Yu.M.Volkov.* // LNPI Research Report 1988-1989, Leningrad, 1990. P.74.

[4] *V.P.Chizhov, V.P.Fominenko, G.A.Kolomensky, E.F.Lakovichev, E.D.Makhnovsky, V.V.Popov, Yu.M.Volkov.* // Yad. Fiz., 1986. V.44. P.1153.

[5] *E.A.Kotikov, E.D.Makhnovsky.* // Yad. Fiz., 1985. V.41. P.289.

[6] *V.P.Chizhov, V.P.Fominenko, A.I.Ignatiev, G.A.Kolomensky, E.F.Lakovichev, E.D.Makhonovsky, A.V.Nadtochy, V.V.Popov, Yu.M.Volkov.* // Pis'ma Zh. Eksp. Teor. Fiz., 1979. V.30. P.67.

[7] *V.P.Chizhov, V.P.Fominenko, A.I.Ignatiev, G.A.Kolomensky, E.F.Lakovichev, E.D.Makhnovsky, A.V.Nadtochy, V.V.Popov, Yu.M.Volkov.* // Yad.Fiz., 1980. V.32. P.595.

[8] *V.P.Chizhov, V.P.Fominenko, A.I.Ignatiev, G.A.Kolomensky, E.A.Lakovichev, E.D.Makhnovsky, A.V.Nadtochy, V.V.Popov, Yu.M.Volkov.* // Proc. the 5th Seminar of INR, Moscow, 1982. P.120 (in Russian).

[9] *V.P.Chizhov, V.P.Fominenko, A.I.Ignatiev, G.A.Kolomensky, E.F.Lakovichev, E.D.Makhnovsky, A.V.Ignatiev, V.V.Popov, Yu.M.Volkov.* // Izvestiya Akademii Nauk SSSR, Ser. Fiz., 1983. V.47. P.182.

[10] *V.P.Chizhov, G.A.Kolomensky, Yu.M.Volkov.* // Yad. Fiz., 1989. V.50. P.305.

[11] *V.P.Chizhov, V.P.Fominenko, G.A.Kolomensky, E.F.Lakovichev, Yu.M.Volkov.* // Prib. Tekh. Eksp., 1986. No 4. P.31.

The information on the widths was obtained from the cross sections of electronuclear reactions $A(e,a)$ initiated by electrons with the energy $E_0$,

$$\sigma_{e,a}(E_0) = \int_0^{E_0} \sum_{\lambda L} \sigma_{\gamma a}^{\lambda L}(E_\gamma) N^{\lambda L}(E_0, E_\gamma, Z) E_\gamma^{-1} dE_\gamma, \tag{1}$$

and photonuclear reactions $A(\gamma,a)$ initiated by real photons of bremsstrahlung ($br.$) of electrons with the energy $E_0$,

$$\sigma_{br.\gamma,a}(E_0) = N_r \int_0^{E_0} \sum_{\lambda L} \sigma_{\gamma a}^{\lambda L}(E_\gamma) \Phi(E_0, E_\gamma, Z) E_\gamma^{-1} dE\gamma. \tag{2}$$

From this data, the cross sections $\sigma_{\gamma,a}^{E1}(E_\gamma)$ and $\sigma_{\gamma,a}^{E2}(E_\gamma)$ were determined as a solution of integral equations of the type (1) and (2). Here $a \equiv p, \alpha$; $\lambda L$ – the multipolarity of transitions ($\lambda L \equiv E1, E2$); $N^{\lambda L}(E_0, E_\gamma, Z)E_\gamma^{-1}$ – the number of virtual photons absorbed by the nucleus with the atomic number $Z$; $\Phi(E_0, E_\gamma, Z_r)E_\gamma^{-1}$ – the cross section for the process of bremsstrahlung production by electrons in the target-radiator with the atomic number $Z_r$, $N_r$ – the number of nuclei per 1 cm$^2$. Fig. 6 shows some results of this work.

