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MONTE-CARLO SIMULATIONS OF ELECTROMAGNETIC CASCADES IN LEAD, EMULSION AND LEAD-EMULSION LAYERS

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Abstract

Results of Monte-Carlo simulations of electromagnetic cascade development in the emulsion and lead are analysed. It is demonstrated that the number of electrons in "core approximation" are significantly greater than this obtained from analytical solutions of diffusion equations, especially at greater depths. The number of electrons for fixed value of depth t and constant $E_o r$ depend on the primary particle energy. It means that there is no universal Nishimura-Kidd curves as in the case of the analytical solutions.

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Introduction

Detailed knowledge of the electromagnetic cascade development is necessary in many cosmic ray applications. The analytical solutions of the cascade development are possible only under crude approximations. It has been demonstrated by one of us /E.Kryś [1] / that the simplified analytical solutions give relatively good description of the longitudinal development of the cascade in air but the lateral distribution obtained analytically differs significantly from that obtained by Monte-Carlo method.

In practical applications for cosmic ray research, it is necessary to consider much more complex situation. In particular situation become very complicated than we consider the applications to X-ray chambers. First of all in such applications we are dealing with high Z material where cascade development is more complicated than in air. Secondly, the chamber is not homogeneous but consist of layers of lead and X-ray films in the first approximation. Thirdly, the observations are restricted to the very central part of the cascade consisting of only a small fraction of the all particles.Finally,at the energies in question here, there exist already some influence of the Landau-Pomeranchuk effect.

It appears that all those complications can be analysed only with detailed simulation of the electromagnetic cascade by the Monte-Carlo method. In the present paper such calculations were performed allowing for following processes: pair production, bremstrahlung including LPM effect with energy dependent cross section /Fig.1/, ionisation losses,Compton effect, single and miltiple Coulomb scattering, the electron and positron inelastic scattering, photoelectric effect and annihilation.

As it is necessary to apply the so-called "thinning method" in which repeating calculations of low energy particles are partly omitted. The essence of method is that only some particles with energies below certain fraction of the primary energy /usually 10^{-3}/ are calculated. It is then assumed that the calculated particles have certain weight larger than unity. This method composed with full Monte-Carlo gives some increase

of fluctuations but that increase is really negligible. At the same time the computer time requirement is reduced by several orders of magnitude.

1. The lateral structure function obtained in Monte-Carlo simulations.

1.1 General remarks

The analytical solutions of the diffusion equations lead to very important phenomenon called the "core approximation". It means that hte lateral structure near the cascade axis can be expressed for a given depth t as a single function of $(E_o r/K)$ where K is a constant slightly dependend on the material /K=19.6 MeV for lead/. That behaviour would allow easy estimation of primary energy if the number of electrons in a circle of given radius is measured. The energy would be simply proportional to that number of electrons /J.Nishimura[2]/. At the first glance that method must fails when we go to higher energies as it is obvious that the necessary inclusion of the Landau-Pomeranchuk-Migdal effect have to destroy the above stated simplicity. In the present paper that point is analysed. Before however we intend to verify the validity of the "core approximation" in more general calculations but performed still without inclusion of the LPM effect.

1.2 Behaviour of the structure functions without the LPM effect.

In order to study the three-dimensional behaviour of the electromagnetic cascades in "core approximation" our simulations were made full Monte-Carlo, separately without and including the LPM effect.

First let us compare the shape of the cascade curves in "core approximation" for constant $E_o r$ for full Monte-Carlo simulations without the LPM effect, with the analytical ones.

In Fig.2 we present the cascade curves in lead for primary photons of energy E= 600 GeV, 3 TeV, 10 TeV, 100 TeV together with analytical solutions of diffusion equations given by Nishimura [2] (for $E_o r = 10^5$ GeVμm and $1.5\ 10^6$ GeVμm).

The cascade curves with primary photons of energy E= 600 GeV and 1 TeV compared with J.Nishimura results /for $E_o r=10^5$GeVμm/ for pure emulsion are shown in Fig.3 .

It can be seen that the simulated curves differ significantly from the analytical ones. At the greater depths where the measurements are usually done the number of electrons at the simulated curves are much higher. It however appears that the idea that the structure functions are almost independent of the primary energy when plotted as the function Er is still valid one. In the other words the "core approximation" seems to be corect but with different than in the analytical case dependencies on the primary energy. The new "core approximation" however is only approximate. That fact is best seen in Fig.4 , where the number of electrons as a function of Er variable for two different depths (for the lead). The systematic "drift" of the points indicate that number of electroms in the circles of a fixed radius increases faster then proportionally to the primary energy. The similar effect is seen in Fig.5 .for the case of the nuclear emulsion absorber.

