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Diffraction scattering of alpha-particles on nuclei at 17.9 GeV/c

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We measured diffractive scattering cross sections of alpha-particles on carbon, aluminium, copper and lead using the beam of the Dubna synchrophasotron at 3.64 GeV/nucleon. The data are compared with model predictions of the Glauber-Sitenko multiple scattering theory. Large discrepancies between experiment and calculations appear at four-momentum transfers above $\sim 0.25\,(\mathrm{GeV}/c)^2$. Various theoretical attempts to improve the description of high-energy alpha-scattering data are discussed.

PACS: 24.10.Ht; 25.55.Ci

1. Introduction

The Glauber-Sitenko diffraction theory [1] of multiple scattering processes has been the generally accepted framework for the interpretation of the high-energy hadron-nucleus scattering. Meanwhile, this theory has been extended for the description of the nucleus-nucleus diffraction scattering, but until now the model predictions have been far from being perfect even for the hadron-nucleus scattering process.

It is often assumed that these shortcomings are mainly due to inelastic shadowing effects, the importance of which has been pointed out by Gribov [2]. Dakhno and Nikolaev [3] could show up a striking disagreement between the high-energy proton-^{4}He and pion-^{4}He scattering data and the Glauber-Sitenko model predictions. Even if they include elastic and inelastic shadowing effects and a realistic ^{4}He wave function into the multiple scattering amplitudes, clear discrepancies remained between the theoretical and experimental $p\,^4$He and $\pi\,^4$He total and differential cross sections. These problems of the multiple scattering theory for the description of high-energy $p\,^4$He scattering data have been investigated also in [4, 5].

Inelastic shadowing effects are assumed to be closely connected with the composite quark structure of the hadrons. Furthermore the structure of complex nuclei - the presence of mesons, of compact multi-quark structures etc. - may influence the scattering process. The authors [3-5] argue that the discrepancies between theory and experiment are due to the neglect of quark degrees of freedom, in particular quark clusterization effects. According to the theoretical estimations, these effects are expected to increase with increasing mass number of the target nucleus.

It is beyond any doubt that the theoretical situation becomes still harder, if not only the target nucleus but also the projectile is a composite nuclear system. In this case of nucleus-nucleus scattering a great many tree and loop diagrams appear, and it is very difficult to account for all these contributions within the framework of the Glauber approximation to estimate the "background" conditions of the scattering process. Note that additional complications may arise in numerical calculations, because the Glauber formula was shown to imply a phase transition in the nuclear matter of the colliding nuclei into a domain-like state [6].

In recent years new calculation methods for Glauber amplitudes [7] and inelastic shadowing effects [8, 9] have been proposed. According to [8] corrections for shadowing effects might be very large for typical nucleus-nucleus scattering data available at present. These effects were shown to increase dramatically with the increase of the four-momentum transfer. While for the elastic scattering at $t \approx 0$ they are of the order of 5%, corrections of 20% and even up to 50% appear at $|t| \approx 0.2\,(\mathrm{GeV}/c)^2$ and $\approx 0.5\,(\mathrm{GeV}/c)^2$, respectively.

New high-energy nucleus-nucleus scattering data preferably at large momentum transfers are necessary in this situation to stimulate actual model calculations. While diffraction scattering processes of the hadron-nucleus interaction have been experimentally investigated up to the highest incident energies available, experiments on the nucleus-nucleus diffraction scattering have been rather scarce until now. Only a few papers have been devoted to alpha-nucleus $(\alpha - A)$ scattering at energies beyond 1 GeV/N. Elastic α-scattering on lightest nuclei at

1.05 GeV/N has been investigated at the Saturne synchrotron [10]. At the same incident energy the Lorentz-invariant cross section for the inclusive scattering process $\alpha + C \rightarrow \alpha + X$ has been published [11]. At the Bevalac energy of 2.1 GeV/N the total and the total inelastic cross sections of the $\alpha - C$ interaction has been measured [12]. Finally, the diffraction scattering of α-particles on C, Al, Cu [13] and on ^{4}He [14] at 3.64 GeV/N has been investigated by using the beam of the Dubna synchrophasotron. At high energies data [15] of the $\alpha - \alpha$ scattering have been obtained at the CERN ISR.