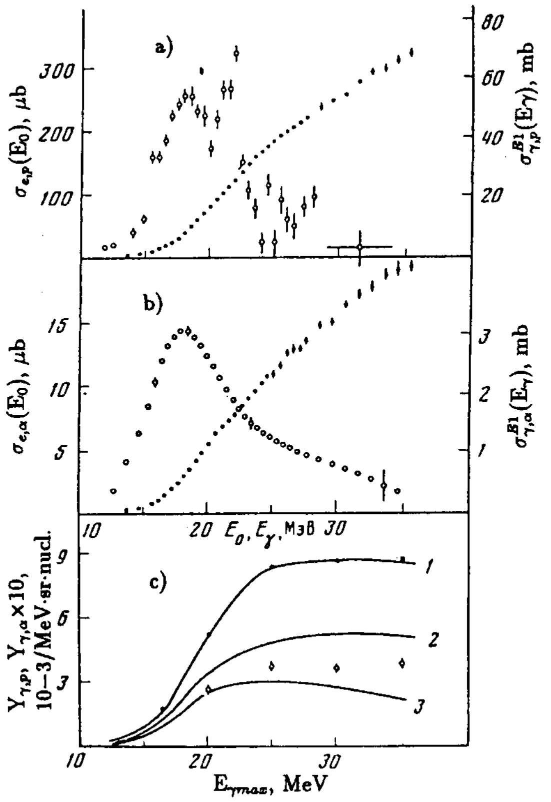


**Fig. 6.** a) Cross sections of the reaction $^{58}$Ni$(e,p)$ (solid circles) and the reaction $^{58}$Ni$(\gamma,p)$ (open circles); b) the same for $(e,\alpha)$- and $(\gamma,\alpha)$-reactions; c) yields of protons $\sigma_{br.\gamma,p}(E_0) \equiv Y_{\gamma,p}$ (solid circles) and of $\alpha$-particles (open circles), curves 1 and 2 – yields of protons and $\alpha$-particles, accordingly, for E1–transitions only, curve 3 – yield of $\alpha$-particles for E2–transitions only.

The analysis of the measured cross sections of the electronuclear reactions $A(e,p)$ and $A(e,\alpha)$ in the energy range $E_0$ = 12–35 MeV and the photonuclear reactions $A(\gamma,p)$ and $(\gamma,\alpha)$ as the function of $E_{\gamma max}$ (A: $^{60}$Ni, $^{58}$Ni, $^{40}$Ca, $^{27}$Al) has shown that

1) the average relative width of the $\alpha$-channel ($\Gamma_\alpha/\Gamma$ of the EDGR decay is a few percent, which can be explained with the theory of statistical mechanism of the $\alpha$-decay of compound states;

