Mechanism of disintegration of emulsion nuclei by relativistic light nuclei

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(Received 5 May 1992)

The charged secondary multiplicity distributions as a function of emitting various noninteracting projectile fragments of ^{12}C at 4.5 GeV/c per nucleon by using nuclear emulsion detectors is presented and discussed. The correlations between various kinds of particles and the angular distributions of multiple production in ^{12}C ion collisions are studied. Also a systematic comparison using the calculations of the cascade-evaporative model is made. An investigation of energy dependence of grey prongs produced in different interaction beams at energy range $\sim$(4–200)A GeV is reported.

PACS number(s): 25.75.+r

INTRODUCTION

In recent years, many experiments [1–3] have been performed to discuss the characteristic features of interactions of relativistic heavy ions. The availability of monoenergetic beams of relativistic heavy ions at LBL, BNL AGS, CERN SPS, and JINR provide the opportunity to investigate nucleus-nucleus interactions at high energies which constitute a new branch of research. Because of the complex nature of these interactions, it depends on the impact parameter B of the collision, i.e., the normal distance between centers of projectile and target nuclei. The limiting values of the impact parameter B give rise to the concepts of peripheral collision (gentle reactions), i.e., $B=r_1+r_2(r_1,r_2$ are radii of target and projectile nuclei, respectively). In central collisions (violent interactions), $0\leq B\leq r_1-r_2$. The nucleons in the overlap region are called participants and the remaining nucleons are spectators. The complete disintegration of the heavy components of nuclear emulsion may occur when large amounts of energy are transferred to the target nucleus. The characteristics of such events can be more critical to the choice of the interaction model than the characteristics of average events without special selection in the degree of disintegration of the target. In such events B is almost zero.

The purpose of the present work is to study a number of basic experimental characteristics of inelastic collisions of carbon nuclei at energy $\sim 3.6A$ GeV with nuclear emulsion. In the former investigations [4,5] we have studied the slow particles emission and search for shock waves in ^{12}C 4.5 GeV/c per nucleon. In this paper the dependence of impact parameters with the multiplicity of charged secondaries and the correlations between various kinds of particles as well as the angular distributions of multiple production in ^{12}C-ion collisions are discussed.

EXPERIMENTAL MATERIAL

The present experiment was performed in a stack of BR-2 nuclear research emulsion pellicles which were bombarded by ^{12}C nuclei with momentum 4.5 GeV/c per nucleon in the Dubna Cynchrotron. The pellicles have dimensions of 20 cm$\times$10 cm$\times$600 μm. Along the track a scanning method was carried out. The pellicles were scanned under 100$\times$ magnification using oil immersion objectives in a binocular orthelux microscope. About 1000 inelastic events were collected; measurements and analyses were made of $\sim$275 inelastic events without discrimination of type $N_h\neq 0$. Each event was classified into two principal categories depending upon visual characteristics. Thus the following can be drawn: (i) Peripheral events with a projectile fragment of charge $Z\geq 2$ emitted in a forward cone, formed with some target fragmentations. (ii) Central events which exhibit no projectile fragments of charge $Z\geq 2$ in the forward cone. Such events are thought to be produced by violent interaction of the projectile and target nuclei at small impact parameter B.

The following experimental definitions of particle categories are used in this work. (i) Shower particles (N_s), singly charged particles with a velocity $v\geq 0.7c$. These particles are almost pions [6]. (ii) Grey prongs (N_g), charged particles producing tracks with range ≥ 3 mm and having a velocity $<0.7c$. These particles are mainly protons in the energy range 26–375 MeV, with an admixture of pions and kaons with about 11% [6]. (iii) Black prongs (N_b), charged particles producing tracks with range <3 mm. These particles include low energy singly and doubly charged particles $<26A$ GeV. (iv) Heavily ionizing tracks, $N_h=N_g+N_b$.

