индекс 3624

ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

ЕФИ-749(64)-84

ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ
ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ
ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

K.V.ALANAKIAN, M.J.AMARIAN, R.A.DEMIRCHIAN,
K.SH.EGIYAN, M.S.OHANJANIAN, S.G.STEPANIAN, YU.G.SHARABIAN

DEUTERON PHOTOPRODUCTION ON NUCLEI BY BREMSSTRAHLUNG γ-QUANTA AT E_{γ}^{max} = 4.5 GEV

ЕРЕВАН 1984

ЕФИ-749(64)-84

К.В.АЛАНАКЯН, М.Д.АМАРЯН, Р.А.ДЕМИРЧЯН, К.Ш.ЕГИЯН,
М.С.ОГАНДЖАНЯН, С.Г. СТЕПАНЯН, Ю.Г.ШАРАБЯН

ФОТООБРАЗОВАНИЕ ДЕЙТРОНОВ НА ЯДРАХ ТОРМОЗНЫМИ γ - КВАНТАМИ ПРИ $E_\gamma^{max} = 4,5$ ГЭВ

В работе приводятся экспериментальные результаты по фотообразованию дейтронов на ядрах C, Al , Cu , Sn , Pb, облученных тормозными γ - квантами с максимальной энергией 4,5 ГэВ при угле регистрации 30° - 120°. Приведены также энергетические спектры дейтронов из ядра Al при $\vartheta_d = 50°$ и 90°. Полученные результаты сопоставляются с предсказаниями различных вариантов модели слипания и модели подхвата. Приводятся также сравнения с аналогичными данными из адронных процессов. Делается вывод, что имеющиеся данные по фотообразованию трудно объяснить указанными моделями, тогда как в адронных процессах, вероятно, основной вклад дает модель слипания, развитая Франкфуртом и Стрикманом.

Ереванский физический институт
Ереван 1984

1. Introduction

On irradiation of nuclei by high energy particles, along with mesons and nucleons a large flux of high energy secondary light nuclei ^2H, ^3H, ^3He, ^4He etc. is observed. The production mechanism of these compound fragments is not completely clear as yet. Both direct mechanisms and mechanisms based on the interaction at the final state are widely discussed. For the definition of contributions of various mechanisms, essential are investigations by means of various primary particles, e.g. high energy hadrons and electrons or γ-quanta [1]. As for hadrons, the yield of light fragments is investigated good enough up to the primary energy 400 GeV [2]. A number of studies are carried out by means of primary relativistic heavy ions [3,4].

The photoproduction of fast light fragments from nuclei at high energies is investigated considerably worse. Relatively more data are available for the reaction $\gamma A \to dX$ in the region of γ-quanta energy up to 1.2 GeV. The first experimental data of the Cornell group on the reaction (γd) at $E_\gamma^{max} = 0.31$ GeV [5] were explained by the pickup mechanism. In [6] at $E_\gamma^{max} = 0.4 - 0.72$ GeV new results were obtained on deuteron photoproduction ($\vartheta_d = 57^o$) that were in a good agreement with calculations based both on photomeson and pickup processes. Subsequent, more detailed investigations of the reaction (γd) were carried out by the Kharkov group and were reported in [7-12] . Their results satisfactorily agree with the photomeson model in the case of allowed kinematics of π -meson production on a quasifree deuteron [12]. For the forbidden kinematics authors of [7-12] have attempted to explain the results obtained by the Batler-Pearson coalescence model [13] and came across significant discrepancies. As far as we know, at present the reaction (γd) in the region $E_\gamma^{max} > 1.2$ GeV is investigated neither in the forbidden (cumulative) nor in the allowed kinematics for the photoproduction on a quasifree deuteron. Meanwhile, the mechanism of production of photodeuterons, in particular of cumulative ones, still remains undetermined.

In the present paper experimental results are given on the investigation of photodeuteron yields from the nuclei ^{12}C, ^{27}Al, ^{63}Cu, ^{118}Sn and ^{208}Pb irradiated by bremsstrahlung γ-quanta of the maximum energy 4.5 GeV and at the deuteron detection angle 30°- 120°. Preliminary results have been presented in [14]. Results are compared to predictions of different versions of coalescence and pickup models.

2. Experimental setup

The data are obtained on the "Deuteron" setup [15] arranged on the beam Γ-3 of the Yerevan electron synchrotron. The setup allows a simultaneous detection of π -mesons, protons and deuterons by a magnetic spectrometer with the time-of-flight measurements. Momentum resolutions were $\Delta P/P = \pm 7.0$ % at

the solid angle $\Delta\Omega = 1.26$ msr. The time-of-flight has been measured in the interval 15 - 50 nsec with relative resolutions $\Delta\tau/\tau = \pm 5\%$. Such errors allow a reliable separation of π -mesons, protons and deuterons. One of the spectra of measured time-of-flights at 0.98 GeV/c is presented in fig.1. Basing on the number of particles of the given type, proportionate to the area of appropriate maxima in fig.1, we have defined the invariant yields

$$f = \frac{E}{p^2} \cdot \frac{d^2\sigma}{d\Omega dp} = K \frac{N}{\Delta\Omega \cdot \Delta p \cdot N_\gamma \cdot N_n} \cdot \frac{E}{p^2} \qquad (1)$$

where N_γ is the number of equivalent γ-quanta defined by the measurement of the beam power by a Gaussian quantometer, N_n- is the number of the target nuclei on beam's way. The coefficient K takes into account the corrections determined by the nuclear absorption and multiple scattering in the target and detectors, pair-production by γ-quanta in the target, decay of π -mesons and the efficiency of particle detection by a spectrometer.

Values of f_d are plotted in table 1. Only statistical errors are shown. Systematical errors conditioned by the definition of values $K, N_n, N_\gamma, \Delta\Omega$ in (1), according to our estimates, do not exceed 20%.