1.3 The Landau-Pomeranchuk-Migdal effect and the electron-photon shower distribution function.

The comparison of the cascade curves for constant $E_0 r$ for pure lead without and including the LPM effect are shown in Fig.6 and Fig.7 . As can be seen in Fig.6 the LPM effect plays an important role giving subsequent reductions of numbers of secondary particles in the early stage of development and deeper position of the shower maximum, smaller size at maximum and increases of numbers of the cascade particles in the late stage. This effect becomes stronger as the energy of primary particle goes higher. In Fig.7 we present the comparison of the cascade curves for constant r and E with data given by Ivanenko[3]. As it can be seen the number of particles obtained in our Monte-Carlo simulations is significantly larger then in the case of the solutions given by Ivanenko, particularly at the greater depths in the lead. These differences have significant consequence for the estimation of the primary particle energy. The energy of each cascade shower, E_γ, is estimated by measuring the shower size and comparing the results with the theoretical calculations. As one can see, the energy of incident particle estimated according to Ivanenko curves is overestimated 2-5 times. The factor depends on the depth where the energy is estimated and on used diaphragm.

2. The influence of the inhomogeneous structure of chamber on the transition curves.

For proper energy estimation of incoming particle in the "core approximation" we have to include additionally the effect that the emulsion chamber is a sandwich of many sheets of metal plates and nuclear emulsion plates.

Now we are to discuss experiment with emulsion chamber irradiated by secondary monoenergetic electrons in FNAL /400 GeV proton beam have been used to generate electrons with energies up to 300 GeV/. The experiment consist of 30 layers of emulsion between lead plates. Total thickness of the lead was 7cm.

We have not simulated the cascade development in identical chamber. Our simulation were performed for a chamber consisting of 1 cm thick layers of lead separated by 2 mm of emulsion. The results are shown in Fig.8 .

As it can be seen the number of electrons in the chamber is smaller than in pure lead at the same radius /100 μm/ although higher than in the emulsion alone.

The experimental results of Hotta et al. [4] are also shown. It is seen that the sequence of the dependencies is following: highest simulations for pure lead, lower simulations for the lead chamber with 1 cm separation of the detection levels and than experimental results for 2.5 mm separation of the detection level. That gives a consistent picture - more layers leads to stronger reduction of particle number in the circle of a given radius.

It appears that the agreement with Nishimura-Kidd curves claimed by Hotta et al. [4] is probably a result of a fortunate coincidence. The actual increase in the "core approximation" number of particles is compensated by reduction due to emulsion layers.

3. Conclusions

a. It was stated that the number of secondary electrons in "core approximation" is much greater than obtained from analytical solutions of diffusion equations.

b. The number of electrons for constant $E_o r$ is greater for larger primary particle energy.

c. On the basis on our simulated data we claim that the energy of the particle which iniciate cascade development estimated according to "core approximation" / for instance Ivanenko curves / may be overestimated 2-5 times.

d. The inhomogeneous structure of chambers has an effect on the transition curves. The numbers of secondary particles for constant radii and constant primary photon energy is determined by properties of the chamber, in particular by thickness and number of the emulsion layers.

Acknowledgments

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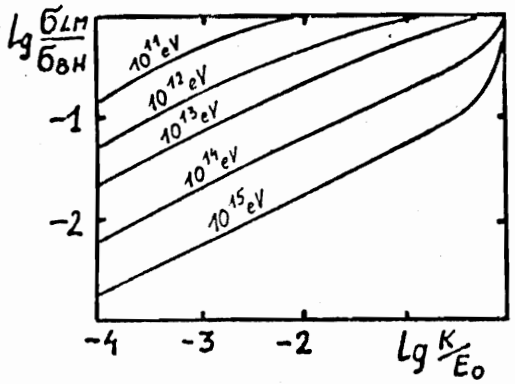

Fig.1 Derivations from the Bethe-Heitler radiation cross section in Pb due to the Landau effect. σ_{LM} and σ_{BH} are the cross sections calculated by Migdal and Bethe-Heitler.

