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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

ФИ-615(5)-83

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THE ANALYSIS OF CUMULATIVE PROTON ANGULAR DISTRIBUTIONS

ԵՐԵՎԱՆ 1983 ԵՐԵՎԱՆ

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АНАЛИЗ УГЛОВЫХ РАСПРЕДЕЛЕНИЙ КУМУЛЯТИВНЫХ
ПРОТОНОВ

В работе приводится анализ угловых распределений кумулятивных протонов, рожденных первичными γ - квантами и адронами. Показано, что эти угловые распределения: а) успешно описываются экспоненциальной зависимостью $f_p(\cos\vartheta_p) = C_p \cdot \exp(b_p \cos\vartheta_p)$; б) сильно зависят от импульсов протонов; в) универсальны по отношению к первичной энергии начиная с ~ 1 ГэВ - для легких частиц (γ - кванты и π - мезоны) и 2-3 ГэВ для протонов; г) универсальны по отношению к ядру-мишени начиная с $A \geq 50$; д) при прочих равных условиях одинаковы для первичных легких частиц (γ - квантов и π - мезонов) и становятся более крутыми для первичных протонов.

Анализ угловых распределений кумулятивных протонов при $T_p = 0$ показывает, что энергетические спектры этих протонов пересекаются при энергиях $T_p \neq 0$, при этом точка пересечения на шкале T_p существенно зависит от типа взаимодействия, от ядра мишени и от первичной энергии.

Ереванский физический институт

Ереван 1983

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THE ANALYSIS OF CUMULATIVE PROTON ANGULAR DISTRIBUTIONS

An analysis of angular distributions of cumulative protons produced by primary χ -quanta and hadrons is presented. It is shown that these distributions: i) are successfully described by the exponential dependence

$$f_p(\cos\vartheta_p) = C_p \exp(b_p \cos\vartheta_p) ;$$

ii) strongly depend on proton momenta; iii) are universal with respect to primary energy beginning with ~ 1 GeV for light particles (χ -quanta and π -mesons) and with 2-3 GeV for protons;

iv) are universal with respect to the target-nucleus beginning with 50;

v) all other conditions being equal, they are identical for primary light particles (χ -quanta and π -mesons) and come to be steeper for primary protons. The analysis of angular distributions of cumulative protons at $T_p = 0$ shows that energy spectra of these protons intersect at energies $T_p \neq 0$, the crossover point on a scale of T_p being essentially dependent on the interaction type, target-nucleus and primary energy.

Yerevan Physics Institute

Yerevan 1983

Y E R E V A N P H Y S I C S I N S T I T U T E

EDM-6I5(5)-83

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Yerevan 1983

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Angular distributions of cumulative protons were in more detail investigated in Refs. [1,2] with primary protons and deuterons with momentum 8.9 GeV/c, in [3,4] with primary χ -quanta with energy up to 4.5 GeV and in [5,6,7] with primary protons and π -mesons with energy up to 400 GeV.

The most characteristic in these data, irrespective of the sort of the incident particle, one may consider their strong forward behaviour in the angular region up to 120° and the tendency to flatten out at angles $\mathcal{V}_p > 120^\circ$.

In Ref. [1] was observed also some structure $\mathcal{V}_p \approx 160^\circ$, however, special investigations [8] carried out with primary χ -quanta did not confirm the presence of such a structure. At present, one may consider firmly established the fact that the invariant angular distributions $f_p(\mathcal{V}_p)$ of protons flatten out at $\mathcal{V}_p \geq 140^\circ$. This apparently is not connected with the process dynamics and rather implies the influence of effects due to phase volume, therefore it would be more correct to carry out the analysis of angular distributions in the form of the dependence $f_p(\cos \mathcal{V}_p)$ (instead of $f_p(\mathcal{V}_p)$).

According to contemporary representations, cumulative particle production is a typical case of limiting fragmentation of one of the objects parti-

icipating in the reaction, in this case of target-nucleus. Therefore the regularities of the nuclear scaling hypothesis are valid in this process [9].

Of most importance is, of course, the statement that for the reaction



the invariant cross section of cumulative particle production becomes universal with respect to the sort and energy of primary particles, beginning with the energy value much less (nearly by an order) than this is the case in collisions of elementary particles

(2)

$$f_c(S, \vec{P}_c, A) \xrightarrow{S \sim E_a \rightarrow E_{a_0}} f_c(\vec{P}_c, A) \rightarrow \psi(A) \cdot f(\vec{P}_c)$$

where $E_{a_0} \leq 4$ GeV (different for various primary particles).