We present in this paper data of the diffractive α-scattering at 17.9 GeV/c on carbon, aluminium, copper and lead targets. We extend the measurements of the differential cross sections to considerably larger values of the four-momentum transfer squared $|t|$ than in [13].

In Sect. 2 we describe the experiment and the data accumulation process. Section 3 presents the evaluation procedure of the differential cross sections. The data are discussed in Sect. 4 by comparing them with model calculations in the framework of the Glauber-Sitenko multiple scattering theory. The conclusions are given in Sect. 5.

2. Experimental procedure

The experiment was carried out with the extracted α-particle beam of the JINR synchrophasotron. Every 10 s a burst of about 10^6 particles over a period of about 0.5 s was available. Targets with thicknesses of the order of 5 g/cm^2 were used. The scheme of the used magnetic spectrometer with a length of about 20 m is shown in Fig. 1. The experimental arrangement enables event-by-event registration of the scattering and the fragmentation processes of the projectile nuclei into the forward direction. For this experiment six multiwire proportional chambers (MWPC) with a wire spacing of 2 mm were arranged in 3 groups to determine the particle trajectories *(i)* up to the target position, *(ii)* between the target and the bending magnet and *(iii)* after the magnet. The incoming particles were selected by 4 scintillation counters. Three counters S_1, S_2, S_3 were operated in coincidence, whereas the fourth anticoincidence counter S_A – with a hole of 5 cm in the scintillator – fixed the beam spot on the target. A ΔE scintillation counter hodoscope $S_{\Delta E}$ consisting of 5 counters enabled us to separate single- and double-charged particles. The scintillators overlap each other to cover completely the area of the last MWPC. To reduce multiple Coulomb scattering effects helium bags were placed between the detectors.

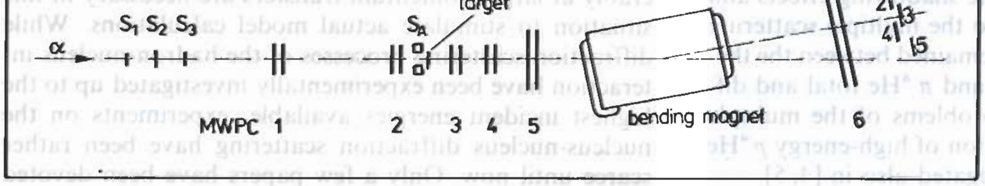

Fig. 1. Scheme of the experimental arrangement; $S_1, S_2, S_3, S_A, S_{\Delta E}$ are scintillation counters, MWPC 1-6 are multiwire proportional chambers. For details see text

For each event the coordinate information of the MWPC's and the ΔE information of the scintillation counter hodoscope have been stored by means of a CAMAC system linked to an online computer. The beam particles with the suitable spatial and angular input parameters relative to the spectrometer axis – so-called monitor particles – have been selected by the coincidence condition

$$TR1 = S_1 \wedge S_2 \wedge S_3 \wedge \bar{S}_A$$

and by requiring a single-wire hit in the MWPC's 1 and 2.

The scattering events had to fulfil additional trigger conditions, namely

$$TR2 = TR1 \wedge (\text{“scattering”}) \wedge \text{MWPC } 5/6$$

and

$$TR3 = TR2 \wedge (\text{“particle charge} > 1\text{”}).$$

The condition "scattering" has been controlled by a specialized processor linked with the MWPC's 1, 2 and 4. The processor allowed event recording only in those cases, if the scattering angle exceeds some cut-off angle fixed but the processor parameters. In the present experiment this value was set to 8 mrad. For the scattering events it was demanded in addition that at least one of the MWPC's 5 or 6 delivered a signal. The condition "particle charge > 1" of the trigger $TR3$ has been set by using the signals of the ΔE-detector hodoscope. An example of amplitude distributions for particles with charge numbers $Z = 1$ and 2 is presented in Fig. 2.