3. Experimental results

The data plotted in table 1 allow analysis of the angular dependence of deuteron yields for the nuclei ^{12}C, ^{27}Al, ^{63}Cu, ^{118}Sn and ^{208}Pb, the A-dependence for $\vartheta_d = 30°, 60°, 90°$ and 120° as well as the energy spectra of deuterons for the nucleus ^{27}Al at $\vartheta_d = 50°$ and 90°.

Angular distributions of the invariant yield of deuterons from nuclei at P_d = 0.98 GeV/c are shown in fig.2. For comparison we have presented similar proton distributions obtained at the same exposure from the nuclei ^{12}C and ^{208}Pb. As is seen, angular distributions of protons for the fixed target decrease with the increase in the angle more than in the case of deuterons. Besides, for light nuclei the yield of deuterons is a little larger than for heavy ones.

In fig.3 a number of A-dependences of photodeuteron yield are presented. Lines are drawn via experimental points by the method of least squares by the relation $f_d \sim A^{n_d}$. As is seen, such a representation satisfactorily describes experimental data. In fig.4 dependences of n_d on the detection angle as well as values of n_p for proton yields of the same momenta from the same measurement series are shown. Dependences $n_d(\vartheta_d)$ and $n_p(\vartheta_p)$ are equal but absolute values of n_d exceed n_p by approximately 0.20. Similar comparisons for primary protons of energy 400 GeV from [2] show that $\Delta n \approx 0.3$.

In fig.5 energy spectra of deuterons from the nucleus Al at the detection angles 90° and 50° are shown. Lines are drawn via experimental points by the method of least squares by the exponential law $f_d = C_d \cdot \exp(-T_d/T_{od})$ at values of the parameter T_{od} = 80±6.5 (50°) MeV and 52±2.6 (90°) MeV.

4. Discussion

The presented data testify to a close relation of deuteron and proton production processes (close angular dependences, similar variations of n_d and n_p depending on the detection angle, difference $\Delta n = n_d - n_p \approx 0.2 - 0.3$ indicating that

deuteron production may be related to the proton passage through the nucleus ($A^{1/3}$)). It therefore, makes sense, as is commonly done, to discuss and compare with predictions of theoretical models not the values of deuteron yields but their ratio to analogous nucleon yields.

In fig.6a angular dependences of the ratio of invariant deuteron and proton yields of similar momenta are presented. Most significant is the fact that at angles in the back hemisphere and heavy nuclei the invariant deuteron yield exceeds that of protons. This apparently is a serious argument against the direct mechanism of cumulative deuteron production. Indeed, e.g. in the framework of the model of few-nucleon correlations [16] as a direct mechanism would have served the triple correlation splitting to a deuteron-spectator with a momentum directed backwards and to a third nucleon (with a forward momentum) with which the γ-quantum has interacted. The excess of f_d over f_p would have meant that the probability of triple and higher order correlations with a given one-particle momentum distribution of nucleons exceeds the same probability for double and higher order correlations which is absurd. Further discussion and comparison will be made for mechanisms based on secondary interactions, especially as the theoretical models available are developed for that case only.

<u>Comparison with the coalescence model.</u> In the basis of this model lies the assumption that deuterons are produced due to coalescence in the nuclear medium of proton and neutron (of similar momenta) produced in the direct interaction of incident particles in a nucleus. It is natural that the probability of deuteron production is proportionate to the probability of proton and neutron productions and the probability of their coales-

cence. This may be written as

$$f_d(P) = \frac{f_p(P/2)\, f_n(P/2)}{\sigma_t} \cdot \varkappa_c \qquad (2)$$

where σ_t is the total cross section of the incident particle inelastic interaction with the target termed in [17] "the $\varkappa_c$ coalescence coefficient", f_p, f_n are the invariant cross sections of proton and neutron production, respectively.

At present a number of approaches are developed in the coalescence model that give various dependences of $\varkappa_c$ on basic parameters of the reaction.

In their classical work [13] Batler and Pearson assume that coalescing nucleons are produced in a nuclear cascade, and the coalescence process proceeds in the nuclear medium with the residual nucleus as a third body. The coalescence coefficient $\varkappa_c$ is then a function of the deuteron momentum and mass number of the target nucleus but is independent of the deuteron detection angle:

$$\varkappa_c^{BP} = 2\left(\frac{48\pi m_N C}{\hbar^2}\right)^2 \cdot \frac{U_0 J(R)}{E_d \cdot P_d^2} \sim \frac{A^{-2/3}}{E_d \cdot P_d^2} \qquad (3)$$

where U_0 is the module of the optical potential of the target nucleus, $C = \frac{m_N \cdot \varepsilon_d}{2\pi\hbar^2}$; ε_d is the deuteron coupling energy.

In the Frankfurt-Strikman approach [16] which is the improved version of the Batler-Pearson model applied to the cumulative particle production (and $P_\perp = 0$)

$$\varkappa_c^{FS} = \varkappa_c(\vartheta_d, P_d, A) \sim \frac{C(\vartheta_d)}{E_d} \cdot \frac{A^{-1/3}}{P_d^2} \qquad (4)$$

A-dependence and the emergence of the dependence on the angle ϑ_d is due to the fact that it is assumed in the model that coalescing nucleon pairs are produced not in all the volume of the nucleus [13] but only in a tube with a radius equal to that of the incident nucleon interaction. Since the existence of the tube implies the existence of a distinguished direction in the nucleus, in this case, as is shown in [17], a kinematic factor emerges depending on the detection angle. It is obvious that for incident γ-quanta the idea of the tube is groundless, therefore, for this case the dependence of $\varkappa_c^{FS}$ on the angle should be lacking.