Almost all experimental investigations on cumulative particle production were devoted to the establishment of universality (2) on the example of energy distributions, i.e. it was clarified from what primary energies and target-nuclei the energy spectra $f(P_c^2)/\nu_c = \text{const}$ or $f(T_c)/\nu_c = \text{const}$ became independent of E_a and A .

The same investigations for $f_c(\cos \vartheta_c)/P_c^e = \text{const}$ are practically not performed except for one attempt [10] for one nucleus and one primary energy. Meanwhile, one may claim that angular distributions are more informative as concerning the establishment of the mechanism of cumulative particle production, since these distributions are less distorted by secondary interactions in a residual nucleus than in energy spectra. Therefore it is necessary to clarify how the angular distributions change with varying the other parameters of the reaction (1), whether there are observed universalities with respect to E and A , etc.

In this work an attempt is made as to analyze systematically angular distributions for cumulative protons in order to establish the above-stated universalities. For this purpose the photo- and hadronproduction data obtained mainly at EPI and ITEP will be used, since these results are most systematical among the ones available.

1. The Shape of Angular Distributions

In Fig.1 there are given angular dependences of invariant yield of photoprotons from nuclei ^{12}C , ^{63}Cu and ^{208}Pb irradiated with bremsstrahlung γ -quanta with a maximum energy of 4.5 GeV. These results were obtained at a set-up "Deuteron" [11] and discussed in [3,4]. The arrows show the boundaries of the cumulative region. Statistical errors do not exceed the sizes of symbols. Lines show the results of a description of the data by the functional dependence

(3)

$$f_p(\cos\vartheta_p) = c_p \exp(b_p \cos\vartheta_p)$$

where c_p and b_p are parameters.

As one can see, such a representation describes rather well only the cumulative region data. Outside of this region the experimental data are systematically higher (particularly for light nuclei and high momenta of protons). Fig.2 presents analogous data from Ref.[6] for nuclei C and Ta and at $E_{op} = 400$ GeV. As is seen, the experimental data of [6] are also well described by functional dependence (3). All available at present more or less systematical data on angular distributions of cumulative protons in the first approximation (just like in the case of the energy spectra) can be described by the relation of (3) type.

2. Universalities of Angular Distributions with Respect to Various Parameters of the Reaction

The representation of (3) type is not necessary for the establishment of any universalities of angular distributions. For that one can each time construct data in the same figure at different values of the parameter with respect to which the universality is to be checked. These data being coincident, one may say on the degree of the universality. However the representation of the reaction yields in the form of elementary functions (exponents in this case) is convenient because instead of such a complicated procedure one can consider the dependence of a characteristic parameter of elementary function (parameter b_p in the given case) on the investigated characteristic of the reaction. Just these dependences of b_p will be analysed below.

1.1. Dependence of the Shape of Angular Distributions on Momentum of Cumulative Protons

The most evident character of distributions $f_p(\cos \vartheta_p)$, as shown in Figs. 1 and 2, is the change of slopes (i.e. b_p) due to proton momenta. Fig.3 illustrates two dependences of b_p on P_p for primary γ -quanta with $E_\gamma^{\max} = 4.5$ GeV (Pb) and for primary protons with $E_p = 400$ GeV (Ta). As one can see, b_p increases with proton momenta almost linearly. Thus the shape of angular dependences is not universal relative to cumulative proton momentum.

1.2. Angular Distributions as Functions of Energy of Primary Particles

Fig.4 presents dependences of b_p on P_p for the nucleus ^{12}C at two energy values of primary γ -quanta. The data at $E_\gamma^{\text{max}} = 1.2$ GeV are recalculated from proton energy spectra at different angles given in Ref. [12]. As is seen, for all the momenta the parameters b_p are equal for the two values of primary energy. Unfortunately, angular distributions for the other values of E_γ^{max} are not studied systematically.