The event sample used for this analysis have been obtained from the raw data after applying a data reduction procedure. These events had to fulfil additional selection criteria:

(i) The trajectory of the incoming particle has the correct geometrical parameters,
(ii) the particle trajectories in front of and behind the target converge within a distance of 2.5 mm,
(iii) the interaction occurs within the target,

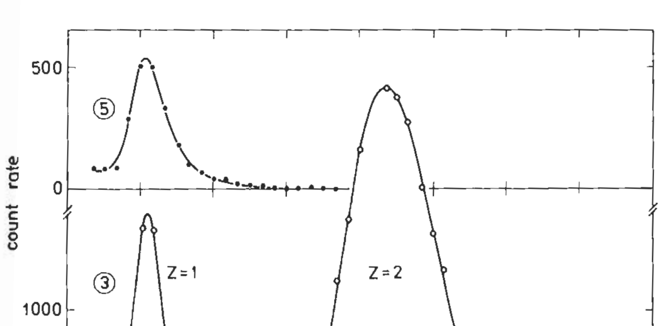

Fig. 2. Amplitude spectra of signals from the counters 1, 3 and 5 of the ΔE hodoscope $S_{\Delta E}$. The peaks correspond to particles with charge numbers $Z=1$ and 2, respectively

(iv) the particle must be double-charged, and
(v) the event belongs to the region of the "elastic scattering" peak. (This notation is explained below).
After this data treatment about 80% of the monitor events and about 25% and 35% of the *TR*2 and *TR3* scattering events, respectively, remained.

In the following we present several characteristic event distributions illustrating the properties of the spectrometer. The momentum distribution of the beam particles, measured with the "empty" target, is presented in Fig. 3a. This distribution can be fitted with a Gaussian function, and one obtains $\sigma_p/p_0=0.007$ for the momentum resolution of the spectrometer. Within this momentum resolution the measured differential cross sections are *sum cross sections* in reality, which include besides the elastic scattering other nuclear processes, i.e. inelastic scattering with target-nucleus excitation, quasielastic knockout of nucleons or nucleon clusters up to target fragmentation. However, scattering events accompanied by pion production could be clearly separated.

With the same data set the angular resolution (σ_θ) of the spectrometer was determined, Fig. 3b. This event distribution can be fitted with a Rayleigh function with $\sigma_\theta \simeq 0.5$ mrad.

In Fig. 4 an event distribution is shown as function of the position of the reconstructed interaction point along the spectrometer axis in the vicinity of the target. The bulk of events clearly comes from the target, while the events on either side of the target peak arise from interactions with the material of the MWPC's 2 and 3. With increasing scattering angle θ this target spot resolution becomes better; a linear dependence of the standard deviation σ_z of the position z and the inverse scattering angle (in rad) was found according to $\sigma_z \approx 0.1$ cm$/\theta$.

3. Differential cross sections

To obtain the absolute differential cross sections the geometrical efficiency (ε_g) of the set-up must be known. This quantity has been calculated in a Monte Carlo simulation by means of the corresponding geometrical parameters of the spectrometer and taking into account the spatial and angular distributions of the incoming beam. For the angular dependence of ε_g it was found that it changes from about 0.85 at small scattering angles down to 0.05 at the largest measured angles of $\approx$40 mrad.