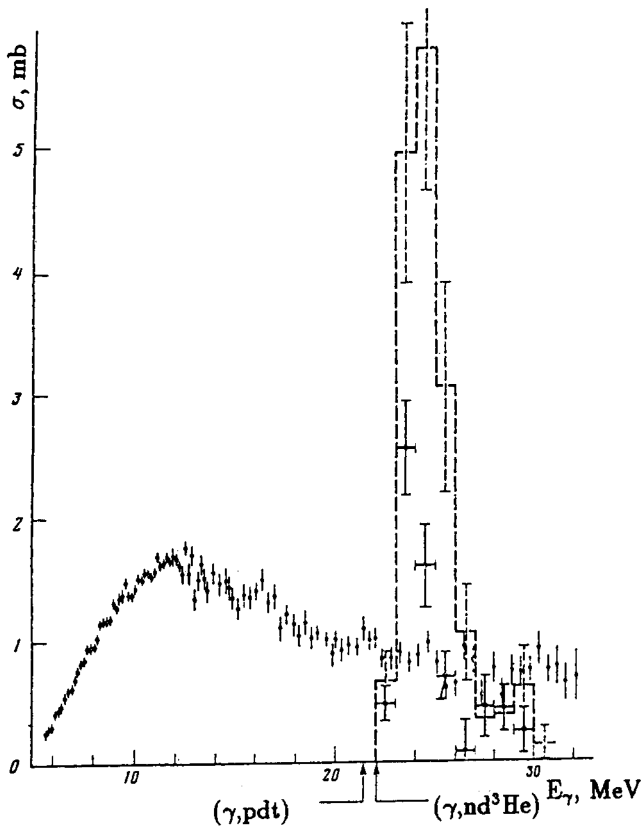


**Fig. 4.** Cross sections of the reaction $\gamma + {}^6Li \rightarrow p + t + d$ (histograms and solid circles with error bars) and that of the photonuclear reactions ${}^6Li(\gamma, n)X$ including the reaction ${}^6Li(\gamma, n{}^3He d)$.

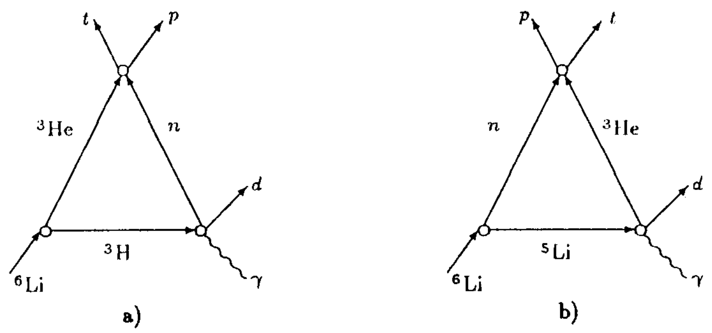


**Fig. 5.**

## Radiation transitions following the electrodisintegration of $^7$Li nuclei to triton and $^4$He in the ground state

The electrodisintegration of $^7$Li to a triton and an $\alpha$-particle by virtual photons with the energies less than the binding energy of a nucleon in $^4$He nuclei ($E_\gamma \leq$22 MeV) was observed for the first time [2,4]. In this reaction the third particle, which is formed along with a triton ($E_t \leq 6$ MeV) and an $\alpha$-particle, is defined as a photon with the energy $E_{\gamma'} = 8 \pm 1$ MeV. The result of this analysis of the experimental data is in correspondence with the well-known result of B.S.Ishanov et al. (Yad. Fiz., 1981. V.33. P.28) who observed in the spectrum of bremsstrahlung $\gamma$-quanta scattered by the $^7$Li nuclei a peak at the energy $E_{\gamma'} = 8.5 \pm 0.1$ MeV (close to the value of the binding energy of nucleons in a triton) attributed by the origin to the hypothetical reaction $\gamma+^7\mathrm{Li}\longrightarrow t + \alpha + \gamma'$, in which the photon $\gamma'$ is a result of a synthesis of triton from three nucleons in the excited $^7$Li nucleus.

## Near-threshold effects of photodisintegration of $^6$Li nuclei to $p + d + t$

One may think that the effects of excitation of the EDGR in $^6$Li and $^7$Li nuclei would manifest themselves in photonuclear reactions initiated by photons with the energies of $\leq$ 30 MeV. However, it turned out that in this energy range of photons there were no striking experimental facts observed that could illustrate the theory of configurative splitting of EDGR. The results of Ref. [5] give a quite obvious indication of the cluster structure of these nuclei and direct mechanism of the interaction of photons with nuclei. In this work, the reaction $\gamma+^6\mathrm{Li}\rightarrow\ p + t + d$ (1) was identified by the analysis of three-prong stars in a nuclear emulsion loaded with $^6$Li nuclei and irradiated by bremsstrahlung $\gamma$-quanta with $E_{\gamma_{max}}$= 46 MeV. The established fact that this reaction dominates over the charge-conjugated reaction $\gamma+^6\mathrm{Li}\rightarrow n+^3\mathrm{He}+d$ (2) in the near-threshold region of $\gamma$-quanta energies 22–24 MeV is illustrated by Fig. 4.