Fig.5 shows the dependences of $b_p(P_p)$ for heavy nuclei Pb (Ta) in the process of cumulative proton production by primary protons with momenta 7.5 GeV/c (Pb) [7] and 400 GeV/c (Ta) [6]. It is seen that at such a sharp change of primary energy the parameter b_p remains constant. In the energy region of primary hadrons $E_\alpha < 7.5$ GeV the most detailed are data [5] obtained by primary π -mesons with momenta 1.2 + 7.0 GeV/c, and by protons with momenta 2 + 5 GeV/c. Unfortunately, obtained in [5] results relate not to fixed energy of secondary protons, but to the whole range $T_p = 60 - 200$ MeV ($P_p = 0.35 - 0.65$ GeV/c); nevertheless, these data allow one to gain information on the dependence of parameter b_p upon the primary energy and target-nucleus.

Fig.6 shows b_p as a function of primary particle momentum for (π Pb) and (p Pb) interactions. As is seen, for π -mesons parameter b_p is independent of primary energy in the whole range of momenta under investigation. In the case of primary protons such independence is reached at 2 - 3 GeV/c. The analogous results are obtained for other nuclei.

Thus, angular distributions are universal relative to the primary energy beginning from $E_\alpha \approx 1$ GeV for light particles (γ -quanta and π -mesons) and at 2 ÷ 3 GeV for primary protons. Note that such a universality in the

energy spectra case is observed for protons at ~ 4 GeV [13] and for primary γ -quanta at 2 - 2.5 GeV [14], i.e. at somewhat lower energies.

1.3. Dependence of Angular Distributions on the Target-Nucleus

Fig.7 illustrates the dependences of parameter ℓ_p on atomic number of the target-nucleus for two limited values of momentum of cumulative protons from the reactions $\gamma A \rightarrow pX$ at $\varepsilon_{\gamma}^{\max} = 4.5$ GeV. One can see that ℓ_p decreases with increasing A almost linearly. Fig.8 shows the analogous dependences in the case of primary protons and π -mesons at 5 GeV/c. In accord with Figs.7 and 8 parameter ℓ_p varies by 30% at varying A from 12 up to 208. If one stops on the level of 10% change and considers ℓ_p independent of A (this is usually done for energy spectra), then the universality of angular distributions may be said about (with 10% accuracy) beginning only with $A \geq 50$.

Thus, angular distributions became universal beginning with $A \geq 50$, whereas in the energy spectra case the same universality takes place beginning with $A \geq 10$.

1.4. Dependence of the Shape of Angular Distributions on the Sort of Incident Particle

From the data in Fig.6, where is given also one point on (γA) interaction, one can conclude that all other conditions being equal, the parameter ℓ_p is larger in the case of primary protons than in the case of γ -quanta and π -mesons for which are equal, i.e. the shape of angular dependence is similar for primary light particles (π -mesons and γ -quanta) and becomes steeper for primary protons

3. Angular Distributions of Cumulative Protons with Momenta Close to Zero

A direct experimental investigation of production of cumulative protons with momenta close to zero is somewhat complicated due to the fact that the evaporation mechanism in this region dominates. Therefore one can extract the contribution of cumulative production by means of extrapolation of energy spectra into the region $T_p \rightarrow 0$. This is equivalent to the analysis of the behaviour of parameter C in the representation

$$f_p(T_p) = C_p \cdot \exp(-T_p/T_0) \quad (4)$$

We discussed such data in Ref. [15]. Fig.9 shows the dependences of parameter C_p^0 over (4) (i.e. $f_p(T_p=0)$) on the detection angle for three nuclei irradiated with γ -quanta with the energy of $E_\gamma^{\text{max}} = 4.5$ GeV. One can readily see that in the region $\nu_p \geq 70^\circ$ (mainly cumulative region) $f_p(0)$ is angular independent if nuclei heavier than copper are used as a target. In the case of carbon nuclei one can observe a fairly strong increase of $f_p(0)$ with decreasing ν_p . The picture observed means that the energy spectra of protons from nuclei of Cu and Pb cross over at $T_p = 0$. In the case of ^{12}C , if such an intersection takes place, the intersection point is in the region $T_p < 0$ (if $C_p(\cos \nu_p)$ would be a function decreasing as $\cos \nu_p$ grows, then, vice versa, the intersection point would locate in the region $T_p > 0$). The calculations have shown that, indeed, such an intersection takes place at $T_p^c = -44 \pm 8$ MeV (for Cu and Pb the calculated values are $T_p^{\text{Cu}} = 4 \pm 5$ MeV and $T_p^{\text{Pb}} = 1.2 \pm 3$ MeV, respectively).