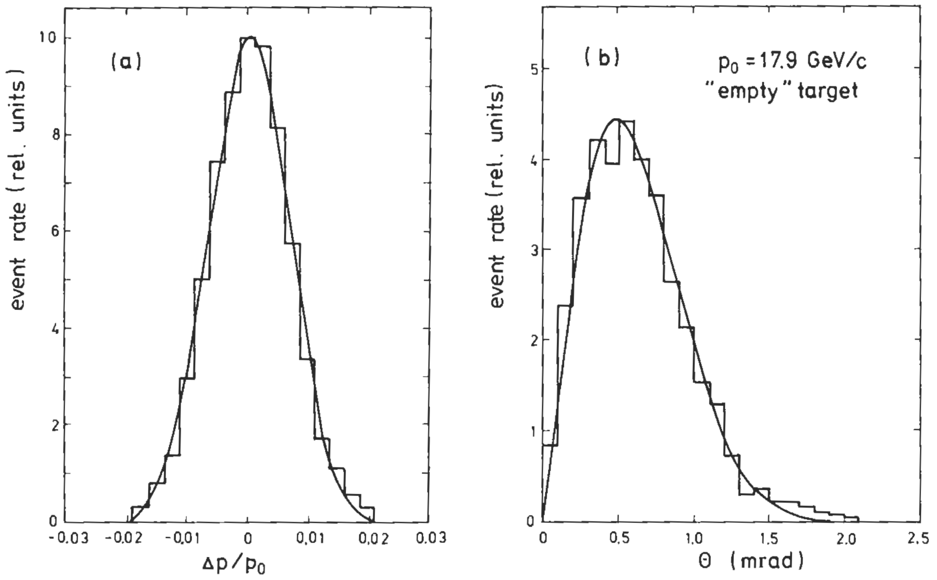

Fig. 3. a "Empty"-target event distributions vs. momentum difference $\Delta p=p-p_0$, p being the momentum measured by the spectrometer and p_0 being the beam momentum. The Gaussian curve represents a fit to the data. **b** The same distribution vs. the scattering angle θ. The Rayleigh curve is fitted to the data. The histograms contain about 2000 events