This observation was explained qualitatively [5] and quantitatively (E.I.Dubovoy, G.I.Chitanova, Yad. Fiz., 1987. V.45. P.677) on the basis of the theory of photonuclear reactions near the energy threshold which considers a mechanism stipulated by the triangle Feynman diagrams. It was shown that the triangle diagrams presented in Fig. 5 define the amplitude of reaction (1). In the near-threshold region this amplitude turns out to be much larger than the amplitudes of reaction (2) calculated with all relevant triangle diagrams being taken into account. In another words, the phase space of reaction (1) is larger than that of reaction (2).

## Alpha-decay of giant resonances of medium nuclei

The investigation of the $\alpha$-particle modes of decay of EDGR and EQDR [1] of medium nuclei was carried out at the PNPI synchrotron [2,6–10]. The determination of widths of the direct ($\Gamma^\uparrow$) and statistical ($\Gamma^\downarrow$) decays is a problem to solve in order to elucidate the structure of resonances.

[1]electric quadrupole giant resonance

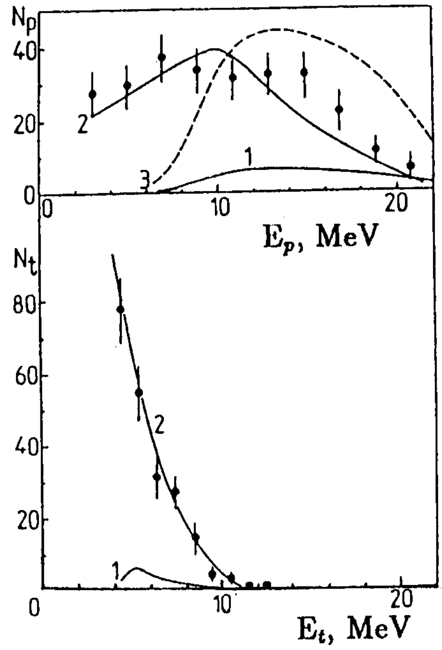


**Fig. 3.** Energy distribution of coinciding protons and tritons in the $^6$Li$(\gamma, pt)$X reaction (solid circles). Curves 1 and 2 correspond to calculations in the version of the process of photodisintegration of $\alpha$-clusters in $^6$Li nucleus to a proton and a triton in the presence of a deuteron spectator and of a $pn$-pair spectator, accordingly, curve 3 corresponds to the version when the three-particle reaction $^6$Li$(\gamma, pt)d$ dominates.

3. Absolute magnitudes of the cross sections for photodisintegration of $\alpha$-clusters in $^{6,7}$Li constitute about a half of the total cross section of photon absorption by the nuclei.

4. Only small contribution to the reaction $^{6,7}$Li$(\gamma, ab)$X arises from excitation of quasi-stationary states of mother nuclei $^6$Li$^*$ ($^7$Li$^*$) and their decay to a single nucleon and excited residual nucleus $^5$He$^*$ ($^6$He$^*$) which decays then to single charged composite particles $d$ and $t$ ($t$ and $t$), or from the direct knock out of protons from the $s$-shell of of $^6$Li ($^7$Li) with the formation of the same residual nuclei $^5$He$^*$ ($^6$He$^*$).

## Investigation of reactions $^7$Li$(e, a)$X ($a \equiv t$, $^3$He, $^4$He)

As a result of investigation of the electronuclear reaction $^7$Li$(e, a)$X ($a \equiv t$, $^3$He, $^4$He) initiated by virtual photons with the energy of (42±2) MeV [2,3], the differential cross sections for inclusive reactions $^6$Li$(\gamma, t)$X and $^7$Li$(\gamma,^{3,4}$He)X were obtained, and it was established that:

1. Experimental data (the shape of the energy distribution of tritons and the absolute magnitude of the cross section for the reaction $^7$Li$(\gamma, t)$X) are in agreement with the conclusion made earlier [1] on the basis of the analysis of the $^7$Li$(\gamma, ab)X$ reaction claiming that the cluster mechanism of the photon absorption by $^7$Li is the dominant one.