In the phenomenological model of coalescence (PMC) [18] it is assumed that any proton-neutron pair in the nucleus, with a relative momentum of nucleus less than some value P_0, produces a deuteron. The difference between (PMC) and (BP) model consists in the fact that in this case the effect of the nucleus on the coalescence coefficient is neglected and

$$\varkappa_c^{PMC} = \frac{2\pi}{3} \cdot \frac{A-Z}{Z} \cdot \frac{P_0^3}{E_d} \qquad (5)$$

i.e. it weakly depends on A. In (5) A is the nucleon mass, Z is the charge of the target-nucleus.

In the thermodynamical model of coalescence (TMC) [19] it is assumed that coalescing nucleons are the product of the nuclear fireball decay that occurs in the incident particle collision with the nucleus and decays after establishment of thermodynamical equilibrium. In this model the expression for the coalescence coefficient reads:

$$\varkappa_c^{TMC} = 4\pi^3 \cdot f(\varepsilon_i, \varepsilon_0) \frac{\hbar^3}{V_0 \cdot E_d} \qquad (6)$$

where $f(\varepsilon_i, \varepsilon_0)$ is some function of the energy of basic (ε_0) and excited (ε_i) states as well as of the fireball temperature (T_0). $\varepsilon_0, \varepsilon_i \ll T_0$ ($T_0 \approx 50$ MeV) is a good approximation [3], and then $f(\varepsilon_i,\varepsilon_o)\approx 1$. In (6) V_o - is the fireball volume. As is seen, the coalescence coefficient, in accord with TMC, is independent of parameters of the target-nucleus and detected deuteron (momentum, angle). The distinctive feature of TMC is the fact that the value $\ae_c$ measured in the experiment gives direct information on the deuteron source dimensions. However, one may obtain such information in the case of PMC as well by using the uncertainty relation, then one may obtain from (5)[20]

$$\ae_c^{PMC} = 4\pi^3 \frac{A-Z}{Z} \cdot \frac{\pi^3}{V_o} \cdot \frac{1}{E_d} \qquad (7)$$

which coincides with (6) at symmetric nuclei and differs by the value $\frac{A-Z}{Z}$ for asymmetric nuclei.

The data obtained allow analysis of the coalescence coefficient $\ae_c$ dependence on the parameters ϑ_d, A and P_d and comparison with appropriate predictions of the above approaches. In table II values of $\ae_c$ are plotted. As σ_t we have used in calculations (see(2)) averaged values of the total cross section by all the bremsstrahlung spectrum of primary γ -quanta. Statistical errors are given only. We have assumed $f_p = f_n$

In fig.6b angular dependences of $\ae_c$ are presented. A fairly strong dependence $\ae_c = \ae_c(\vartheta_d)$ is observed that contradicts all the approaches of the coalescence model (remind that for (FS) the predicted ϑ_d -dependence is not applicable for primary γ -quanta).

In fig.7a dependences of $\ae_c$ on the target nucleus are presented. As is seen, $\ae_c$ is actually independent of A. If $\ae_c \sim A^{n_c}$, the factor ($n_c \approx 0.08\pm0.26$), i.e. it contradicts approaches of (BP) and (FS) but is consistent with (TMC) approaches and is close to PMC predictions.

In fig.8a dependences of $\ae_c$ on P_d at $\vartheta_d = 50^\circ$ and 90° are presented. As is seen, $\ae_c$ does not only fall but increases with deuteron momenta which contradicts the coalescence model.

Let us define the dimensions of the deuteron emission source by predictions of (TMC) and (PMC) models. Values of radii obtained by (6) and (7) are plotted in table II. First, as is expected from (6) and (7), these radii depend on the detection angle which is not expected in the framework of these models. Secondly, in the range of angles 120° absolute values of R(independent of A) exceed radii of nuclei in the range of small A, which is impossible.

Thus, it is difficult to explain the whole set of data on deuteron photoproduction at $E_\gamma^{max} = 4.5$ GeV (see also 7-11) by the coalescence model.

Comparison with the pickup model. In this model it is assumed that the nucleon produced in the interaction of the incident particle with the nucleus during its motion within the nucleus may come across an appropriate nucleon from the remaining nucleus and "pick it up" forming a deuteron. Conservation laws require that the energy of this moving in the nucleon nucleus be $T_p = T_d + \varepsilon + T_{A-1}$, where ε is the coupling energy of the nucleon in the nucleus. Since $m_{A-1} \gg m_d$, then $T_{A-1} \ll T_d$, therefore, $T_p \approx T_d + \varepsilon$. As is done in [18], let us take the value $\varepsilon = 10$ MeV. The probability of deuteron production is proportionate to that of nucleon production of the energy $T_p = T_d + \varepsilon$ as well as to the probability $F(\vec{P}_N)$ of finding a nucleon in the nucleus with the momentum $P_p = P_p(T_p)$ and to the probability of "coalescing" of two such nucleons. The coalescence coefficient, defined as [18]

$$\text{æ}_p = f_d / f_p \qquad (8)$$

will be proportionate to the momentum distribution of nucleons in the nucleus, i.e. it should decrease with the increase in the deuteron momentum, and to $A^{1/3}$ (to the length of the nucleon path within the nucleus) but should be independent of the detection angle.

Experimentally obtained values of æ_p are plotted in table II.

In fig. 6c angular dependences of æ_p are plotted. A noticeable dependence of æ_p on ϑ_d is observed.

In fig.7b dependences of æ_p on A at P_d = 0.98 GeV/c are presented. If $\text{æ}_p \sim A^{\bar{n}}$, the value of the factor $\bar{n}$ = 0.25 satisfactorily agrees with the model predictions.

In fig.8b dependences of æ_p on the momentum P_d for Al at $\vartheta_d = 50^\circ$ and 90° are presented. It is seen that æ_p is actually independent of P_d, which contradicts predictions of the model.

Thus, the obtained set of data on deuteron photoproduction contradict predictions of both coalescence and pickup models.

Comparison with hadronic data. Similar data for primary hadrons are analyzed in [17,20,21,22]. It is relevant to compare our data with these results.

