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PHOTOPROTON PRODUCTION BY 0.13 AND 0.25 GEV BREMSSTRAHLUNG

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ФОТООБРАЗОВАНИЕ ПРОТОНОВ НА ЯДРАХ В ОБЛАСТИ ЭНЕРГИИ γ -КВАНТОВ ДО 0,25 ГЭВ

В работе приведены экспериментальные данные по инклюзивному фотообразованию протонов на ядрах C^{12}, Mg^{24}, Cu^{63}, Sn^{118} и Pb^{208}, облученных тормозными γ -квантами с максимальной энергией 0,13 Гэв и 0,25 Гэв. Были исследованы области углов $30^0 - 90^0$ и импульсов фотопротонов 0,24 - 0,48 Гэв/с. Анализ энергетических спектров показывает, что если инвариантное сечение (выход) представить в виде $f \sim exp(-BP^2)$, то параметр наклона В меняется сильно с изменением энергии γ -квантов в области до 0,25 Гэв и незначительно - при изменении атомного числа ядра-мишени, т.е. имеет место ядерный полускейлинг. Особый интерес представляет А-зависимость инвариантного сечения (выхода). Если его представить в виде $f \sim A^n$, то показатель n меняется скачком со значения 0,6 до 1,15 при переходе $(E_\gamma)_{макс.}$ от 0,13 Гэв к 0,25 Гэв для одинаковых углов и импульсов регистрируемых протонов. Такой скачок в значении n свидетельствует о большом вкладе в образовании кумулятивных протонов, обусловленном механизмом перепоглощения фотопионов в ядре-мишени.

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1. Introduction

Recent investigations of the inclusive production of particles on nuclei resulted in both cumulative effect [1,2,3] and nuclear scaling [4,5,6]. The essence of the cumulative effect is that one can experimentally observe the particles whose production at collision with a free nucleon is kinematically forbidden. According to the hypothesis of nuclear scaling, if for cumulative protons and other baryons the invariant normalized cross section can be presented as

$$\rho = \frac{1}{\sigma_t} f = \frac{1}{\sigma_t} \frac{E}{P^2} \frac{d^2\sigma}{dP\,d\Omega} = C \exp(-T/T_0) \simeq C \exp(-BP^2) \qquad (1)$$

where T, P and E is respectively the kinetic energy, the momentum and the total energy of the detected particle, σ_t is the total cross section, C, B and T_0 are the constants, then the parameters C and B do not depend on both the type and the energy of the incident particle, and besides, B does not depend on the target nucleus [4-10]. The above invariances can be achieved asymptotically at initial energies 2 ÷ 3 GeV.

At present there is a number of theoretical models [11-15] to explain the cumulative effect and the nuclear scaling. Nevertheless, none of them permits to finally reveal the physical nature of these phenomena.

For further development of theoretical representations the investigations at low energies seem to be useful. In the case of primary protons with the energy less than 100 MeV this problem was discussed in Ref. 16 and it was found that the parameter B in Eq.(1) is independent of the target nucleus, but considerably varies with the incident energy. The author of Ref. 16 called this phenomenon semi-scaling and made an attempt to explain the experimental results by a pre-equilibrium particle emission model[17,18].

In the present work the experimental data on proton photoproduction at maximum energy of bremsstrahlung γ-quanta 0.13 GeV and 0.25 GeV on different nuclei and for different kinematic conditions are given.

2. Experimental data.

The results are obtained at Kharkov 300 MeV electron linear accelerator. The detailed description of the experimental facility is given in Ref.19.

The yield of protons from different nuclei irradiated by 0.13 and 0.25 GeV electrons was measured. The intensity of the electrons which passed through the target was measured with the secondary-emission monitor with the relative errors of 2-3%. The protons were identified by the "momentum-range" method. The momentum was measured by means of magnetic analysis, whereas the range was measured with the scintillator counter by the "maximum-pulse" method.