2. There is no evidence of formation and decay of excited mother nucleus $^7$Li$^*$ or direct knock out of nucleons from the $s$-shell, which leads to formation of the excited residual $^6$He$^*$ nucleus decaying with the emission of an $\alpha$-particle and two neutrons.

Table

Relative number of $(ab+ba)$ coincidences (experiment and calculation); reaction $^6$Li$(\gamma, ab)$X; $\Theta_1 = 90°$, $\Theta_2 = 76°$

| Coincidence mode $ab+ba$ | Relative number of coincidences | Dynamics of $\alpha$-cluster photodisintegration | | Phase space dynamics | | Process of consecutive decay $^6$Li$(\gamma,p)^5$He$^*$ $\searrow d+t$ |
|---|---|---|---|---|---|---|
| | | reaction $^6\mathrm{Li}(\gamma,{}^{tp}_{pt})d$ | reaction $^6\mathrm{Li}(\gamma,{}^{tp}_{pt})pn$ | reaction $^6\mathrm{Li}(\gamma,{}^{tp}_{pt})d$ | reaction $^6\mathrm{Li}(\gamma,{}^{tp}_{pt})pn$ | |
| $tp+pt$ | 1.00±0.04 | 1 | 1 | 1 | 1 | 1 |
| $td+dt$ | 0.14±0.01 | <0.01 | | 1.3 | | |
| $pd+dp$ | 0.20±0.06 | <0.01 | | 1.3 | | >1 |
| $pp$ | 0.18±0.02 | | 0.15 | | 0.45 | |
| $dd$ | 0.02±0.005 | | | | | |