From the available data on cumulative proton photoproduction only Ref. [12]

allows one to estimate the quantity T_p^c at $E_\gamma^{max} = 1.2$ GeV. It turns out that here $T_p^c = -20 \pm 7.5$ MeV, i.e. with decreasing the primary energy the intersection point approaches to axis $T_p = 0$.

For the hadron processes similar results can be derived from Refs. 6,7. In Ref. [6] there are proton spectra from different nuclei irradiated with 400-GeV protons. In Ref. [7] such spectra are only for Pb at 7.5 GeV/c momentum of primary protons. The processing of results [6] shows that cumulative proton spectra at different angles intersect at the energies $T_p^c = 10 \pm 2$ MeV, $T_p^{Cu} = 20 \pm 5$ MeV and $T_p^{Pb} = 45 \pm 7$ MeV. According to the data of [7] $T_p^{Pb} = 20 \pm 7$ MeV.

Thus it is noticed that both in photon and hadron processes the point of spectra intersection shifts into the region of large energies of protons with increasing the target-nucleus. With decreasing the primary energy for the given nucleus the intersection point approaches to the axis $T_p = 0$. However, there is an essential difference for electromagnetic and strong interactions. While in the former case the intersection points are in the region $T_p \leq 0$, in the latter case they are in $T_p \geq 0$.

It should be noted that such type of the analysis of angular distributions at $T_p \rightarrow 0$ was for the first time mentioned about in the lecture of G.A.Leksin at the First All-Union School on physics of low-particle and quark-hadron systems, in summer, 1982, at Kalinin. The lecturer tried to explain the presence of intersection points in the region $T_p \neq 0$ by the influence of the Coulomb field on the proton spectra. However this concept, as is seen from the data presented, cannot be considered a satisfactory one. It is clear only that an interesting effect has been observed, which requires a theoretical interpretation.