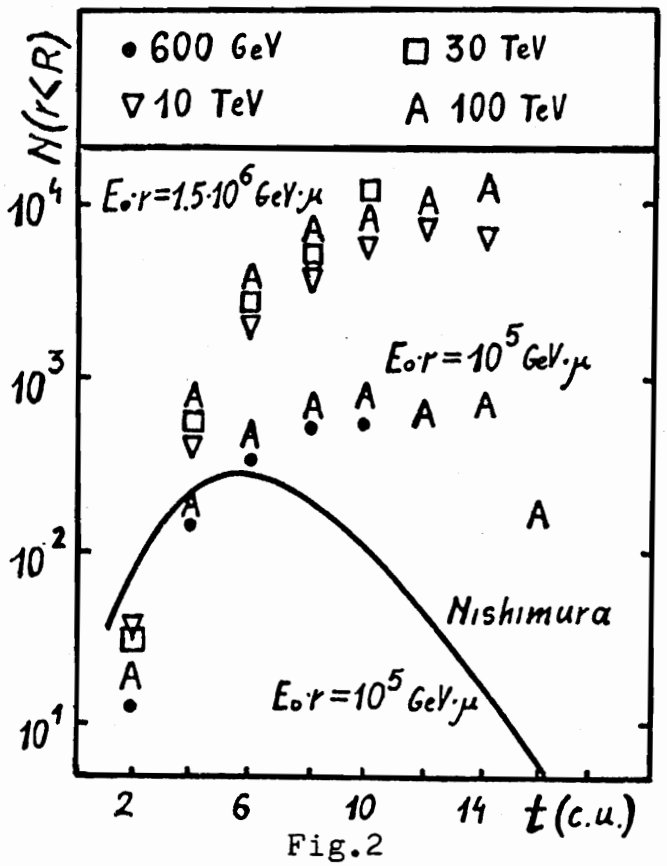

Fig.2

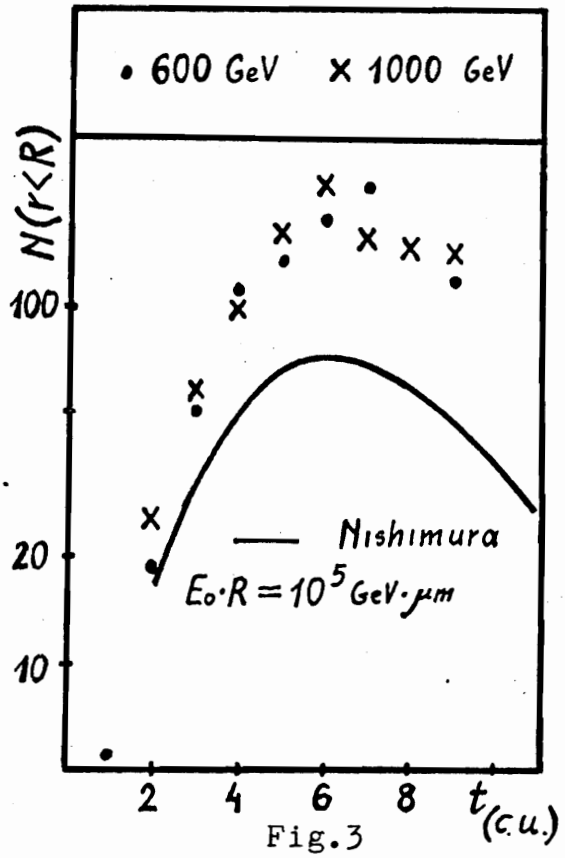

Fig.3

Number of electrons within a circle of radius r, for constant $E_o r$, for showers initiated by photon in lead /Fig.2/ and in emulsion /Fig.3/.

