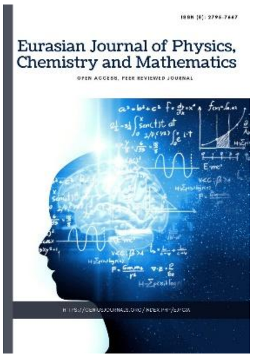

Stopping power of the ^{12}C carbon nucleus for a projectile in $p^{12}C$ collisions at a momentum of 4.2 GeV/s

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ABSTRACT

In this paper, the stopping power of carbon nuclei in interactions of protons with a momentum of 4.2 GeV/s with carbon nuclei is studied, based on the study of multiple spectra of secondary charged particles, π- mesons, π+ mesons and protons of the participants depending on the degree of centrality. The obtained experimental data are compared with the calculations of the theoretical CEM model (cascade-evaporation model) and the FRITIOF model with and without taking into account Δ+ and Δ0-isobars. It is shown that in central interactions the primary proton loses a significant part of its energy and the fraction of leading protons increases, while the fraction of target protons is maximal in events with $Q = 1$ and decreases rapidly in events with $Q \geq 5$. This result reflects the softening of the spectrum of fast target protons as the centrality of collisions increases.

Keywords: Proton, spectrum, energy, centrality, momentum, particles, deuterium, pC interactions, target protons.

Introduction

When nuclei with energies up to 10 GeV/s per nucleon interact, several mechanisms of secondary particle formation are realized: evaporation, stripping, and multiple particle formation. As a result of these mechanisms, not only particles are formed, but also various fragments (both light and medium fragments by atomic weight) of colliding nuclei.

For a propane bubble chamber (propane molecule composition C_3H_8) the following light nuclei can be formed from carbon nuclei: protons, deuterium, tritium, helium. Particles and light nuclei that correspond to their formation in the first two mechanisms are particles that are not participants in the multiple particle formation process. Consequently, the obtained experimental distributions are the sum of the spectra of particles that are not participants and particles that participate in strong interactions. When studying a multiple mechanism, non-participant particles can significantly change the sought-after physical distributions. This implies the need for detailed knowledge of the properties of these particles and their share among all the particles formed. Therefore, when studying the latter mechanism, non-participant particles must be separated using the characteristics of evaporative and stripping protons and neutrons, as well as nuclear fragments [1-3].

2. Experimental Procedure

Experimental data on pC interactions at 4.2 GeV/c were obtained using the bubble chamber method placed in a magnetic field in collaboration with the Joint Institute for Nuclear Research. This technique allows studying the interactions of particles with specific target nuclei under 4π-geometry conditions with sufficiently high accuracy in measuring the momentum and angular characteristics of the resulting particles. The experimental material from the JINR High Energy Laboratory (Dubna, Russian Federation) and the Laboratory of Multiple Processes of the Physical-Technical Institute of the Academy of Sciences of the Republic of Uzbekistan on the interactions of protons with carbon nuclei was used, obtained using a 2-meter propane bubble chamber of the JINR High Energy Laboratory at the Dubna Synchrophasotron. Separation of protons and π+-mesons was carried out visually by ionization in the region of $p \leq 0.8$ GeV/s. The lower limit of the momentum of the registered protons was determined by the minimum track length ($L \geq 2$ mm) and for the propane bubble chamber is equal to 0.14 GeV/s. Methodological issues related to the processing of stereo photographs, the restoration of the kinematic characteristics of secondary particles, their identification, and the introduction of corrections for the loss of protons emitted at a large angle to the plane of photography are described in [3-5].

To select events of inelastic pC interactions from the total number of events with propane, the criteria described in [3] were used. The procedure for selecting elastic pp and pC events, introducing corrections for the number of secondary particles and their momentum and angular characteristics, as well as introducing “weights” for positively charged particles with momenta greater than 0.5 GeV/s are described in detail in [6]. Let us recall that, according to the experimental conditions (without measuring the ionization of positively charged particles), π+ mesons and protons are reliably identified up to momenta of 0.5 GeV/s.