Angular and energy distributions and A-dependence of deuterons produced in (γA) and (hA) processes are qualitatively similar. There is a possibility for a quantitative comparison of energy spectra and A-dependences. In fig.9 the slope parameters of deuteron spectra are presented in the representation

$f_d \sim \exp(-BP_d^2)$ from [21] with our points drawn at 90° and 50°. As is seen, within errors the results agree with each other. If we represent the A-dependence of deuteron yields as A^{n_d}, we shall have for primary hadrons $n_d \approx$ 1.5-1.8 [17], then, as is seen from fig.4, in photoprocesses $n_d \approx$ 1.2-1.5. A similar difference occurs for cumulative protons as well.

The comparison of coalescence coefficents of the above models for two types of interactions is very important. In table III predictions of these models by various dependences and experimental observations for hadron and photon processes are plotted. Data of hadron processes are in a satisfactory agreement with both coalescence model developed by Frankfurt and Strikman and the pickup model. As for photoproduction results, it is impossible to completely describe them by any approach, but most close are TMC and FMC predictions.

The comparison of absolute values of coalescence coefficients obtained in hadron and photon processes are also very important.

In the case of the pickup model the coalescence coefficient is apparently independent of the type of the primary interaction and is determined by the behavior of secondary nucleons in the residual nucleus only. Therefore, it is expected by this model $\text{æ}_p^\gamma = \text{æ}_p^h$. The comparison of our data with results of [17, 21] shows that æ_p^h exceeds æ_p^γ approximately by a factor of 3. Since γ-quanta interact within the nucleus once (and not $\nu \sim A^{1/3}$ times, as is the case with hadrons), and cascades do not make a noticeable contribution, which is testified by the similarity of angular dependences æ_c^γ for light and heaviest nuclei (see fig.7) according to approaches of (BP) and (FS) coalescence models, $\text{æ}_c^\gamma \ll \text{æ}_c^h$ is expected. Comparison of the present data with those from [2,17,21] shows that $\varkappa_c^h$ is indeed 5-10 times as large as $\varkappa_c^\gamma$.

Using explicit expressions (6) and (7) for coalescence coefficients, one may estimate dimensions of the regions $R \sim V_0^{1/3}$ where deuterons are produced. In table II the obtained values of radii of sources R^{TMC} and R^{PMC} for (TMC) and (PMC), respectively, are presented. As is seen, R is independent of the target nucleus, i.e. the deuteron source has a local character and by its absolute value is of the order of the carbon nucleus dimensions. However, the dependence of R on the angle stays inexplicable.

All the above mechanisms apparently contribute in the resulting experimentally observed deuteron yield. However, comparison of experimental and theoretical dependences of coalescence coefficients on various parameters (see table III) and absolute values of $\varkappa^\gamma$, $\varkappa^h$ (R_γ , R^h) shows that in the case of primary hadrons the dominant contribution is apparently made by the coalescence mechanism by the Frankfurt-Strikman model. And in the case of primary γ-quanta the basic contribution is apparently made by approaches of the type (TMC) and (PMC) or some other unknown mechanism.

Authors are indebted to Prof.A.Ts.Amatuni for his interest in the work, Prof.H.A.Vartapetian and Prof.S.G.Matinyan for discussions, J.V.Karumian and Zh.L.Kocharova for their help in data processing, and the staff of the YePI electron synchrotron for providing with a beam.

Table I. Invariant yields of the reaction $\gamma + A \rightarrow d + X$ in $\mu b \cdot sr^{-1} \cdot c^{-3} \cdot GeV^{-2}$

A	^{12}C	^{27}Al	^{27}Al	^{27}Al	^{27}Al	^{63}Cu	^{118}Sn	^{208}Pb
P_d GeV/c / ϑ	0.98	0.84	0.98	1.13	1.25	0.98	0.98	0.98
30°	132±5	-	348±12	-	-	1134±33	1956±74	4340±160
50°	-	272±18	133±8.5	755±0.43	29.6±2.3	-	-	-
60°	35±5	-	87±5	-	-	273±15	615±29	1265±70
90°	4.9±0.4	60±3.7	197	6.5±0.8	-	64±4	166±7	288±13
120°	1.56±0.2	-	5. ±0.6	-	-	15.2±2	50.7±6	105.5±10

Table II. Coalescence coefficients $æ_c$ ($GeV^2 \cdot c^{-3} \cdot sr$), $æ_p$ and radii of the region of deuteron emission from nuclei by (TMC) and (PMC).