In fact the summary yield of protons was measured in the following two reactions

$$\gamma + A \to P + A' \tag{2}$$

$$e + A \to e' + P + A' \tag{3}$$

The cross section $(d^2\sigma/d\Omega dE)_e$ of reaction (3) can be expressed by the cross section $(d^2\sigma/d\Omega dE)_\gamma$ of reaction (2) by the following experimentally checked expression[20, 21].

$$(d^2\sigma/d\Omega dE)_e = 0,02\,(d^2\sigma/d\Omega dE)_\gamma \tag{4}$$

Then the measured summary cross section of reactions (2) and (3) is

$$(d^2\sigma/d\Omega dE)_{ex} = \left(0,02 + t + \frac{t_\mu}{2}\right)(d^2\sigma/d\Omega dE)_\gamma \tag{5}$$

where t_μ and t are thicknesses of the target and the whole material up to the target, respectively, in rad. len. Thus

$$(d^2\sigma/d\Omega dE\,Q)_\gamma = (d^2\sigma/d\Omega dE\,Q)_{ex}\cdot\left(0,02 + t + \frac{t_\mu}{2}\right)^{-1} = C\,\frac{N_{ex}}{\Delta\Omega\Delta E N_n Q} \tag{6}$$

where $Q = \left(0,02 + t + \frac{t_\mu}{2}\right)N_e$ is the number of equivalent γ-quanta, N_e is the number of incident electrons, N_{ex} is the number of detected secondary protons, C takes into account the corrections caused by the absorption of protons in the target and in the detector's material, by decreasing of the number of equivalent γ-quanta due to the pair production in the target, by the energy losses in the target and by the Coulomb barrier of target-nucleus.

For the two values of the incident electron energy E_e =0.13 GeV and 0.25 GeV were carried out three groups of measurements in which the dependences of the invariant cross section of reactions (2) and (3) on the detection angle and energy of the secondary protons as well as on the atomic number of the target-nuclei were investigated.

If the processes (2) and (3) are considered on a free nucleus, then at $E_\gamma \leq$ 0.25 GeV the two processes of proton photoproduction are possible i.e. the π-meson photoproduction and the Compton effect. For $E_\gamma \leq$0.13 MeV only the second process is possible. Fig.1 shows the kinematic curves of these processes and of experimentally measured phase points. As is seen in the case of $E_\gamma \leq 0.25$ GeV, the protons from the π -meson photoproduction are possible only in three points (T_p =40 MeV and 50 MeV, ϑ_p =30 ; T_p =40 MeV; ϑ_p =35°). In other cases the protons are cumulative relative to the - photoproduction. For the Compton effect the six points are kinematically allowed (T_p =40 and 50, 60 MeV at ϑ_p =30° and ϑ_p =35°, 40°, 45° at T_p =40MeV). The other points are cumulative. At $_\gamma \leq$ 0.13 GeV all the measured points are cumulative, too.

3. Discussion

a) Angular dependence. Fig.2 shows the angular dependences of the invariant cross sections for P_p =0.29 GeV/c, 0.34 GeV/c and 0.40 GeV/c at E_e =0.25 GeV on C^{12} , Cu^{63} and Pb^{208} and at E_0=0.13 MeV on C^{12}. As one can see, all the angular dependences are nearly similar. A considerable asymmetry can be observed at $\vartheta_p < 60$. Such a behaviour testifies to a possible significant contribution of the evaporation processes at these angles. It is necessary to specially note the fact that the angular distributions on C^{12} at $(E_\gamma)_{Max}$=0.13 GeV and 0.25 GeV are identical (at the same proton momenta), though at $(E_\gamma)_{Max}$=0.25 GeV the essential contribution to the proton yield gives the process of π -meson photoproduction[22], while at $(E_\gamma)_{Max}$=0.13 GeV this mechanism is forbidden.

b) The momentum spectra In Fig.3 in semi-logarithmic scale the dependences of the invariant cross section f on P^2 for the three nuclei are given.