In nucleus-nucleus interactions there is an additional group of secondary charged particles together with fragments of incident nucleus with charges $Z=1$ and $Z\geq 2$. These fragments are emitted within an angle $\theta\leq 3°$ for 4.5 GeV with respect to the incident particles and they are classified by means of special measurements [7,8].

RESULTS AND DISCUSSIONS

The average values of secondary charged particles multiplicity $\langle N_s\rangle$, $\langle N_g\rangle$, $\langle N_b\rangle$, and $\langle N_h\rangle$ produced from a complete set of inelastic interactions of ^{12}C with emulsion of type $N_h\neq 0$ as a function of noninteracting projectile fragments are given in Table I. The first two rows in this table represent the average multiplicity of secondary charged particles for central collision according to two criteria. (1) Events that exhibit no visible forward cone fragments P_{fs} of charge $Z \geq 2$; such events are thought to be created by interactions of projectile and target nuclei of small values of impact parameter B of collision. (2) Events without projectile fragments P_{fs} emitted in a forward cone with charge $Z \geq 2$, and having $N_h \geq 28$. These events are thought to be created by violent destruction of the projectile and target nuclei at almost zero impact parameter.

Other rows in Table I show the average multiplicities of secondary charged particles with various particle modes of the breaking up of the ^{12}C projectile. In other words, these events represent peripheral collisions at different impact parameters B. From these data, the following conclusions can be made. (a) Although $\langle N_s \rangle$ and $\langle N_b \rangle$ are nearly the same within experimental errors for the above definitions of the two central collisions, there are big differences in $\langle N_g \rangle$. This may indicate that the energy transferred from the projectile to the target is almost the same for both of the central lines, which show from the same average of pion creation $\langle N_s \rangle$ within errors. But in spite of that, the number of collisions, which is a function of N_g, is more in the second line of the central collision. $\langle N_b \rangle$ as it is shown is an indication of saturation with increasing centrality. (b) With an increase of the participant nucleons of the incident nucleus and a decrease of the number of noninteracting nucleons on the incident carbon, the average multiplicity of singly charged relativistic particles $\langle N_s \rangle$ rises rapidly, and the average number of grey $\langle N_g \rangle$ tracks also increases substantially but not to that extent. At the same time the multiplicity of slowest fragments of target $\langle N_b \rangle$ increases weakly with increasing participant nucleons of the incident carbon. (c) It is interesting to point out that $\langle N_s \rangle$ as given in Table I slowly increases if Z_{pfs} emitted singly charged particles. At the same time the value of $\langle N_s \rangle$ slowly decreases when the accompanying Z_{pfs} is greater than one. It should be mentioned that in both cases the total value of Z_{pfs} remains unchanged. (d) The last row in Table I presents the characteristics of secondaries when the total noninteracting outgoing charges is equal to 6, which is the charge of incident carbon. These values may be due to either a neutron interacted with emulsion or one proton interacted with production of one π meson in the forward cone counted as proton fragment. (e) For a complete disintegration, the multiplicity of shower particle was established by the equation [2]

$$\langle N_s \rangle_{\text{center}} = Z_{\text{proj}} \langle N_s \rangle_{p+\text{Em}} + (A_{\text{proj}} - Z_{\text{proj}}) \langle N_s \rangle_{n+\text{Em}} .$$

There the value of $\langle N_s \rangle_{n+\text{Em}}$ was estimated on the basis of proton stripping events in $d+$Em interactions as equal to 1.8 ± 0.1. $\langle N_s \rangle_{p+\text{Em}}$ is 1.63 ± 0.02 at similar energy per nucleon. In the present work the values $\langle N_s \rangle_{\text{center}}$ obtained by using the above equation was found to be equal to 20.6 ± 0.7. While the $\langle N_s \rangle_{\text{theo}}$ in the framework of the nuclear poinization model [2,9] equals 18, both values of $\langle N_s \rangle$ match well with the experimental value for central collisions.