In the analyzed ensemble of pC interactions, among the secondary particles, π+ and π- mesons, proton participants with a momentum p greater than 0.3 GeV/c, and evaporative protons ($0.15<p<0.3$ GeV/s) stood out. In addition, two groups of protons were considered: protons with momenta from 0.3 to 0.75 GeV/s (these are mainly participant protons from the target nucleus) and protons $p>0.75$. The latter group consists mainly of protons interacting with the target nucleus and some protons from the carbon nucleus that received a large momentum transfer during interaction with the primary proton.

The value Q was taken as a measure of the centrality of the pC interaction, which was defined as

$Q=n_{-}+n_{+}-n^{eva}_{p}$,

Where n_- and n_+ –are the numbers of positively and negatively charged particles in the event, n^{eva}_{p} is the number of evaporating protons.

The value of Q is equal to the total charge of the particles in the event that actively participate in the interaction. It correlates with the value of the collision parameter of the colliding nuclei. The degree of centrality of the interaction increases with increasing Q. Experimental results and discussions: An idea of the distributions of pC events by the multiplicities of secondary particles of different types is given by Fig. 1. The largest number of charged particles registered in pC interactions reaches 13, π+ and π- mesons - 4, and the number of participating protons - 8 (taking into account the charge exchanges p→n and n→p).

The number of analyzed pC events and the average multiplicities of secondary particles for all pC interactions and for six groups of events with different degrees of centrality determined by the value of Q are presented in Table 1. It can be seen that peripheral interactions ($Q \leq 2$) account for more than 70% of all inelastic pC collisions. For the most central ones ($Q \leq 4$) is small and amounts to only a few percent. As a consequence of this, all pC interactions are characterized by an average number of participating protons, $< n^{eva}_{p} >$, less than two. The average multiplicity of π+ mesons, < π+>, significantly exceeds < π->, which is typical for interactions of protons with symmetric nuclei Np=Nn. In pC interactions, the average multiplicities of π+ and π- mesons exceed the corresponding multiplicities in proton-nucleon (pN) collisions (<n(π-)pN=0.31, and

<n(π+)>pN=0.51 when normalized to the total cross section of pN interactions, σ_{pN}^{tot} [2,6-8]. Comparison of the average pion multiplicities in pC and pN collisions allows us to conclude that ~30% of π- mesons and ~40% of π+ mesons are produced in secondary interactions in the carbon nucleus.