If assuming $f \sim \exp(-BP^2)$, then the slope parameter B does not depend on the target nucleus within the errors (see Table 1), but it varies strongly with the initial energy (for C^{12}). The tendency of decreasing the value of B is observed with decreases of the emission angle of protons. It is most evident for 60 and 30 angles. If in the angular range $\vartheta_p < 60°$ the main photoproton contribution had been stipulated by the evaporation process as it could be expected proceeding from the angular distributions in Fig.2 (in $\vartheta_p < 60$ the tendency of isotropy is observed), then the slope parameter B must have increased at transition from the region $\vartheta_p > 60°$ to the region $\vartheta_p < 60°$, since the typical nuclear temperature for the evaporation process is of order 10 MeV, i.e. $B \simeq 50$ (GeV/c) $(B \simeq 1/2mT_0)$. This analysis shows that the character of the angular distribution in Fig.2 is stipulated not by the significant contribution of the evaporation process to the small-angle range, but by the specificity of other direct processes.

In Fig.4 the dependences of the B on the energy of incident photons up to 4.5 GeV[9,10] are given. Although the slope parameter B was determined in various momentum intervals for different $(E_\gamma)_{Max}$, nevertheless, the given dependences are useful and should be explained by the future theory.

c) A -dependence. The dependences of cross sections (yields) of the inclusive particles on the atomic number of the target-nucleus seem to be one of the most sensitive tests on the applicability of different theoretical models which attempt to explain the interaction nature.

It has been observed that the exponent n in A^n -dependence for inclusive protons is larger than that for π -mesons (under the same kinematic conditions)[2,3]. It is impossible to explain this effect by absorption in target-nuclei, since the total cross section of π -mesons is less than that for the proton. Most likely, the increasing of the exponent n in the case of protons is due to the additional flux of protons produced in interactions of secondary particles (e.g.π-mesons)[22] in target-nucleus. The contribution of these processes to the π-meson production should be considerably suppressed. If it is so, then the A-dependence of the proton yield must be essentially different when the production of the additional protons is possible and when it is impossible.

In particular, the mentioned variations in the value of n must be observed at the transition over the threshold of π-mesons photoproduction on nuclei, since at $E_\gamma \geq$ 0.15 GeV the π-mesons can be the source of the secondary (additional) protons.

In Fig.5 in twice-logarithmic scale the A-dependences at $(E_\gamma)_{max}$=0.13GeV and 0.25 GeV for different proton angles and energies are given. Only statistic errors are shown.

For the same momenta and emission angles of protons the exponents are different at $(E_\gamma)_{max}$=0.13 GeV and 0.25 GeV (see Table II). At P_p=0.29GeV/c, 0.34 GeV/c and ϑ_p=30, n (0.13 GeV)$\simeq$ 0.6, whereas n (0.25 GeV)$\simeq$1.15. Such a considerable jump in the value of n is difficult to be explained within the framework of the theoretical models suggested for the cumulative effect and nuclear scaling. It cannot be explained by the account of the secondary protons interactions in the final state, too.

From Fig.5 and Table II one can see that at $(E_\gamma)_{max}$=0.25 GeV there are small variations of the value of exponent n. It increases with variations of kinematic parameters of protons; with increasing of momentum at given angle and with decreasing of emission angle at given momentum. This fact also does not contradict the assumption about possible production of additional protons in the interactions of slow photopions with the nuclei in which they were produced. Due to the limitation of the incident photon energy, with the increase of the protons energy the contribution of secondary interactions must decrease. On the other hand, for the given proton energy this contribution must increase with the decrease of the detection angle (due to the π-meson angular dependence).

In conclusion the author should like to express his gratitude to S.R.Gevorgyan for the detailed discussion.