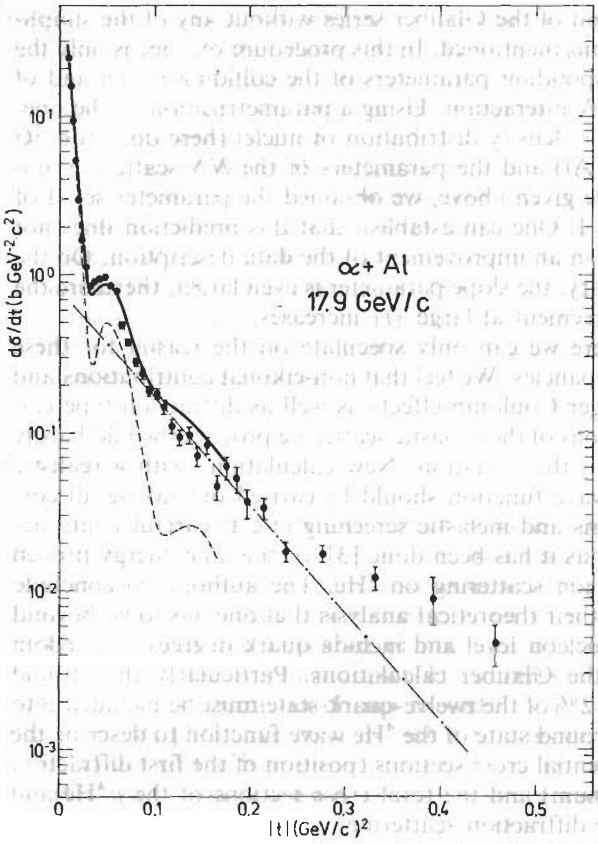

Fig. 6. The same as Fig. 5 for α-Al scattering

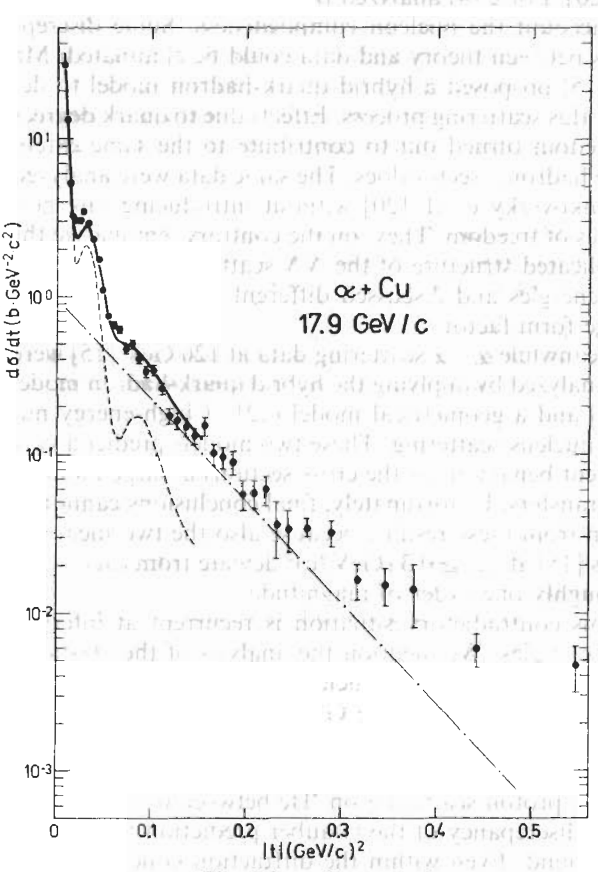

Fig. 7. The same as Fig. 5 for α-Cu scattering

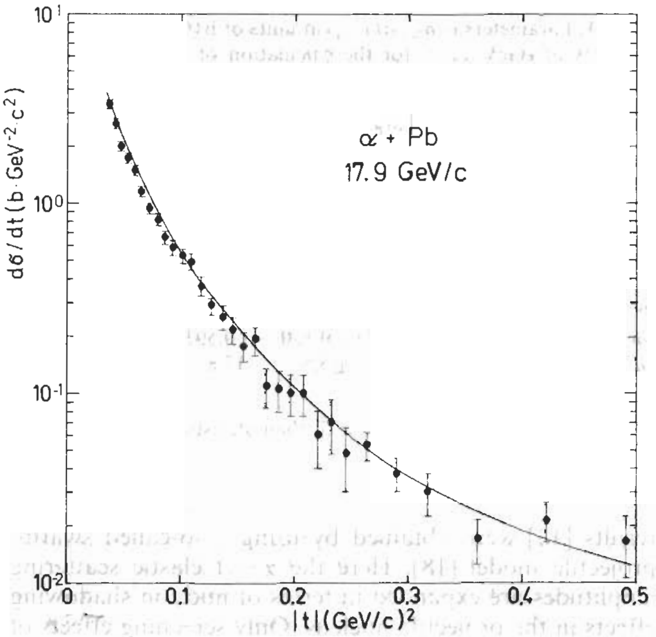

Fig. 8. Sum differential cross section of α-Pb diffraction scattering. The curve represents a fit to the data with a function given in the text

which is reminiscent of the Rutherford scattering. The fit parameters of this cross section (Fig. 8) are $a_1 = 0.003$ b·(GeV/c)^2, $a_2 = 2.161$ b·(GeV/c)$^{-2}$ and $a_3 = 22.61$ (GeV/c)$^{-2}$.

In the following we compare our data with Glauber model predictions. Calculations of the $\alpha - A$ diffraction cross sections below $|t| = 0.18$ (GeV/c)^2 were carried out [13] for the target nuclei ^{12}C, ^{27}Al and ^{64}Cu by using standard assumptions of the multiple scattering theory. With the conventional high-energy parametrization of the nucleon-nucleon (NN) scattering amplitude the spin-independent profile function depending on the impact parameter b is given by

$$\Gamma_{NN}(b) = (\sigma_{\text{tot}}^{NN}/4\pi B)(1 - i\varrho)\cdot\exp(-b^2/2B),$$

where σ_{tot}^{NN}, ϱ and B are the isospin-averaged NN total cross section, the ratio of the real to the imaginary part of the forward scattering amplitude and the slope parameter of the diffraction cone of the elastic NN cross section, respectively. In the calculation [13] the values $\sigma_{\text{tot}}^{NN} = 42$ mb, $\varrho = -0.43$ and $B = 7.62$ (GeV/c)$^{-2}$ were used.