TABLE I. Detailed experimental information of the average multiplicities for different producing projectile fragments of ^{12}C 4.5 GeV/c per nucleon with emulsion nuclei. The values (in parentheses) were taken from Ref. [2]. p = proton, α = alpha.

Noninteracting	Frequency	$\langle N_s \rangle$	$\langle N_g \rangle$	$\langle N_b \rangle$	$\langle N_h \rangle$
0	36	16.3±0.7	9.4±0.5	11.8±0.6	21.1±0.8
$0, N_h \geq 28$	10	17.5±1.3	22.2±1.3	12.5±1.4	34.7±1.9
		(18.8±0.7)	(22.5±0.8)	(11.9±0.5)	(34.4±0.9)
$1p$	21	13.1±0.8	5.6±0.5	5.8±0.5	11.4±0.7
$2p$	30	8.5±0.5	3.8±0.4	5.9±0.4	9.7±0.6
1α	17	6.8±0.6	2.8±0.4	6.5±0.6	9.3±0.7
All	47	7.9±0.4	3.5±0.3	6.1±0.4	9.5±0.5
$3p$	10	8.8±0.9	4.2±0.7	6.6±0.8	10.8±1.0
$1\alpha+1p$	18	7.7±0.7	2.3±0.4	4.7±0.5	7.1±0.6
All	28	8.1±0.5	3.0±0.3	5.4±0.4	8.4±0.6
$1\alpha+2p$	23	5.0±0.5	2.3±0.3	3.3±0.4	5.6±0.5
2α	11	4.1±0.6	1.5±0.4	2.6±0.5	4.0±0.6
All	34	4.7±0.4	2.1±0.2	3.0±0.3	5.3±0.4
$1\alpha+3p$	14	2.9±0.5	1.3±0.3	2.7±0.4	4.0±0.5
$2\alpha+1p$	16	2.6±0.4	0.9±0.2	2.1±0.4	3.3±0.5
$5P$	2	4.5±1.5	2.0±1.0	2.0±1.0	4.0±1.4
All	32	3.2±0.3	1.3±0.2	2.4±0.3	3.7±0.3
$3\alpha, 2\alpha+2p$ and $1\alpha+4p$	8	1.6±0.5	0.7±0.3	2.4±0.6	3.1±0.7

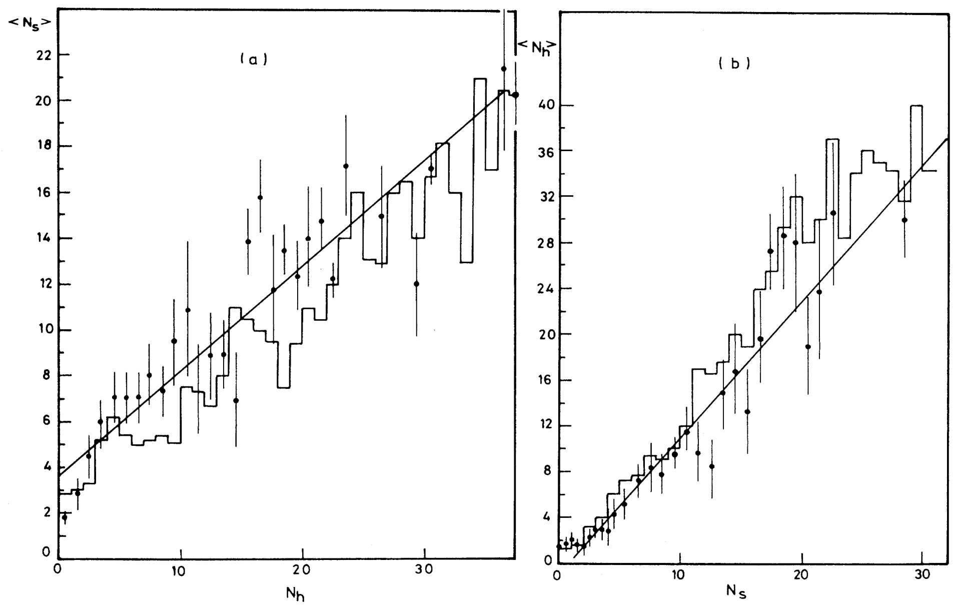

FIG. 1. Dependences (a) of $\langle N_s \rangle$ on N_h and (b) of (N_h) on N_s in the interactions of carbon with emulsion nuclei. The points represent the experimental data, the line represents the best fit of the experimental points, and the histogram is a calculation with the cascade-evaporation model [2].