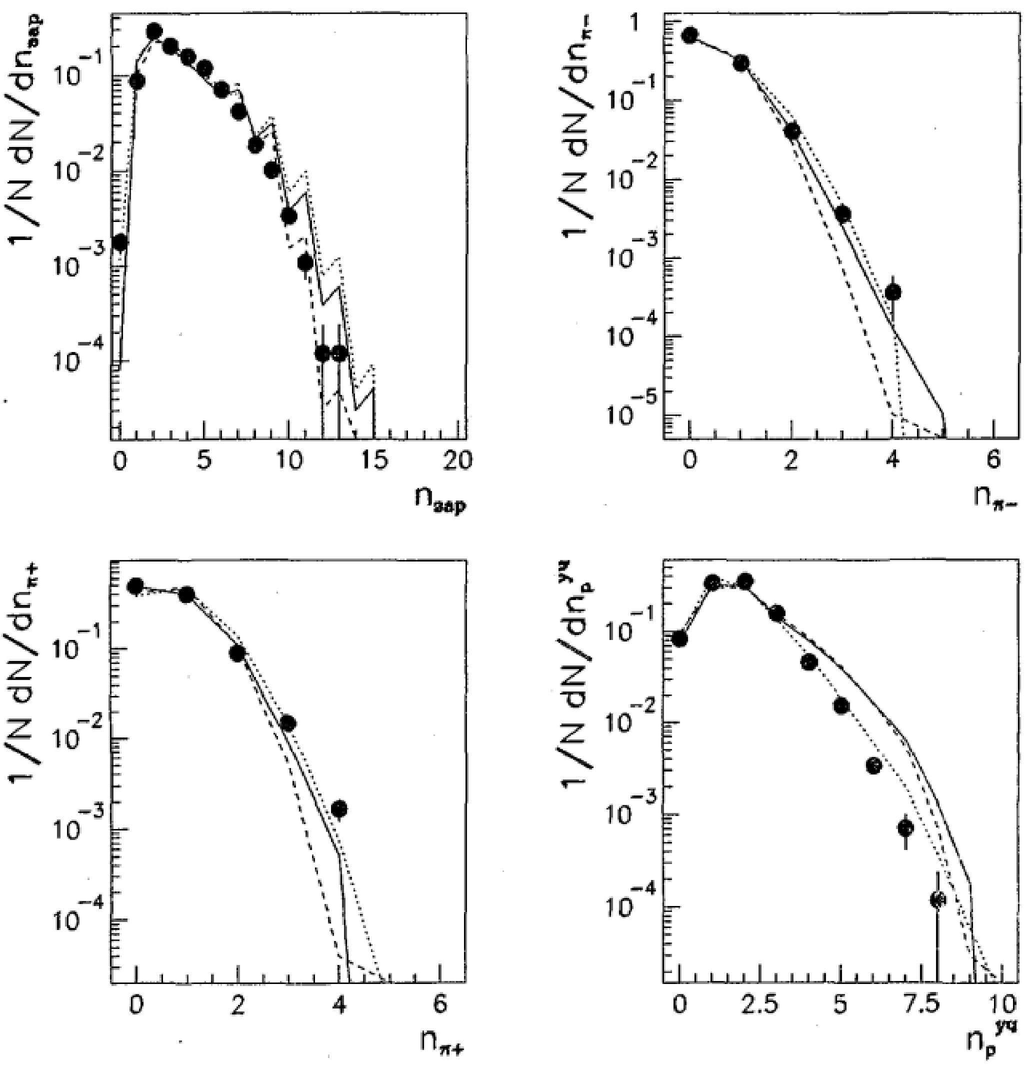

Fig. 1. Distributions of pC interactions by multiplicity: a) charged particles, b) π- mesons, c) π+ mesons, d) participant protons. ● – experiment, solid and dashed curves – calculations according to the FRITIOF model with and without taking into account Δ^+ and Δ^0 isobars, dotted curves – calculations according to CEM.

Luctuates depending on The stopping power of a target nucleus is characterized by the energy lost by the incident particle during its interaction with the target. Therefore, to determine the stopping power of a target nucleus, it is necessary to isolate the primary particle remaining after the interaction from the secondary particles and measure its energy. In reality, this is not always possible.

Table 1. Average particle multiplicities in pC interactions at 4.2 GeV/s depending on the degree of interaction centrality. e – experiment, m – FRITIOF model taking into account Δ-isobars.

Q	1	2	3
N_{even}(%), e m	2289(27,3) 28457(28,4)	3814(45,6) 37635(37,6)	1477(17,6) 16675(16,7)
$\langle n_{\pm} \rangle$, e m	2,72±0,08 2,152±0,008	3,15±0,02 2,926±0,007	4,697±0,04 4,594±0,014
$\langle n(\pi^{-}) \rangle$, e m	0,522±0,013 0,479±0,004	0,321±0,007 0,321±0,003	0,423±0,016 0,424±0,005
$\langle n(\pi^{+}) \rangle$, e m	0,416±0,010 0,379±0,003	0,660±0,008 0,662±0,004	0,965±0,020 0,787±0,006
$\langle n_{p}(acct) \rangle$, e m	1,054±0,015 1,088±0,005	1,743±0,010 1,658±0,004	2,526±0,024 2,624±0,007
$\langle n_{p}(acct) \rangle$, e $0,3<p<0,75$ m	0,241±0,009 0,114±0,002	0,584±0,009 0,454±0,003	1,212±0,024 1,219±0,006
$\langle n_{p}(acct) \rangle$, e $p>1,4$ m	0,588±0,020 0,206±0,004	0,740±0,018 0,794±0,005	0,664±0,027 0,712±0,007
$\langle n_{p}(acct) \rangle$, e $0,15<p<0,3$ m	0,732±0,020 0,206±0,004	0,425±0,0,013 0,284±0,004	0,779±0,026 0,759±0,009
$\langle n_{p}(acct \rangle$, e $P<0,15$ m	5,32±0,02 5,800±0,003	0,49±0,01 4,716±0,003	3,15±0,03 3,255±0,009