A	ϑ_d degree	P_d, GeV/c	$æ_c \cdot 10^{-3}$	$æ_p \cdot 10^{-2}$	$R^{TMC} \cdot 10^{-13}$ cm	$R^{PMC} \cdot 10^{-13}$ cm
^{12}C	30	0.98	5.41±0.31	4.13±0.18	2.77±0.09	2.77±0.12
	60	-"-	3.66±0.71	3,63±0.53	3.10±0.16	3.10±0.16
	90	-"-	1.68±0.30	1.78±0.16	4.0 ±0.23	4.0 ±0.23
	120	-"-	1.81±0.34	1.95±0.25	3.91±0.20	3.91±0.20
^{27}Al	30	0.98	5.64±0.79	5.7 ±0.25	2.73±0.09	2.81±0.09
	50	0.84	5.07±0.41	4.9 ±0.50	2.8 ±0.06	2.88±0.15
	50	0.98	4.77±0.41	4.3 ±0.30	2.82±0.09	2.91±0.09
	50	1.13	7.28±0.46	4.8 ±0.30	2.42±0.05	2.50±0.15
	50	1.25	6.45±0.46	3.8 ±0.30	2.50±0.06	2.57±0.15
	60	0.98	3.41±0.51	4.14±0.26	3.18±0.13	3.27±0.13
	90	0.84	2.67±0.30	3.7 ±0.40	3.48±0.13	3.58±0.23
	90	0.98	2.23±0.36	3.23±0.35	3.48±0.16	3.58±0.16
	90	1.13	4.61±0.67	3.8 ±0.6	2.82±0.14	2.9 ±0.3
	90	1.25	6.1 ±1.61	4.2 ±0.7	2.55±0.12	2.63±0.13
	120	0.98	1.77±0.31	2.43±0.27	4.09±0.06	4.24±0.06
^{63}Cu	30	0.98	6.54±1.1	8.24±0.33	2.6 ±0.11	2.88±0.11
	60	-"-	3.92±0.63	5.49±0.31	3.05±0.23	3.35±0.23
	90	-"-	2.23±0.39	3.20±0.23	3.63±0.20	4.0 ±0.23
	120	-"-	1.62±0.31	2.41±0.29	4.17±0.20	4.62±0.23
^{118}Sn	30	0.98	6.31±0.87	8.48±0.39	2.61±0.11	2.92±0.12
	60	-"-	3.82±0.62	5.97±0.32	3.06±0.09	3.42±0.11
	90	-"-	2.37±0.39	3.9 ±0.19	3.56±0.20	4.01±0.23
	120	-"-	1.35±0.25	2.98±0.36	4.39±0.06	4.92±0.06
^{208}Pb	30	0.98	5.87±0.67	9.4 ±0.4	2.65±0.06	3.05±0.08
	60	-"-	3.71±0.55	6.52±0.39	3.1 ±0.12	3.56±0.023
	90	-"-	2.88±0.46	4.2 ±0.21	3.34±0.18	3.86±0.23
	120	-"-	1.52±0.26	3.4 ±0.33	4.24±0.23	4.85±1.06

Table III. Comparison of predictions of theoretical models by various dependences of coalescence coefficients observed in experiment by the reactions (γA) and (hA). Signs "+" and "-" in columns denote respectively coincidence and noncoincidence with predictions of theoretical models.

	Model	Type of dependence of coales.coef	Predictions of the model	Agreement of exp.with theory	
				γA	hA
Coalescence model	Batler-Pearson (BP)	Momentum	P^{-2}	-	-/17/+/21/
		Angular	no dependence	-	-
		A-dependence	$A^{-2/3}$	-	-
	Frankfurt-Strikman (FS)	Momentum	P^{-2}	-	-/17/+/21/
		Angular	$\sim[\sin^2\vartheta+\gamma^2(\beta-\cos\vartheta)^2]^{1/2}$	-	+
		A-dependence	$A^{-1/3}$	-	+
	Phenomenological model of coalescence (PMC)	Momentum	no dependence	+	-
		Angular	no dependence	-	-
		A-dependence	$(A-Z)/_Z$	+	-
	Thermodynamical model of coalescence (TMC)	Momentum	no dependence	+	-
		Angular	no dependence	-	-
		A-dependence	no dependence	+	-
Pickup model		Momentum	or	-	+
		Angular	no dependence	-	+
		A-dependence	$A^{1/3}$	+	+