Correlations between different particles

A more detailed characteristic of the nucleus-nucleus interactions is the correlation between the multiplicities of different types of particles. The correlation dependences $\langle N_s(N_h) \rangle$ and $\langle N_h(N_s) \rangle$ for ^{12}C-Em interactions in comparison with the calculation using the cascade-evaporation model [10] are given in Fig. 1. It is shown that the model is in agreement with experiment. The dependences may be represented approximately by a linear dependence. The relationships for both lines are fitted by

$$\langle n_s \rangle = 0.44 N_h + 3.84 \ ,$$

$$\langle N_h \rangle = 1.20 N_s - 1.54 \ .$$

The multiplicities correlations of $\langle N_s(N_g) \rangle$ and $\langle N_b(N_g) \rangle$ are in different S groups of events 0,1,2; here S is the total charge of noninteracting fragments of the incoming nucleus. In determining S in individual events, the charge conservation for ^{12}C was used. Such correlations are plotted in Fig. 2. The following can be concluded from the data: (i) $\langle N_s \rangle$ increases linearly with N_g in each group (except in the region of highest N_s) and $\langle N_s \rangle$ increases as S decreases. (ii) The dependences of correlations between heavy particle multiplicities $\langle N_b(N_g) \rangle$ are independent on S. On the other hand, $\langle N_b \rangle$ increases linearly with N_g up to the value of $N_g \approx 6$, for all groups. At higher values of N_g, $\langle N_b \rangle$ is unchanged. The linear relationship can be expressed by $\langle N_b \rangle = 1.22 N_g + 1.41$. It is possible that this is a consequence of the decrease of nuclear density during the cascade development inside the target (the so-called trailing effect).

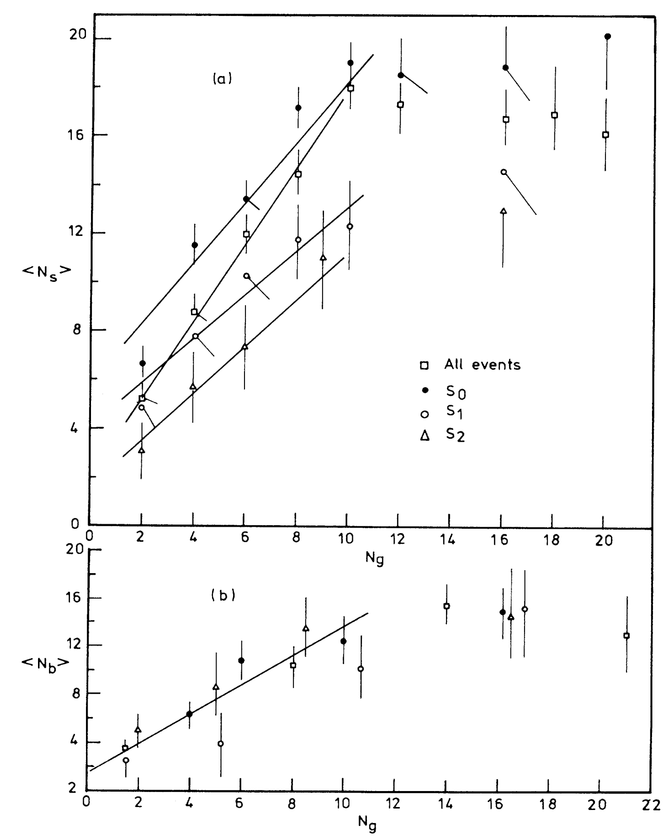

FIG. 2. Multiplicity correlations (a) $\langle N_s(N_g) \rangle$ and (b) $\langle N_b(N_g) \rangle$ in different S groups 0,1,2 (S is the charge of noninteracting fragments of the carbon nucleus).