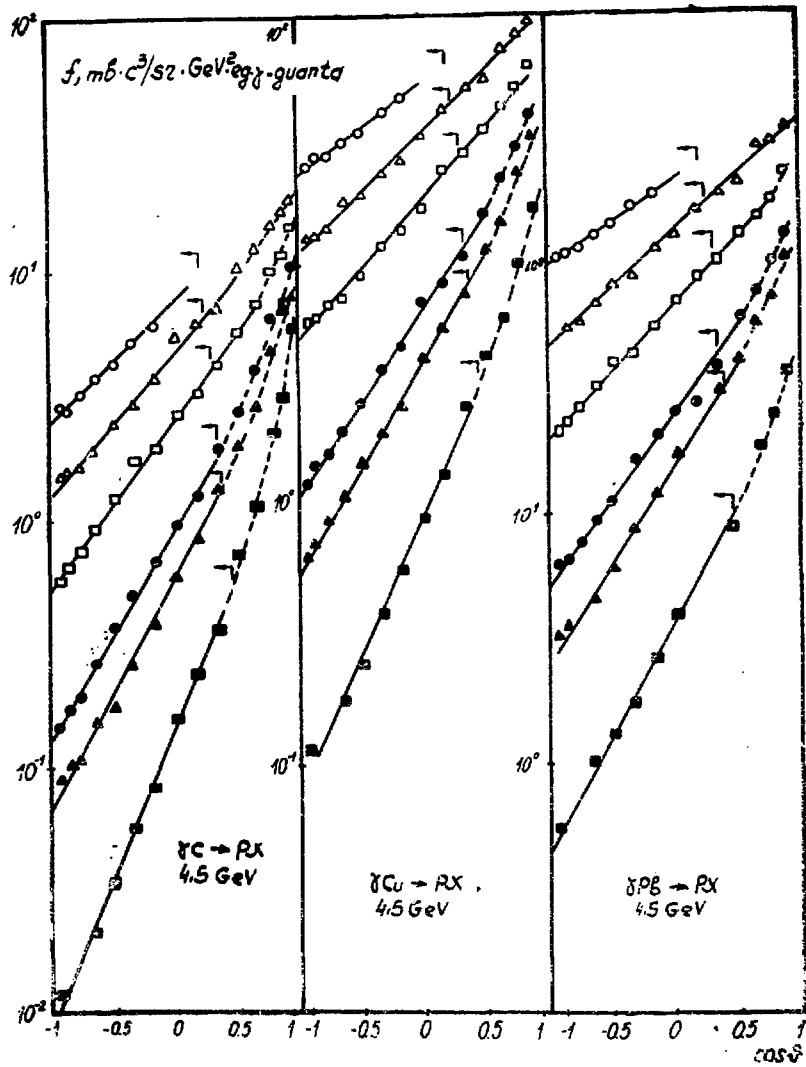


Fig.1 Angular dependence of the invariant yield of photoprotons from nuclei ^{12}C , ^{63}Cu , ^{208}Pb irradiated with bremsstrahlung γ -quanta with $E_{\gamma}^{\text{max}} = 4.5 \text{ GeV}$. Experimental points:
 \circ - $p = 0.4 \text{ GeV/c}$, Δ - 0.44 GeV/c , \square - 0.52 GeV/c ,
 \circ - 0.61 GeV/c , \blacktriangle - 0.66 GeV/c , \blacksquare - 0.79 GeV/c .
 The arrows show the boundaries of cumulative region.

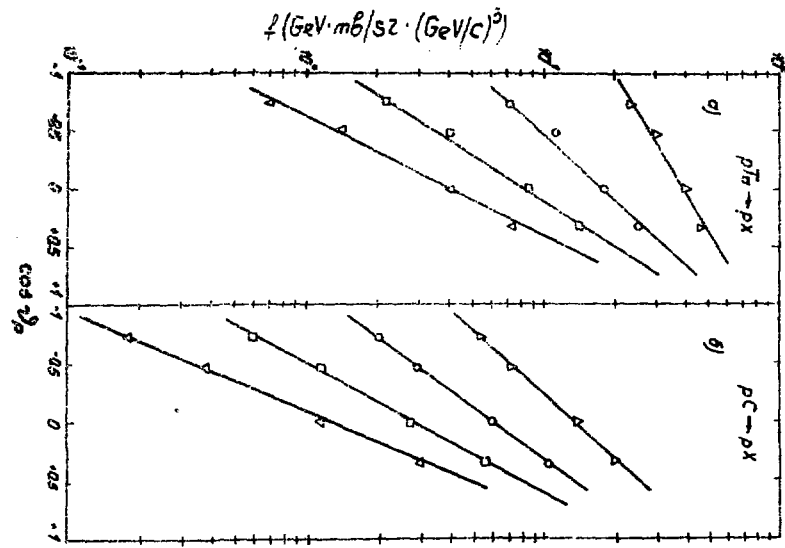


Fig.2 Angular dependence of the invariant cross section of protons produced from the reactions $pTa \rightarrow pX$ and $pC \rightarrow pX$ at $E = 400$ GeV. Experimental points: Δ - for $P_p = 0.4$ GeV/c, \circ - 0.5 GeV/c, \square - 0.6 GeV/c, ∇ - 0.7 GeV/c.

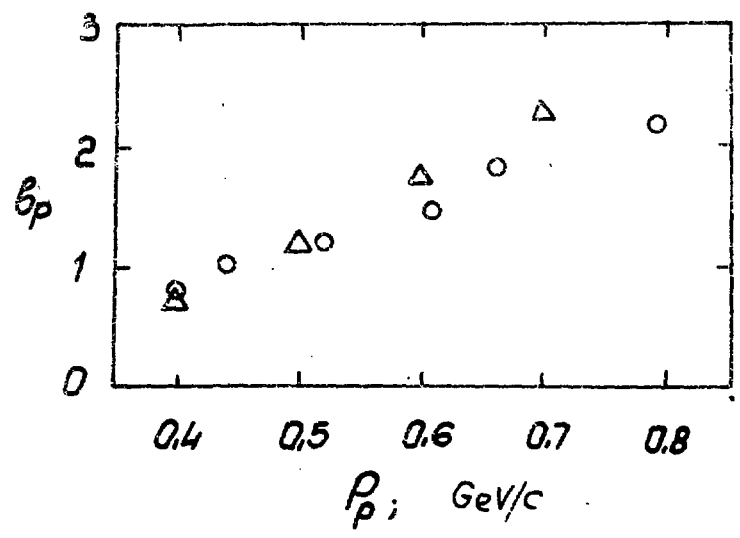


Fig.3 Parameter b_p (from relation (3)) as a function of secondary proton momentum for the reactions: $\circ - \gamma Pb \rightarrow pX$ with $E_\gamma^{max} = 4.5$ GeV and $\Delta - pTa \rightarrow pX$ with $E = 400$ GeV.