For the density distribution of nucleons in the projectile nucleus a Gaussian form was assumed, and for the target nuclei Fermi distributions were used. Coulomb effects were taken into account by adding the Coulomb phase shifts to the nuclear ones. Corrections due to the centre-of-mass motion in the projectile nucleus were included.

Calculations of the elastic $\alpha - A$ scattering particularly on medium and heavy nuclei meet with considerable difficulties because many terms of slowly converging Glauber series have to be considered. To overcome the difficulties simplified calculation methods have been developed. The

Table 1. Parameters $(d\sigma_{\text{in}}/dt)_{t=0}$ (in units of b (GeV/c)$^{-2}$) and B_{in} (in units of (GeV/c)$^{-2}$) for the calculation of the inelastic $\alpha-A$ diffraction scattering cross sections

Parameter	Target nucleus		
	^{12}C	^{27}Al	^{64}Cu
Set I[a]			
$(d\sigma_{\text{in}}/dt)_{t=0}$	0.585	0.735	0.972
B_{in}	15.3	15.1	14.4
Set II[b]			
$(d\sigma_{\text{in}}/dt)_{t=0}$	0.677 ± 0.120	0.593 ± 0.184	
B_{in}	20.7 ± 3.5	17.8 ± 6.0	

[a] [16]

[b] this work, parameter values with their statistical errors

results [13] were obtained by using a so-called swarm-projectile model [18]. Here the $\alpha-A$ elastic scattering amplitudes are expanded in terms of nucleon shadowing effects in the projectile nucleus. Only screening effects of nucleon pairs were taken into account, because higher-order shadowing effects were estimated to be of the order of 3%, and they turned out to depend weakly on the mass number between $A=12$ and 64.

Calculations of the inelastic $\alpha-A$ scattering can in principle be done as in the case of the elastic scattering. However, this calculation procedure is rather bulky within the swarm-projectile model. Therefore, the sum inelastic scattering cross sections were represented [13] by using the relation

$$(d\sigma/dt)_{\text{in}} = (d\sigma_{\text{in}}/dt)_{t=0} \cdot \exp(B_{\text{in}} \cdot t).$$

The parameters $(d\sigma_{\text{in}}/dt)_{t=0}$ and B_{in} (Table 1, parameter set I) have been obtained [16] in an optical approximation.

The Glauber model predictions of the elastic and inelastic scattering processes are shown in Figs. 5–7. If we sum up these two cross sections, at low $|t|$ only some minor differences between the experimental and theoretical cross sections can be seen. However, the deviation of the Glauber calculation from experiment becomes drastic above $|t| \approx 0.25$ (GeV/c)^2. The inelastic cross sections predicted in the model approximation [13] are clearly lower than the data points, and the discrepancies reach up to one order of magnitude at largest $|t|$ measured.

Essential limitations of the approximation commonly used to calculate the inelastic scattering cross sections are the following: *(i)* Approach of large mass numbers of the colliding nuclei and corrections evaluated only due to the low-mass value of the projectile nucleus; *(ii)* choice of a limited number of specific diagrams of the Glauber series; *(iii)* neglect of the NN interaction range compared with the usual nuclear dimensions. However, as shown recently [19], this procedure strongly influences the cross section values.

These deficiencies stimulated us to newly calculate the inelastic cross sections by applying the Monte Carlo method. Our procedure is equivalent to the *direct* calculation of the Glauber series without any of the simplifications mentioned. In this procedure one needs only the corresponding parameters of the colliding nuclei and of the NN interaction. Using a parametrization of the one-particle density distribution of nuclei (here done for ^{12}C and ^{27}Al) and the parameters of the NN scattering amplitude given above, we obtained the parameter set II of Table 1. One can establish that this prediction does not result in an improvement of the data description. On the contrary, the slope parameter is even larger, therefore the disagreement at large $|t|$ increases.