Angular distribution of grey prongs

Figure 3 presents the angular distribution of grey prongs for ^{12}C-Em in comparison with those calculated according to the cascade model. The experimental and theoretical values of the anisotropy parameters $\alpha_i = (F-B)/(F+B)$ of grey particles are 0.47 ± 0.03 and 0.46 ± 0.02, respectively. The shape of the angular distribution is satisfactorily described by the cascade model, Fig. 3(a). In Fig. 3(b) the results from ^{12}C-Em at 4.5 GeV/c per nucleon for central and peripheral events are shown. Figure 3(c) shows the present data together with results of angular distributions for ^{16}O-Em for 14.6A, 60A, and 200A GeV taken from Ref. [11]. As shown in Figs. 3(b)–3(c), either peripheral or central collisions for the same or different beams, as well as various energies, follow an exponential shape and the slopes are close. We can say that the angular distribution of grey prongs is independent on the projectile size, projectile energy, and the centrality of the events.

Angular distribution of shower particles

In Fig. 4(a) we show the angular distribution of shower particles of ^{12}C-Em with corresponding predictions according to the calculations of the cascade-evaporative model. There is no agreement with this model. The model underestimates somewhat the number of particles with small θ and appreciably exaggerates the number of shower prongs produced in the backward hemisphere in the laboratory system. In Fig. 4(b) are shown the normalized pseudorapidity [$\eta_{\text{lab}} = -\ln \tan(\theta/2)$] distributions of charged shower particles of ^{12}C-Em at 4.5 GeV/c per nucleon for $N_h > 6$, $N_h \geq 0$, and $N_h \leq 6$. It is seen from this figure that the heights of these distributions increase with N_h. This may be due to the fact that the yield of pion production is much more in events with large N_h values. The centers of these distributions are close to $\eta \approx 2$ with $\langle \eta \rangle = 1.8$, 2.1, and 2.4, respectively. The widths of the plateaus at peaks increase as N_h decreases in the projectile fragmentation region ($\eta > 3$). The small differences in