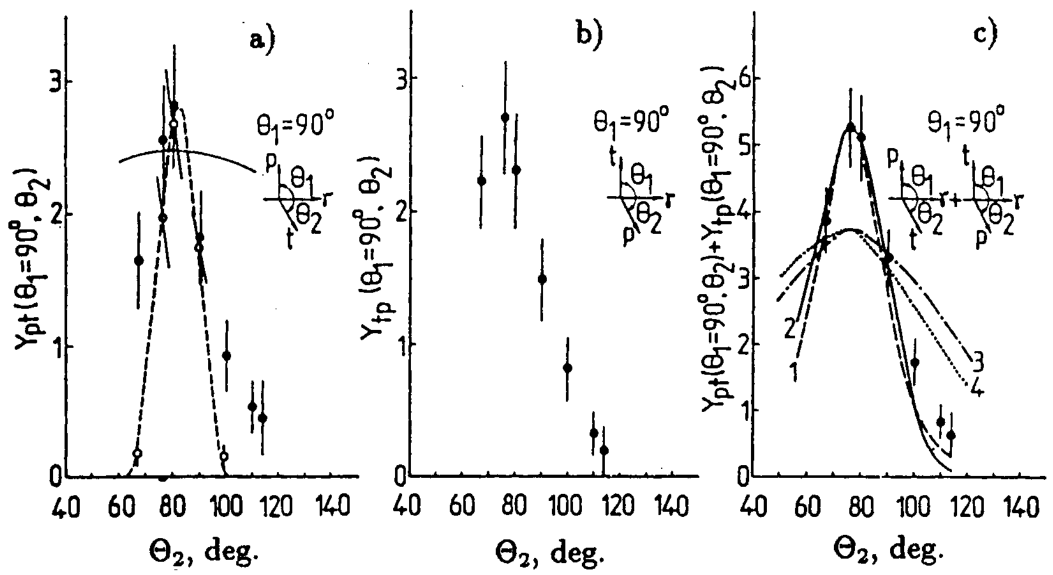


**Fig. 2.** The angular correlation of proton-triton emission in the reaction $^6$Li$(\gamma, pt)$X (solid circles); vertical scale is $1.72\times10^{-32}$ cm$^2$/(MeV·sr$^2$). Open circles reflect the angular resolution of the apparatus obtained by measuring the yield of reaction $^6$Li$(\gamma, t)^3$He. Solid curve in a) is the phase space dynamics. Curves 1 and 2 in c) – proton and triton angular correlation in the version of photodisintegration of $\alpha$-clusters in the presence of the deuteron spectator (1) and the $pn$-pair spectator (2); curves 3 and 4 correspond, respectively, to the version of the process of knock out of protons from the $s$-shell with formation of $^5$He$^*$ decaying to $d+t$ and to the version of excitation of EDGR of nuclei $^6$Li$^*$, which decay then by the emission of a proton with the formation of the residual nucleus $^5$He$^*$ in highly excited hole states.

(diagram a) in Fig. 1).

$$\gamma+{}^6\text{Li}\longrightarrow{}^6\text{Li}^* \longrightarrow p(n)+{}^5\text{He}^*({}^5\text{Li}^*)$$
$$^5\text{He}^* \longrightarrow^* d+t; \qquad {}^5\text{Li}^* \longrightarrow d+{}^3\text{He}.$$

$$\gamma+{}^7\text{Li}\longrightarrow{}^7\text{Li}^* \rightarrow p(n)+{}^6\text{He}^*({}^6\text{Li}^*)$$
$$^6\text{He}^* \longrightarrow t+t; \qquad {}^6\text{Li}^* \longrightarrow t+{}^3\text{He}.$$

At the same time, for explaining the magnitude and the energy dependence of the total cross section $\sigma_{tot}(E_\gamma)$ of photon absorption by these nuclei up to the energy of 100 MeV, alternative theories of the photonuclear absorption process were suggested: the theory of direct photoeffect (diagram b) in Fig. 1) and the theory of direct photodisintegration of clusters (diagram c) in Fig. 1).

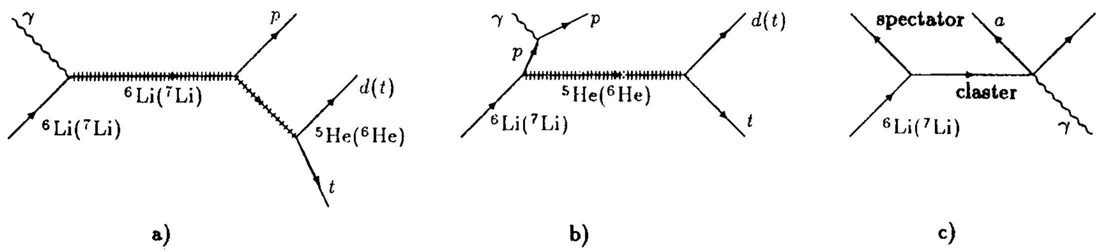


**Fig. 1.**

All the three theories, without pretending to describe photoabsorption quantitatively, were able to reproduce qualitatively with more or less equal success the experimental function $\sigma_{tot}(E\gamma)$.

To choose the most realistic theory, it was necessary to identify various particles produced in nuclear reactions and to measure their angular and energy correlations. For the first time experiments of that kind were carried out at the PNPI synchrotron. Exclusive reactions $^{6,7}\text{Li}(\gamma, ab)\text{X}$ [1,2] initiated by the bremsstrahlung of electrons with the energy $E_0 = 55$ MeV were investigated (here $a$ and $b$ are the charged particles: one is emitted at the fixed angle $\Theta_1 = 90°$, and the other – at the varying angle $\Theta_2$). The established type of particles $a$ and $b$ and the relative frequency of $(a, b)$-coincidences ($\Theta_1$=90°, $\Theta_2$=76°) are shown in Table. The relative numbers of events expected in different versions of the mechanism of photodisintegration of nuclei are also shown there. The angular correlations and the energy distributions of protons and tritons in the reaction $^6\text{Li}(\gamma, pt)\text{X}$ are shown in Figs. 2,3.