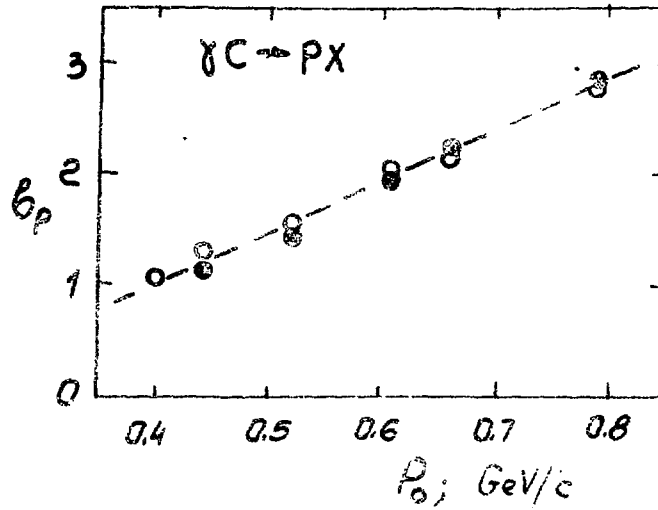


Fig.4 Parameter b_p as a function of secondary proton momentum for the reaction $\gamma C \rightarrow pX$ at $E_\gamma^{\max} = 1.2$ GeV - \odot and 4.5 GeV - \circ .

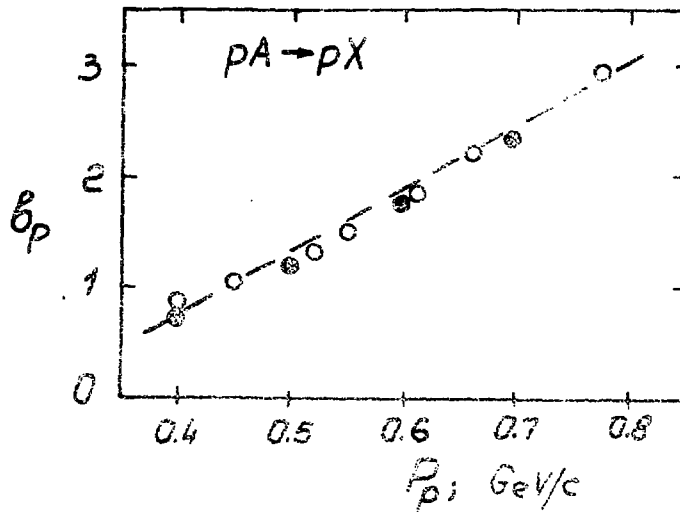
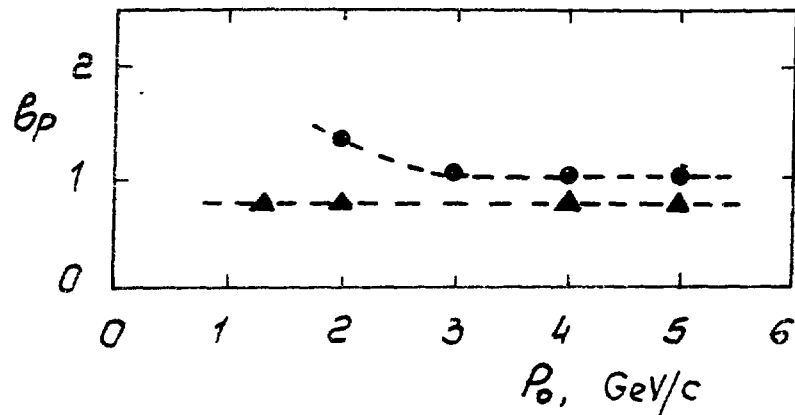


Fig.5 Parameter b_p as a function of secondary proton momentum for the reactions: $\circ - p Pb \rightarrow pX$ with $E = 3.5$ GeV and $\odot - p Ta \rightarrow pX$ with $E = 400$ GeV.



Parameter b_p as a function of momentum of primary π -mesons (\blacktriangle), protons (\bullet) and γ -quanta (\circ) for Pb.