Table I

Values of the slope parameter B in (GeV/c)

in relation (1) for reactions (2) and (3)

A	C^{12}			Cu^{63}			Pb^{208}		
ϑ_o / E_γ GeV	30^0	60^0	90^0	30^0	60^0	90^0	30^0	60^0	90^0
0,250	I7,5± I,5	2I± 2	24± 2,5	I6± I,5	2I,0 ±2,5	2I± 2,3	-	2I,5 ±2,5	22± 2,8
0,I30	30 ± 2	42± 2	38,5 ±4	-	-	-	-	-	-

Table II

Values of the exponent n in A^n-dependence

of the proton yield in reactions (2) and (3)

E_γ	0,250			0,I3	
ϑ / P_p GeV/c	0,29	0,34	0,40	0,29	0,34
30^0	I,I5±0,04	I,I7±0,04	I,20±0,05	0,59±0,08	0,62±006
60^0	-	I,I7±0,02	I,22±0,03	-	-
90^0	I,02±0,03	I,II±0,03	I,24±0,05	-	-

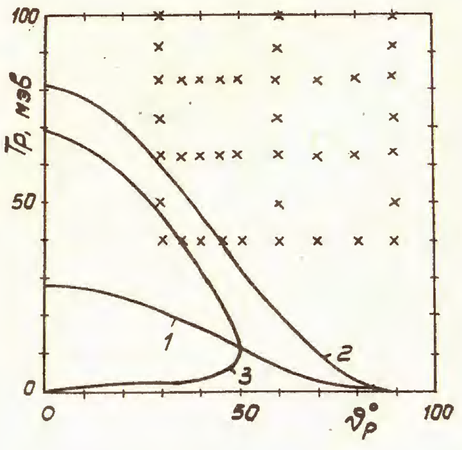

Fig. 1

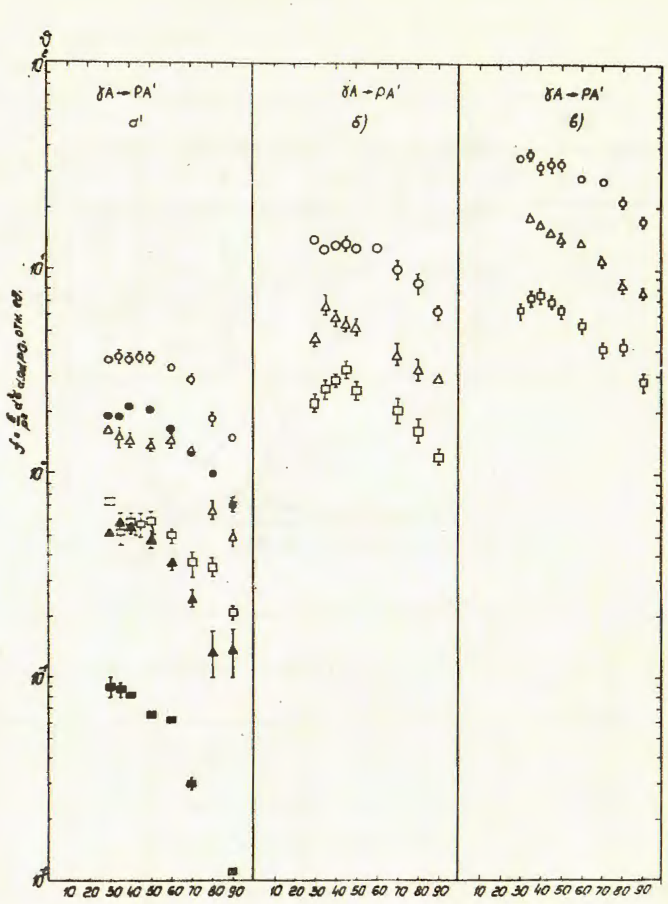
γA → ρA'
а)
б)
в)
$f = \frac{E}{P^3}\frac{d^2\sigma}{d\Omega dP}$, отн ед.
10^2
10^1
10^0
10^{-1}
10^{-2}
10 20 30 40 50 60 70 80 90
ϑ