Q	4	5	6	All events
N_{even} (%), e m	575(6,9) 95551(9,6)	164(1,9) 5166(5,2)	52(0,62) 2516(2,5)	8371(100) 100000(100)
$\langle n_{\pm} \rangle$, e m	5,73±0,07 6,00±0,02	6,72±0,12 6,96±0,02	7,60±0,20 7,71±0,03	3,61±0,02 3,627±0,007
$\langle n(\pi^{-}) \rangle$, e m	0,476±0,027 0,448±0,006	0,43±0,05 0,45±0,01	0,36±0,07 0,46±0,01	0,407±0,006 0,406±0,002

$<n(\pi^+)>$, e	1,22±0,04	1,40±0,08	1,58±0,16	0,706±0,007
m	0,875±0,008	0,89±0,01	0,93±0,02	0,640±0,002
$<n_p(acct)>$, e	3,22±0,04	4,02±0,09	5,10±0,18	1,860±0,010
m	3,54±0,01	4,46±0,02	5,75±0,03	2,085±0,004
$<n_p(acct)>$, e	1,84±0,05	2,61±0,10	3,39±0,21	0,747±0,009
$0,3<p<0,75$ m	2,03±0,01	2,89±0,02	4,17±0,03	0,855±0,004
$<n_p(acct)>$, e	0,57±0,04	0,47±0,06	0,56±0,11	0,668±0,010
$p>1,4$ m	0,62±0,01	0,54±0,01	0,44±0,01	0,739±0,003
$<n_p(acct)>$, e	0,82±0,04	0,87±0,03	0,56±0,08	0,640±0,009
$0,15<p<0,3$ m	1,15±0,01	1,16±0,01	0,57±0,01	0,476±0,003
$<n_p(acct)>$, e	2,22±0,05	1,15±0,01	0,11±0,15	4,20±0,02
$P<0,15$ m	1,89±0,01	0,94±0,01	0,21±0,01	4,204±0,006

In the works [1] the leading proton was considered to be a positively charged particle with the maximum momentum in the event. In experiments with the electronic method it was possible to identify the majority of leading protons [3-5] We used a different approach to isolate the leading protons. Using the FRITIOF model, which takes into account Δ-isobars, we obtained spectra of the leading protons and protons-fragments of the carbon nucleus. Based on them, the optimal boundary between the two spectra was chosen – 1.4 GeV/s. In this case, the average multiplicity of leading protons with p ≤ 1.4 GeV/s was equal to 0.1, and the multiplicity of protons from the target with p < 1.4 GeV/s was equal to target. From the point of view of the modified FRITIOF model with Δ-isobars, the chosen boundary for the selection of leading protons is better suited for leading protons from peripheral (Q ≤ 2) interactions, i.e. for most pC interactions. In these events $<n_p^{lead}>$ with p<1.4 GeV/s is less than 10%. In central interactions, the primary proton loses a significant part of its energy (Table 2) and the proportion of leading protons with p<1.4 GeV/s increases to 40%. The proportion of such events, as follows from Table 2, does not exceed 8%.

As for the fraction of target protons with p>1.4 GeV/s, it is maximum in events with Q = 1 and quickly decreases to 1% in events with Q ≥ 5. This result reflects the softening of the spectrum of fast target protons as Q increases. According to the modified FRITIOF model [1], which takes into account Δ-isobars, the admixture of target protons with p>1.4 GeV/s fthe value of Q from 15% to 8%, and the admixture of leading protons among protons with momenta in the range of 0.3-1.4 GeV/s is 7-8%.