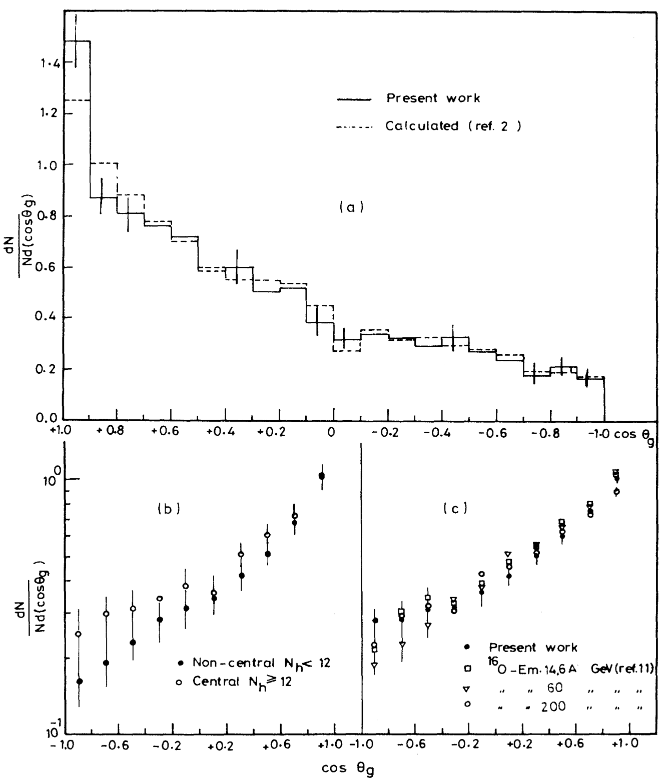

FIG. 3. (a) Angular distribution of grey particles from minimum bias of ^{12}C-Em interactions (solid histogram) in comparison with a calculation according to the cascade model (dashed histogram). (b) Angular distribution of grey particle from central and noncentral events of the present work, and (c) a total sample in comparison with the data for ^{16}O at 14.6A, 60A, 200A GeV taken from Ref. [11].

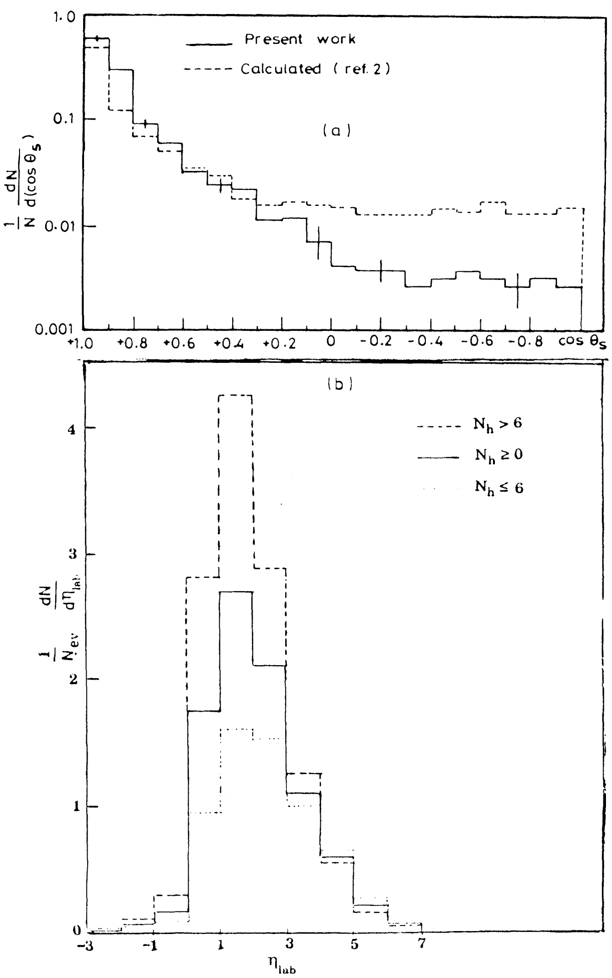

FIG. 4. (a) Angular distribution of the shower particle from the present data. The solid histogram is experimental, and the dashed histogram is calculated according to the cascade-evaporation model taken from Ref. [2]. Both are normalized. (b) The normalized pseudorapidity (η) distributions of charged shower particles in the laboratory frame for $N_b > 6$, $N_h \geq 0$, and $N_h \leq 6$ in the interactions of ^{12}C at 4.5 GeV/c per nucleon with emulsion nuclei.

the distributions in the target fragmentation region ($\eta < 0.8$) may be due to the impact parameter of the collisions.

CONCLUDING REMARKS

From this study we can conclude with the following remarks.

(1) The creation of pions (N_s) is strongly dependent on the number of interacting nucleons while the total charge of the noninteracting fragments remains constant. A slight increase in (N_s) accompanying singly charged projectile fragments is observed. On the other hand, a slight decrease in the value of $\langle N_s \rangle$ is noticed in association with higher projectile charges. $\langle N_g \rangle$ tracks increase substantially with an increase of participant nucleons on the incident carbon.

(2) The evaporated particles (N_b) are independent of the impact parameter for events having up to half charges of noninteracted incident beam. This reflects that the complete excitation of target occur if the charge of interacting nucleons is equal to about half of the carbon charges. $\langle N_b \rangle$ decreases weakly at emission of noninteracting total charges ≥ 4.