Fig. 2

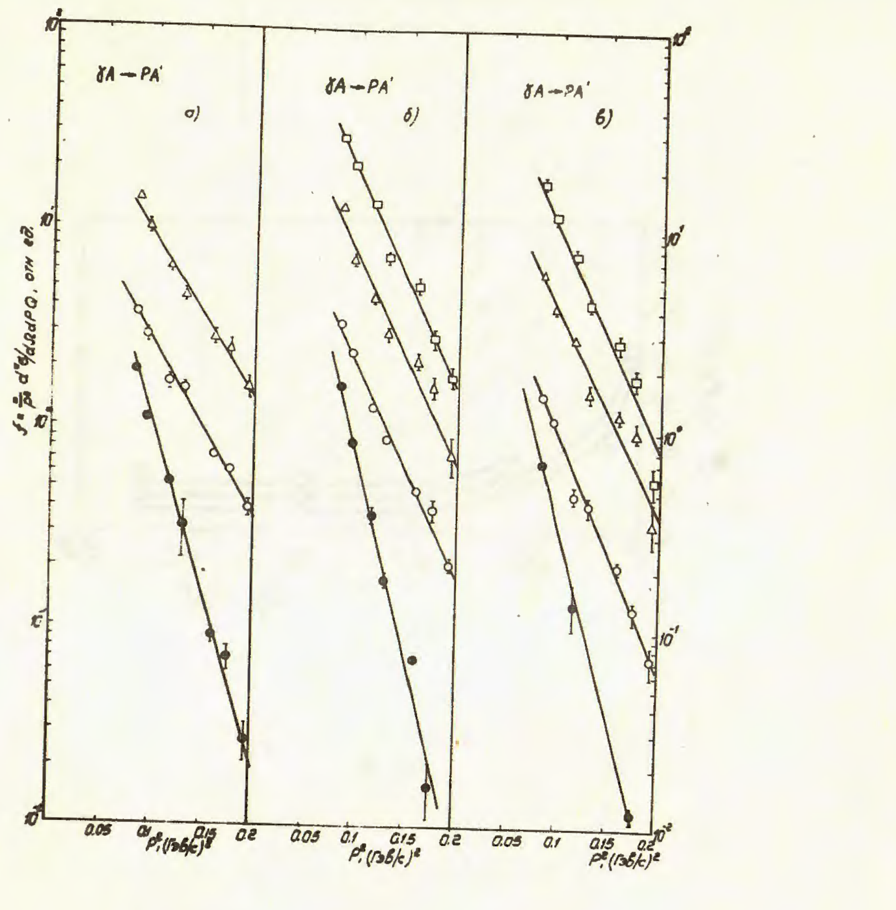
γA → ρA'
а)
б)
в)
$f = \frac{E}{P^3}\, d^2\sigma / d\Omega dP$, отн ед.
10^2
10^1
10^0
10^{-1}
10^{-2}
0.05
0.1
0.15
0.2
$P_\perp^2$, (Гэв/с)^2

Fig. 3

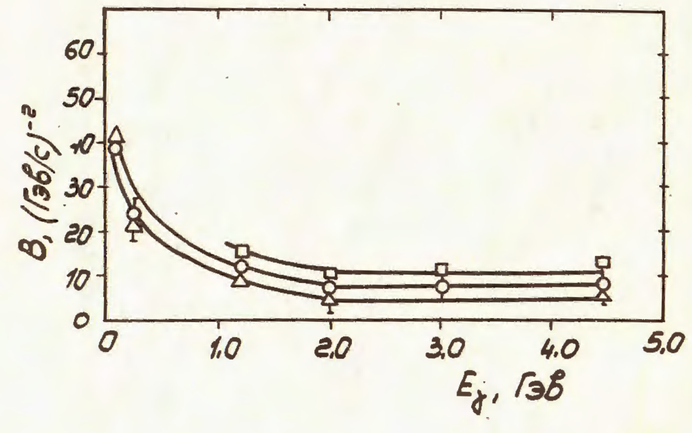
60
50
40
30
20
10
0
B, (ГэВ/c)$^{-2}$
0
1.0
2.0
3.0
4.0
5.0
E_γ, ГэВ