Here we can only speculate on the reason for these discrepancies. We feel that non-eikonal contributions and stronger Coulomb effects as well as diffraction-type calculations of the inelastic scattering processes would hardly help in this situation. New calculations with a realistic ^{4}He wave function should be carried out taking all corrections and inelastic screening effects carefully into account as it has been done [3] for the high-energy proton and pion scattering on ^{4}He. The authors [3] conclude from their theoretical analysis that one has to go beyond the nucleon level and include quark degrees of freedom into the Glauber calculations. Particularly they found that 12% of the twelve-quark state must be included into the ground state of the ^{4}He wave function to describe the differential cross sections (position of the first diffraction minimum) and the total cross sections of the $p\,^4$He and $\pi\,^4$He diffraction scattering.

Predictions of the Glauber-Sitenko theory for the high-energy elastic $p\,^4$He scattering were also discussed in [4, 5, 20]. Forte [4] analyzed the data by taking explicitly into account the nucleon compositeness. Some discrepancies between theory and data could be eliminated. Ma et al. [5] proposed a hybrid quark-hadron model to describe this scattering process. Effects due to quark degrees of freedom turned out to contribute to the same extent as the hadronic sector does. The same data were analyzed by Jenkovszky et al. [20] without introducing any new degrees of freedom. They, on the contrary, emphasize the complicated structure of the NN scattering amplitude at high energies and discussed different choices of the ^{4}He charge form factor.

Meanwhile $\alpha-\alpha$ scattering data at 126 GeV [15] were also analyzed by applying the hybrid quark-hadron model [5, 21] and a geometrical model [22] of high-energy nucleus-nucleus scattering. These two models predict a very different behaviour of the cross sections at large momentum transfers. Unfortunately, final conclusions cannot be drawn from these results, because also the two measurements [15] at $|t| \gtrsim 0.3$ (GeV/c)^2 deviate from each other by roughly one order of magnitude.

This contradictory situation is recurrent at intermediate energies. We mention the analysis of the elastic α-scattering on very light nuclei done by Franco and Yin [23]. To a large extent the Glauber model description of data [10] can be improved by phase variation of the NN scattering amplitude using a complex slope parameter. For the proton scattering on ^{4}He between 0.7 and 1 GeV [24] a discrepancy of the Glauber prediction to data has been found. Even within the diffraction cone the calculation turns out to drop more rapidly than the experimental cross section independent of whether or not corrections to the Glauber theory were taken into account. Typically, at incident energy of 1 GeV and $|t| = 0.08\,(\text{GeV}/c)^2$, the ratio of the experimental and the theoretical cross section is about 1.2.

Finally, we mention the Glauber model calculation [25], where the internal nucleon structure was explicitly taken into account by using a non-relativistic quark-cluster model. Within this model the α-C diffraction cross section at 18 GeV/c was calculated. The authors [25] reduce the gap between their calculation and our experimental data at large $|t|$ compared with the Glauber model predictions discussed in this paper.

5. Conclusions

We discussed in this paper differential cross sections of the diffractive α-scattering on C, Al, Cu and Pb at 3.64 GeV/N. We measured sum cross sections of the elastic scattering and inelastic processes (i.e. target nucleus excitations, quasi-free knockout of nucleons or clusters up to target nucleus fragmentation). The uncertainties of the absolute normalization do not exceed 3%. Previous measurements [13] have been extended to considerably larger values of the four-momentum transfer $|t|$ up to $0.55\,(\text{GeV}/c)^2$; data of α-Pb diffraction scattering at this incident energy are published for the first time.

Calculations [13] carried out with a standard version of the Glauber-Sitenko multiple scattering theory are in conflict with the experimental cross sections at large $|t|$. New model calculations according to [7] presented here do not change the situation. In the energy range of several GeV/N for α-particles scattered diffractively on protons or nuclei, non-nucleonic degrees of freedom are supposed to appear. This problem evidently demands further investigation.

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