A comparison of the experimental average multiplicities of leading and target protons with calculations using the modified FRITIOF model, which takes into account Δ-isobars, shows that for most groups the difference does not exceed 10%. The average momentum and angular characteristics of leader and fragment protons are presented in Table 2. It can be seen that the primary proton loses a significant portion of its momentum when interacting with the carbon nucleus. In central collisions [3-8], this fraction is on average equal to half the initial impulse..

A distinctive feature of the leader protons from experimental events is a sharp increase in their average transverse momentum as they move from peripheral to central interactions, in contrast to the predictions of models (Table 2). The experimental value $\Delta y = y_0 - y_{lid}$ ($y_0 = 2.22$) varies from 0.59 in events with Q = 1 to 1.10 in events with Q ≥ 6.

Table 2. Energy carried away by secondary particles in pC interactions at 4.2 GeV/s depending on the value of Q. e-experiment, M-FRITIOF model taking into account Δ-isobars).

Q		1	2	3
$\Delta T_{p\text{-lits}}$, GeV	e	2.193±0.032	1.962±0.018	2.299±0.031
	m	1.703±0.005	1.871±0.007	2.270±0.008
$\sum E_{\pi^-}$, GeV	e	0.311±0.012	0.175±0.005	0.193±0.009
	m	0.250±0.003	0.154±0.002	0.175±0.002
$\sum E_{\pi^+}$, GeV	e	0.245±0.007	0.383±0.006	0.515±0.012
	m	0.234±0.003	0.371±0.003	0.362±0.004
$T_{p\text{-eva}}$, GeV	e	0.138±0.004	0.267±0.004	0.440±0.008
0,3≤ p < 1,4 GeV	m	0.110±0.001	0.257±0.002	0.474±0.003
$T_{p\text{-eva}}$, GeV	e	0.018±0.005	0.012±0.007	0.019±0.019
	m			
$\sum E_{n\pm}$, GeV	e	0.712±0.015	0.837±0.009	1.167±0.017
	m	0.595±0.004	0.789±0.004	1.030±0.006
$\sum E_{n\pm\pi 0}$, GeV	e	1.481±0.035	1.125±0.020	1.132±0.035
	m	1.108±0.006	1.081±0.008	1.240±0.010

Table 2 (continued)

Q	4	5	≥6	All events

$\Delta T_{p\text{-lits}}$, GeV e m	2.565±0.035 2.507±0.010	2.755±0.062 2.668±0.012	2.642±0.130 2.846±0.015	2.145±0.013 2.028±0.006
$\sum E_{\pi^-}$, GeV e m	0.195±0.014 0.165±0.003	0.179±0.026 0.158±0.004	0.174±0.041 0.154±0.004	0.217±0.004 0.187±0.012
$\sum E_{\pi^+}$, GeV e m	0.615±0.022 0.348±0.004	0.650±0.040 0.333±0.006	0.757±0.082 0.321±0.008	0.393±0.004 0.326±0.012
$T_{p\text{-eva}}$, GeV e 0,3≤ p < 1,4 m	0.582±0.015 0.654±0.006	0.727±0.032 0.812±0.008	0.881±0.061 0.994±0.010	0.297±0.004 0.337±0.002
$T_{p\text{-eva}}$, GeV e m	0.020±0.029	0.021±0.031	0.014±0.016	0.015±0.012
$\sum E_{n\pm}$, GeV e m	1.412±0.030 1.204±0.008	1.577±0.057 1.333±0.010	1.826±0.110 1.486±0.014	0.922±0.007 0.862±0.003
$\sum E_{n\pm\pi 0}$, GeV e m	1.153±0.046 1.306±0.013	1.178±0.084 1.337±0.016	0.816±0.170 1.361±0.021	1.223±0.022 1.166±0/007

The average momentum of target protons decreases with increasing Q, but to a lesser extent and mainly due to protons with p > 0.75 GeV/s, since the average momentum of protons 0.3 ≤ p ≤ 0.75 GeV/s is practically independent of Q. The average transverse momentum of target protons is independent of Q for all events with Q > 1 and remains at a level of ~ 400 MeV/s. Target protons are characterized by large emission angles. The FRITIOF model reproduces satisfactorily (deviation no more than 10%) the characteristics of protons with 0.3 ≤ p ≤ 0.75 GeV/s in groups with Q > 1. Knowing the energy carried away by leading protons with p>1.4 GeV/s, we can determine the kinetic energy $\Delta T = T_0 - \langle n_p^{lead} \rangle \langle T_p^{lead} \rangle$ that the incident proton will expend when interacting with the carbon nucleus.