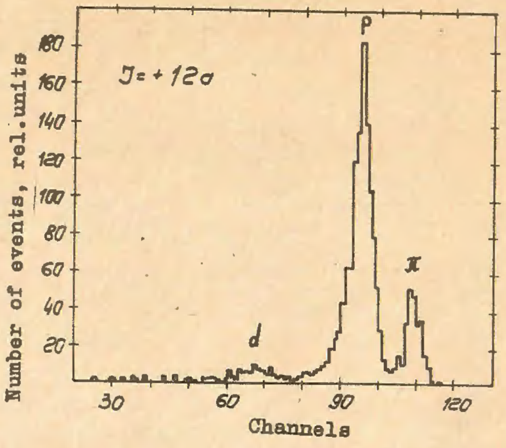

Fig.1

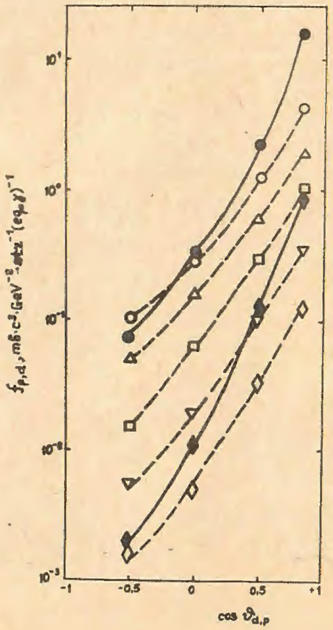

Fig.2

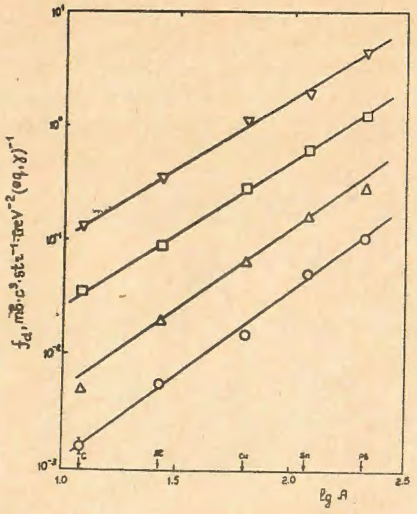

Fig.3

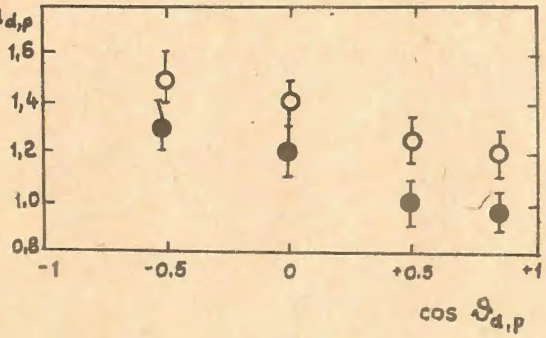

Fig.4

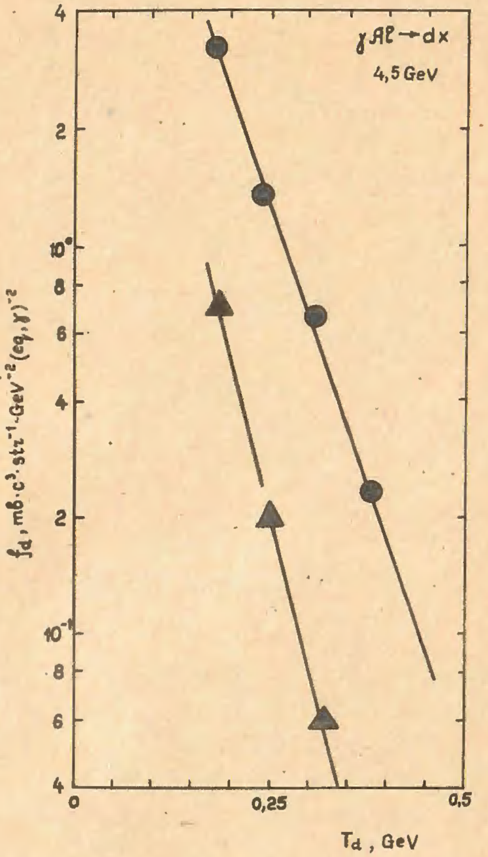

Fig.5

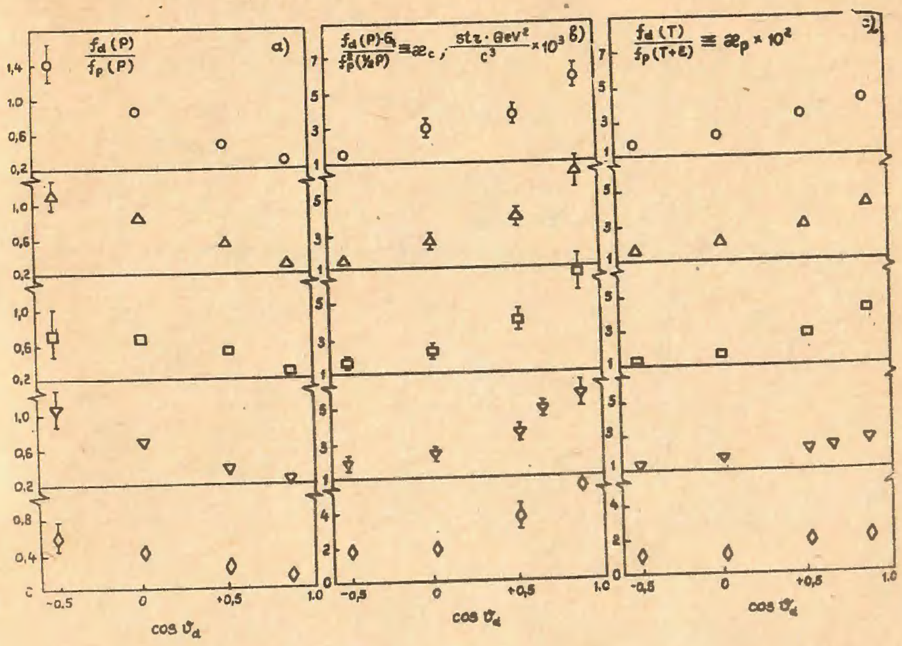

Fig.6

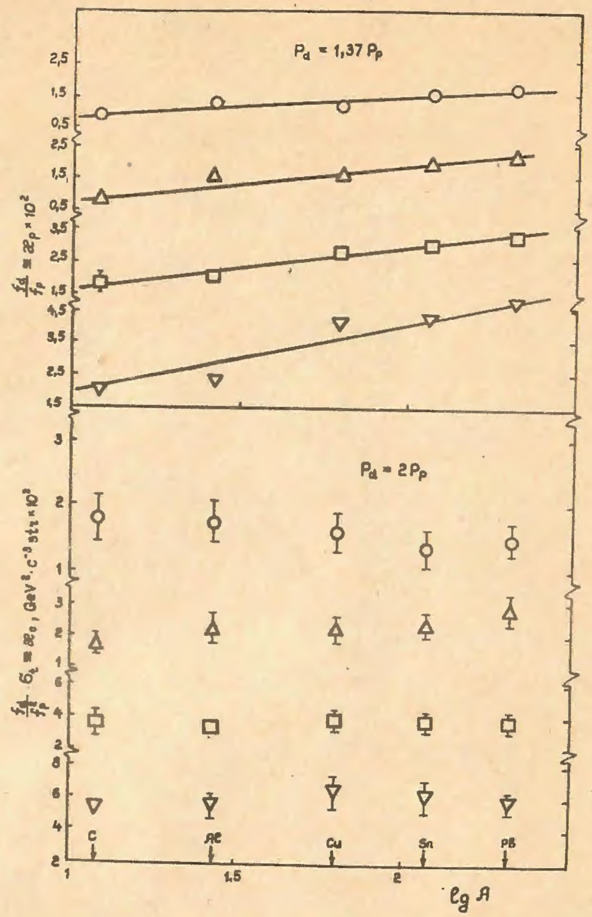
$P_d = 1{,}37\,P_p$
$P_d = 2P_p$
$\frac{f_d}{f_p} \equiv \text{æ}_p \times 10^2$
$\frac{f_d}{f_p^2} \cdot \sigma_t \equiv \text{æ}_c$, $GeV^2 \cdot c^{-3}\, str \times 10^2$
C
Al
Cu
Sn
Pb
lg A