As the result of the analysis of the experimental data, several new facts were established:

1. In the considered photonuclear reactions the absorption of photons occurs in the range of 30–55 MeV by the clusters in nuclei $^6$Li and $^7$Li of the type $^2$He,$^3$He, $^5$He,$^6$He which decay then into two particles $(a, b)$ with the nuclear residual X as a spectator.

2. In the process of the photodisintegration of $\alpha$-clusters in $^6$Li to the $pt$ pair, the spectators appeared to be more often $pn$ pairs but not deuterons (in the ratio of 3:1). In the case of $^7$Li nuclei, the spectators are tritons and $pnn$ triplets (in the ratio of 1:1).

# EXPERIMENTS AT PNPI ELECTRON SYNCHROTRON

V.P.Chizhov

A synchrotron accelerating electrons up to 100 MeV was operated from 1952 to 1967 in the Leningrad Physical-Technical Institute (LPTI). It was A.P.Komar's brainchild created on the basis of a magnet brought from Moscow. In less than two years, a team of young scientists headed by A.P.Komar not only restored the synchrotron as a working accelerator of electrons, but also developed experimental methods and equipment for the investigation of photonuclear reactions. The methods were developed for stabilizing the energy of accelerated electrons and the beam intensities, for precise variation of the electron energy, for measuring the energy of the bremsstrahlung beam intersecting the target. These methods made the synchrotron a comfortable and promising instrument for investigation of the photonuclear reactions at that time. The main contributions were made by N.N.Chernov as the chief engineer of the synchrotron, by A.V.Kulikov, G.F.Mikheev, V.P.Fominenko, B.K.Shcherbakov, V.P.Yashukov, S.P.Kruglov, and I.V.Lopatin.

Many of the experiments undertaken at that time were aimed at determination of the photonuclear absorption mechanism and at the choice of nuclear structure models. For example, by investigations of the $A(\gamma,p)X$ reactions, initiated by gamma-quanta with energies of $\geq$50 MeV, the mechanism of the direct knock out of nucleons by photoeffect (from $^{12}$C and heavier nuclei) and the mechanism of quasideuteron absorption of photons were revealed (E.B.Bazhanov, Yu.M.Volkov, L.A.Kulchitski, V.P.Chizhov). Also, the "pick-up" mechanism of high energy deuterons formation was determined (Yu.M.Volkov, A.V.Kulikov, L.A.Kulchitski, V.P.Chizhov). A method for separation of partial channels of the $A(\gamma,a)X$-reactions ($a$ – charged particle) was developed by V.P.Denisov, L.A.Kulchitski, I.Ya.Chubukov on the basis of the yield of the reactions initiated by a bremsstrahlung with different values of $E_{\gamma max}$. Experiments were carried out with the aim to check the theory of the configurative splitting of the giant electric dipole resonances (EDGR) of 1$p$-shell light nuclei. Photonuclear absorption cross sections for argon, neon, and krypton nuclei were measured (I.P.Yavor – Wilson chamber), a number of experiments on nuclear fission was made (B.A.Bochagov – ionization chamber), the nuclear photoemulsion method was developed (E.G.Stepanova and E.D.Makhnovsky). Certainly, we have not mentioned here all the experiments carried out at the synchrotron at that time.

In 1967 the synchrotron was moved to PNPI and in two years it started to work again (to a great extent due to V.P.Fominenko). We will mention here some experiments carried out at PNPI.

## Investigation of reactions $^{6,7}$Li$(\gamma,ab)$X

At that time, the theory of configurative splitting of the EDGR in the 1$p$-shell light nuclei ($^6$Li, $^7$Li, $^9$Be) was developed. It was stated that, as a consequence of a large difference in the binding energy of the 1$p$-shell and 1$s$-shell nucleons (up to 15–20 MeV), the EDGR in these nuclei does not form a compact resonance but turned out to be smeared over a wide interval of the excitation energy about 40 MeV and more. It was predicted that the transitions from the 1$s$ shell should be most intense and the decay of these excited nuclear states would take place (by the selection rules, according to Jung's scheme) due to emission of composite particles