(3) The multiplicity correlations for $\langle N_s(N_h) \rangle$ and $\langle N_h(N_s) \rangle$ may be represented by linear dependences and are satisfactorily described by the cascade-evaporative model. The dependences $\langle N_s(N_g) \rangle$ and $\langle N_b(N_g) \rangle$ for different groups of noninteracting fragments $S=0,1,2$ are also fitted linearly by one relation for $\langle N_b \rangle$ versus N_g and four relations with nearly the same slopes for $\langle N_s \rangle$ versus N_g.

(4) The angular distribution of grey particles are satisfactorily described by the cascade-evaporative model. The angular distribution of grey prongs for peripheral, central, minimum bias, and various beams as well as different energies follows the exponential shape with nearly equal slopes. In other words, the angular distribution of grey prongs is independent of the projectile size, projectile energy, and the centrality of the events.

(5) The angular distribution of shower particles cannot be described by the cascade-evaporative model. The normalized pseudorapidity distributions of charged shower particles are close to $\eta \approx 2$ for $N_h > 6$, $N_h \geq 0$, and $N_h \leq 6$.

ACKNOWLEDGMENTS

This work was carried out at Mohamed El-Nadi Nuclear Research Center, Experimental High Energy Physics Laboratory, Physics Departments, and Faculty of Science, University of Cairo. The author would like to express deep thanks to Prof. M. El-Nadi for his valuable discussions and continuous encouragement. The author is indebted to the late Prof. O. E. Badawy for his devotion to the high energy groups in Egypt. We are thankful to the Dubna (Joint Institute of Nuclear Research, JINR, Dubina, USSR) technical staff for providing us with the irradiated emulsions.

[1] H. H. Heckman, D. E. Griener, P. L. Lindstrom, and H. Shwe, Phys. Rev. C **17**, 5 (1978).

[2] V. G. Bogdanov, N. A. Perfilov, V. A. Plyushchëv, and Z. A. Solov'ëva, Yad. Fiz. **38**, 1493 (1983) [Sov. J. Nucl. Phys. **38**, 909 (1983)], and references therein.

[3] Bucharest-Warsaw, Dubna, Kosice, Leningrad-Moscow, Tashkent Collaboration, Yad. Fiz. **29**, 3 (1979) [Sov. J. Nucl. Phys. **29**, 1 (1979)], and references therein.

[4] M. El-Nadi, O. E. Badawy, M. T. Ghoniem, M. Sherif, and M. El-Nagdy, Egypt. J. Phys. **15**, 2 (1984); **15**, 179 (1984).

[5] M. El-Nadi, O. E. Badawy, M. T. Ghoniem, M. Sherif, and M. El-Nagdy, Egypt. J. Phys. **16**, 1 (1985); **16**, 23 (1985).

[6] M. I. Adanovich *et al.*, EMUO1 Collaboration, Phys. Lett. B **262**, 2 (1991); **262**, 3 (1991); **262**, 369 (1991).

[7] A. Z. M. Ismail, M. S. El-Nagdy, K. L. Gomber, M. M. Aggarwal, and P. L. Jain, Phys. Rev. Lett. **52**, 15 (1984); **52**, 1280 (1984).

[8] V. A. Antonchik, V. A. Bakaev, A. V. Belousov, S. D. Bogdanov, V. I. Ostroumov, and M. A. Pavlovets, Yad. Fiz. **39**, 1228 (1984) [Sov. J. Nucl. Phys. **39**, 774 (1984)].

[9] B. N. Kalinka, S. N. Koltochnile, and V. L. Shmonin, Phys. Scripta **21**, 792 (1980).

[10] K. K. Gudima and V. D. Toneev, JINR Dubna Report R2-10431, 1977.

[11] M. I. Adamovich *et al.*, EMUO1 Collaboration Cosmic and Subatomic Physics Report LUIP 8907, 1989.