Fig.7

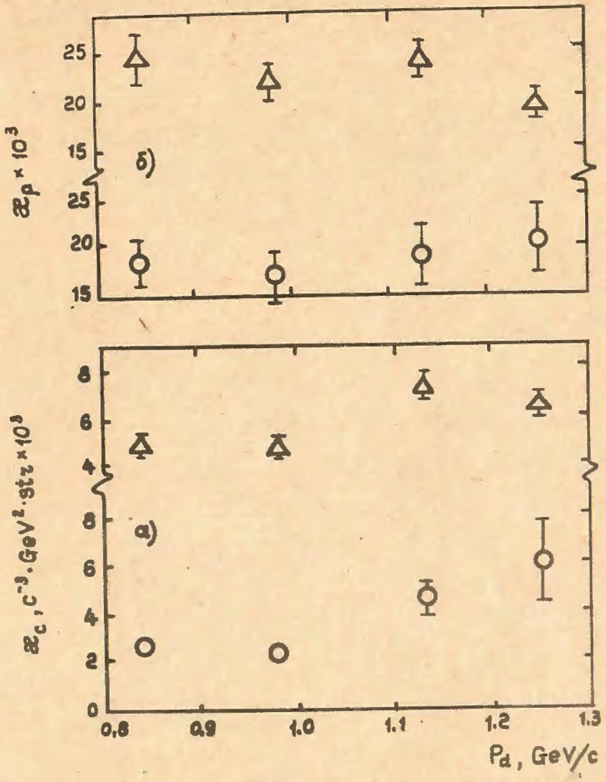
$\text{æ}_p \times 10^3$
б)
а)
æ_c, $c^{-3} \cdot GeV^2 \cdot str \times 10^3$
P_d, GeV/c

Fig.8

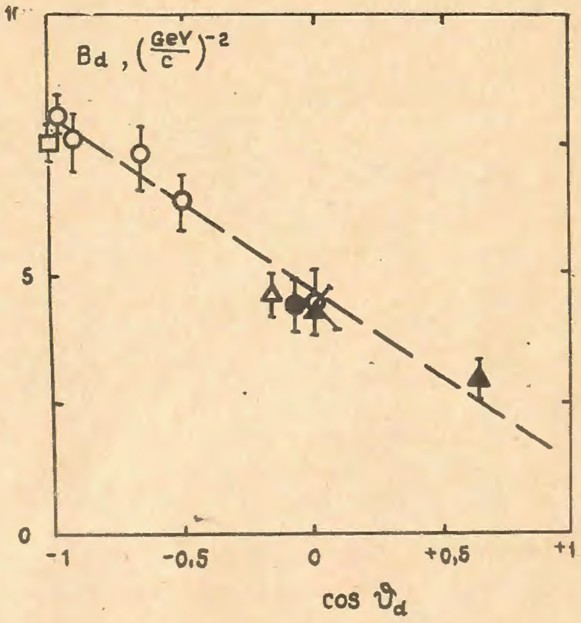

Fig.9

Figure Captions

1. Spectrum of measured time-of-flights (mass spectrum) in the magnetic spectrometer at the momentum 0.98 GeV/c. Peaks correspond (from right to left) to π-mesons, protons and deuterons.
2. Angular distribution of invariant deuteron yields (open signs) and protons (darkened signs) at 0.98 GeV/c. Experimental points: ○ , ● - Pb, △ - Sn, □ - Cu, ▽ - Al, ◇ , ◆ - C. Lines are drawn via experimental points for obviosness.
3. Dependence of the invariant yield of photodeuterons on the atomic number of the target nucleus (A-dependence) at P_d = 0.98 GeV/c. Experimental points: ○ - 120°, △ - 90°, □ - 60°, ▽ - 30°. Lines are drawn via experimental points by the method of least squares by the relation $f_d \sim A^{n_d}$.
4. Dependence of factors n_d (○) and n_p (●) in the relations $f_d \sim A^{n_d}$ and $f_p \sim A^{n_p}$ on the particle detection angles at $P_{d,p}$ = 0.98 GeV/c.
5. Photodeuteron spectra from the reaction $\gamma Al \rightarrow dX$ at E_γ^{max} = 4.5 GeV. Experimental points: ● - 50°, ▲ - 90°. Lines are drawn via experimental points by the method of least squares by the relation $f_d \sim exp(-T/T_0)$.
6. Angular dependences: a) of the ratio f_d / f_p at similar momenta $P_d = P_p$; b) of the coalescence model coalescence coefficient $\ae_c \equiv \frac{f_d \cdot \sigma_t}{f_p^2}$ at $P_d = 2P_p$; c) of the pickup model coalescence coefficient $\ae_p = \frac{f_d}{f_p}$ at $T_p = T_d$ + 10. Experimental points: ○ - Pb, △ - Sn, □ - Cu, ▽ - Al, ◇ - C.
7. A-dependence of coalescence coefficients: a) for coalescence model; b) for pickup model. Experimental points: ○ - 120°,

Δ - 90°, $\square$ - 60°, ∇ - 30°.

8. Dependences of coalescence coefficients on the deuteron momentum: a) for coalescence model; b) for pickup model. Experimental points: O - 90°, Δ - 50°.
9. Dependence of the parameter B_d on the deuteron emission angle in the representation $f_d \sim exp(-Bp^2)$ for the reactions (γd) and (hd). Experimental points: ▲ - the present work, O - $pA \to dX$ at P_p = 400 GeV/c [2], ● - $\pi A \to dX$ at P_π = 1.5 GeV/c [21], $\square$ - $pA \to dX$ at P_p = 8.6 GeV/c [23].

References

1 Стрикман М.И., Франкфурт Л.Л. Кумулятивные нуклоны и короткодействующие корреляции в ядре. Материалы XIII зимней школы ЛИЯФ 1978, с.139-191.

2 Bayukov Y.D., Efremenko V.I., Leksin G.A. et al. Production of Light Ions in the Interaction of 400 GeV Protons with Nuclei.- Phys.Rev., 1979, vol.C20, N.6, p.2257-2266.