Fig. 4

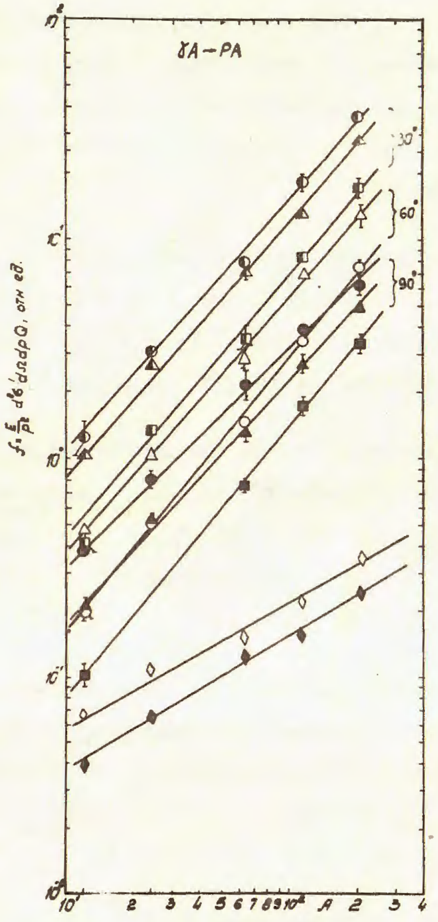
γA−PA
30°
60°
90°
$f = \frac{E}{p^2}\frac{d^2\sigma}{d\Omega dp}$, отн. ед.
10^2
10^1
10^0
10^{-1}
10^{-2}
10^1
2
3
4
5
6
7
8
9
10^2
A
2
3
4

Fig. 5

FIGURE CAPTIONS

Fig.1 The kinematic curves (regions) of the proton photoproduction; curve 1 was obtained for recoil protons in $\gamma P \rightarrow \gamma' P$ at $(E_\gamma)_{max}$=0.13 GeV, curves 2 and 3 were obtained for processes $\gamma P \rightarrow \gamma' P$ and $\gamma N \rightarrow \pi P$ at $(E_\gamma)_{max}$=0.25 GeV. The experimentally measured phase points are denoted by crosses.

Fig.2 The relative photoproton yields as a function of the emission angle: the experimental points: ○, ● - for P_P =0.29 GeV/c; △, ▲ -0.34GeV/c, □, ■ -0.40 GeV/c. Open points - for $(E_\gamma)_{max}$ =0.25 GeV, dark points for $(E_\gamma)_{max}$ =0.13 GeV: a)-for C^{12} , b) - for Cu^{63} , c) - for Pb^{208},

Fig.3 The momentum spectra of protons. The experimental points: ○ and ● for C^{12}, △ - for Cu^{63}; □ -for Pb^{208}. Open signs for $(E_\gamma)_{max}$ =0.25GeV, dark signs for $(E_\gamma)_{max}$=0.13 GeV; a)- for ϑ_P =30 , b) - for ϑ_P =60 , c) - for ϑ_P =90 . The lines are drawn through the experimental points by the least squares method.

Fig.4 Values of the slope parameter B in representation $f \sim exp(-BP^2)$ for the $\gamma A \rightarrow P A'$ reaction as a function of the incident energy of γ -quanta. The experimental points: △ -for ϑ_P =60 ; ○ -for ϑ_P =90 , □ -for ϑ_P =150 . The data at $(E_\gamma)_{max}$=1.2 GeV are taken from Ref. 25 ; at $(E_\gamma)_{max}$=2 $\div$ 4.5 GeV from Refs. 9,10 .

Fig.5 A -dependences of the photoproton yield in reactions (2) and (3). The experimental points: for $(E_\gamma)_{max}$=0.25 GeV; circles - P_P =0.29GeV/c, triangles - P_P = 0.34 GeV/c, squares - P_P =0.40 GeV/c; semiopen signs for ϑ_P =30 , open signs for ϑ_P =60 , dark signs for ϑ_P =90; ◇ - $(E_\gamma)_{max}$ =0.13 GeV and P_P =0.29 GeV/c; ϑ_P =30; ◆ -$(E_\gamma)_{max}$=0.13GeV and P_P =0.34 GeV/c; ϑ_P =30 .

The lines are drawn through the experimental points by the least-squares-method.

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(на английском языке)

Ереванский физический институт

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