At a momentum of 4.2 GeV/s, the kinetic energy of the proton before interaction is T_0 3.36 GeV. Table 1 shows the values of ΔT for all groups of pC events obtained in the experiment and according to the FRITIOF model with Δ-isobars [1,5]. It can be seen that the proton loses a significant portion of its energy when interacting with the carbon nucleus, even in peripheral interactions. When moving from events with Q = 1.2 to events with Q = 5.6, this portion increases from 60% to 80%. Similar results are obtained by calculations using the FRITIOF model (see Table 2). Consequently, even such a light nucleus as the carbon nucleus has a high stopping power for protons with a momentum of 4.2 GeV/s.

The conditions of our experiment allow us to obtain the distribution of this energy among secondary particles – to determine the total energies of π+ and π- mesons, protons-participants from the target nucleus ($0.3 \leq p$ and $p < 1.4$ GeV/s) and evaporative protons ($p < 1.3$ GeV/s). The values of these energies are presented in Table 2.

3. Conclusion

From the presented experimental results and theoretical calculations we can conclude:

1. The average momentum of target protons decreases with increasing Q, but to a lesser extent and mainly due to protons with $p > 0.75$ GeV/s, since the average momentum of protons $0.3 \leq p \leq 0.75$ GeV/s is practically independent of Q.

The average transverse momentum of target protons does not depend on Q for all events with $Q > 1$ and remains at a level of ~ 400 MeV/s. Target protons are characterized by large emission angles;

2. In events with Q = 1.2, less than half of the ΔT value falls on charged particles. As Q increases, the energy carried away by π+ mesons increases due to the growth of their multiplicity, in contrast to the total energy of π- mesons, which remains virtually unchanged in the range Q = 2-6. As Q increases, the share of energy falling on target protons also increases due to the increase in their multiplicity. The general picture is as follows: with an increase in Q of the energy loss of the primary proton during a collision with a carbon nucleus, the energy carried away by π+ mesons and protons increases, and the energy attributed to negative and neutral particles is practically independent of Q (the exception is events with Q = 1).

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Приложение:

1. pp-протон-протонное взаимодествие
2. pC-протон углеродное взамодействие (взаимодействия протона с углеродом (carbon)
3. pN-протон нуклонное взаимодействие (нуклон-частица)
4. n^{eva}_p-число испарительных протонов
5. GeV- гигоэлектронвольт, мера энергии заряженных частиц
6. $T_{p\text{-}eva\text{-}}$ энергия испарительной частицы
7. p→n and n→p) – протон нейтронное или нейтрон-протонное превращение
8. $<n_p^{lead}><T_p^{lead}>$ - среднее значения энергия, ведущих протонов
9. Np=Nn – нуклон-протонное и нуклон нейтронное взамодействие (нуклон-частица)
10. n_- and n_+ число отрицательно и положительно заряженных частиц
11. σ_{pN}^{tot} –полное сечение взамодействие

Appendix – Glossary of Terms

pp — proton-proton interaction

- pC — proton-carbon interaction (interaction of a proton with a carbon nucleus)
- pN — proton-nucleon interaction (nucleon = proton or neutron)
- n^{eva}_p — number of evaporated protons
- GeV — gigaelectronvolt, a unit of energy for charged particles
- $T_{p\text{-}eva}$ — energy of the evaporated particle
- p→n and n→p — proton-to-neutron or neutron-to-proton conversion
- $<n_p^{lead}><T_p^{lead}>$ — average values of the energy of leading protons
- Np = Nn — nucleon-proton and nucleon-neutron interactions (nucleon = proton or neutron)
- n_- and n_+ - number of negatively and positively charged particles
- σ_{pN}^{tot} - total cross section of the interaction