3 Lemaire M.C., Nagamiya S., Schmetzer S. et al. Composite Particle Emission in Relativistic Heavy Ion Collisions.- Phys.Lett., 1979, vol.85B, N.1, p.38-42.

4 Gosset J., Gutbrod H.H., Meyer W.G. et al. Central Collisions of Relativistic Heavy Ions.- Phys.Rev., 1977, vol.C16, N.2, p.629-658.

5 Dewire J.W., Silverman A. and Wolfe B. High Energy (γd) Reactions.- Phys.Rev., 1953, vol.92, N.2, p.519-520.

6 Kihara M. Photoproduction of Deuterons from Carbon. - Journ. of the Phys.Soc.Japan, 1965, vol.20, N.8, p.1313-1320.

7 Антуфьев Ю.П., Агранович В.А., Ганенко В.Б. и др. Зависимость сечения реакции (γp) и (γd) от массового числа ядер при энергиях фотонов 700 и 1200 МэВ. УФЖ 1969, т.14, № 2, с.248-253.

8 Антуфьев Ю.П., Агранович В.А., Ганенко В.Б. и др, Реакции (γp), (γd) и (γt) на ядрах ^7Li, ^{12}C и ^{181}Ta при энергиях фотонов 400-1300 МэВ. УФЖ 1969, т.14, № 3, с.499-506.

9 Антуфьев Ю.П., Агранович В.А., Ганенко В.Б. и др. Функция возмущения реакции (γp) и (γd) на C^{12} при энергиях фотонов 400-1400 МэВ. ЯФ 1969, т.9, № 5, с.921-924.

10 Антуфьев Ю.П., Агранович В.А., Ганенко В.Б. и др. Проверка модели Батлера-Пирсона в фотоядерных реакциях при E_γ^{max} = 1140 МэВ. УФЖ 1972, т.17, № 6, с.928-933.

11 Антуфьев Ю.П., Агранович В.А., Ганенко В.Б. и др. Исследование спектров протонов и дейтронов при фотодезинтеграции ядер фотонами с максимальной энергией до 1200 МэВ. ЯФ 1971, т.13, № 3, с.473-477.

12 Levinger J.S. The High Energy Nuclear Photoproduction.- Phys.Rev., 1956, vol.84, N.1, p.43.

13 Batler T. and Pearson C.A. Deuterons from High Energy Proton Bombardment of Matter.- Phys.Rev., 1963, vol.129, N.2, p.836-842.

14 Аланакян К.В., Амарян М.Дж., Демирчян Р.А. и др. А-зависимость выхода инклюзивного фоторождения дейтронов на ядрах. Препринт ЕФИ-490(33)-81, Ереван, 1981.

15 Аланакян К.В., Амарян М.Дж., Демирчян Р.А. и др. Установка для исследования кумулятивного фоторождения частиц на ядрах ("Дейтрон") Препринт ЕФИ-408(15)-80, Ереван, 1980.

16 Frankfurt L.L. and Strikman M.I. High Energy Phenomena, Short-Range Nuclear Structure and QCD.- Phys.Rep., 1981, vol.76, N.4, p.217-347.

17 Башков Ю.Д., Гаврилов В.Б., Горяинов Н.А. и др. Образование дейтронов в протон-ядерных взаимодействиях при 7,5 ГэВ/с. Препринт ИТЭФ-123, Москва, 1982, с.30.

18 Schwarzshild A., Zupancic C. Production of Tritons, Deuterons, Nucleons and Mesons by 30 GeV Protons on Al,Be and Fe Targets.- Phys.Rev., 1963, vol.129, N.2, p.854-862.

19 Mekjan A. Direct Interaction, Classical Thermodynamics and Quantum Statistical Theories of Heavy Ion Collisions.- Phys. Lett., 1980, vol.89B, N.2, p.177-180.

20 Ложкин О.В., Мурин Ю.А. Феноменологический анализ процесса испускания кумулятивных сложных ядер. Препринт РИ-145, Ленинград, 1981, с.17.

21 Буклей А.Е., Бургов Н.А., Власов М.К. и др. Образование дейтронов под углом 100° на ядрах ^{12}C, ^{16}O, ^{63}Cu, ^{208}Pb в инклюзивных реакциях $\pi^- A \to dx$ при импульсе π^- - мезонов 1,5 ГэВ/с. Препринт ИТЭФ-136, Москва, 1982, с.12.

22 Гаврилов В.Б., Лексин Г.А. Глубоконеупругие ядерные реакции. Препринт ИТЭФ 124, Москва, 1983, с.30.

23. Балдин А.М., Бондарев В.К., Манзявский А.Н. и др. Энергетические спектры и А-зависимость кумулятивного рождения барионных систем. Препринт Р1-11302, Дубна, 1978.

The manuscript was received 26 June 1984.

К.В.АЛАНАКЯН, М.Д.АМАРЯН, Р.А.ДЕМИРЧЯН, К.Ш.ЕГИЯН,
М.С.ОГАНДЖАНЯН, С.Г.СТЕПАНЯН, Ю.Г.ШАРАБЯН

ФОТООБРАЗОВАНИЕ ДЕЙТРОНОВ НА ЯДРАХ ТОРМОЗНЫМИ γ - КВАНТАМИ ПРИ E_{γ}^{max}= 4,5 ГЭВ

(на английском языке, перевод Л.Н.Багдасаряна)

Редактор Л.П.Мукаян

Технический редактор А.С.Абрамян

Подписано в печать 29/XП-84г. ВФ-00650 Формат 60х84/16
Офсетная печать. Уч.изд.л.2,0 Тираж 299 экз. Ц. 30к.
Зак. тип.№ 977 Индекс 3624

Отпечатано в Ереванском физическом институте
Ереван 36, Маркаряна 2