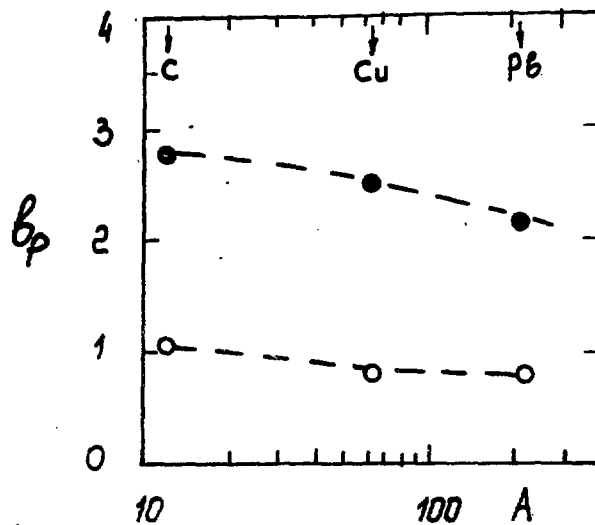


Fig.7 Parameter b_p as a function of atomic number of the target-nucleus for the reaction $\gamma^A \rightarrow pX$ with $E_{\gamma}^{\max} = 4.5$ GeV: \circ — at $P_p = 0.4$ GeV/c, \bullet — 0.79 GeV/c.

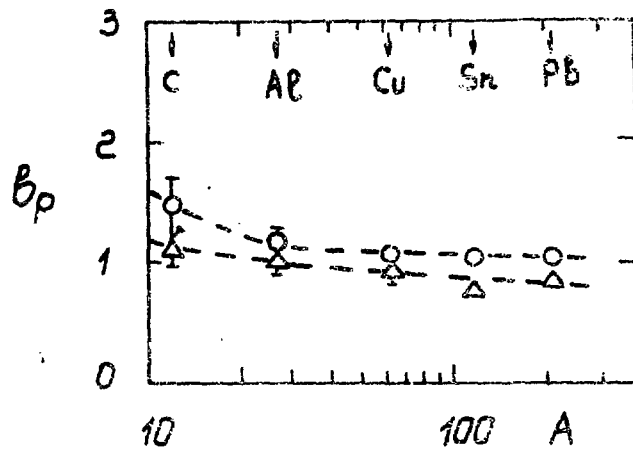


Fig.8 Parameter b_p as a function of atomic number of the target-nucleus for primary protons (\circ) and π -mesons (Δ) with momentum 5 GeV/c.

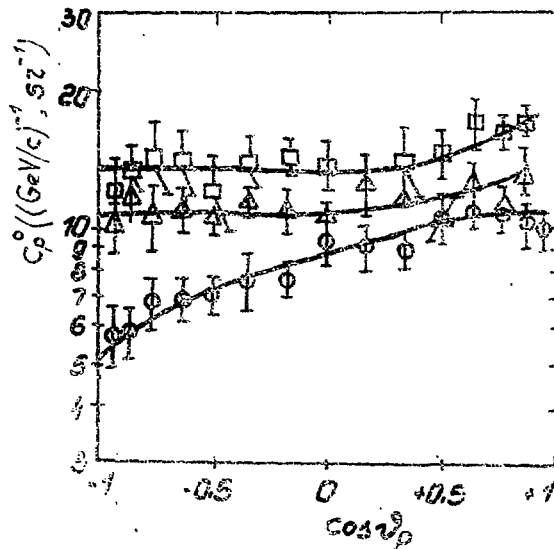


Fig.9 Parameter C_p^0 (from relation (4)) as a function of the detection angle of secondary protons from nuclei ^{12}C (circles), ^{63}Cu (triangles) and ^{208}Pb (squares) irradiated with bremsstrahlung γ -quanta with $E_{\gamma}^{\text{max}} = 4.5 \text{ GeV}$.

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The manuscript was received 13 October 1982

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ПРОТОНОВ

(на английском языке, перевод Э.Н.Асланян)

Редактор Л.П.Мукаян
Тех.редактор А.С.Абрамян

Заказ 28

ВФ- 04254

Тираж 299

Препринт ВФИ

Формат издания 60x84/16

Подписано к печати 10/II-83

1,5 уч.-изд.л. Ц.20 к.

Издано Отделом научно-технической информации
Ереванского физического института, Ереван 36, Маркарян 2

индекс 3624