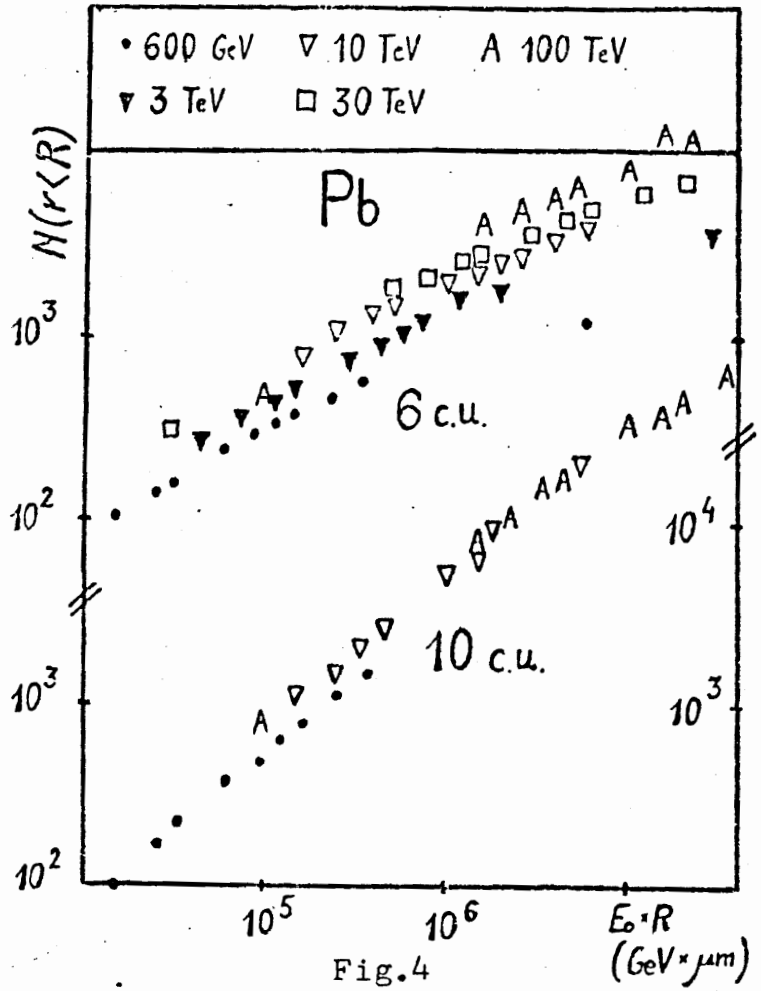

Fig.4

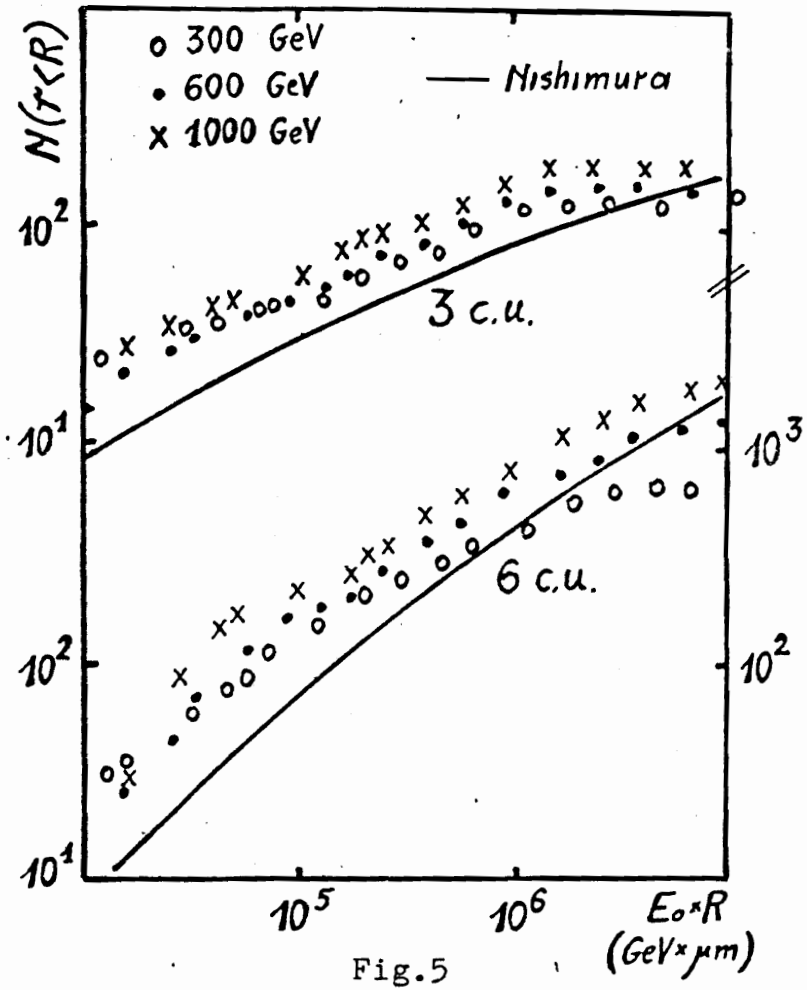

Fig.5

The lateral distributions of high energy shower electrons /without LPM effect/ in lead for 6, 10 c.u. /Fig.4/ and in emulsion for 3, 6 c.u. /Fig.5/.

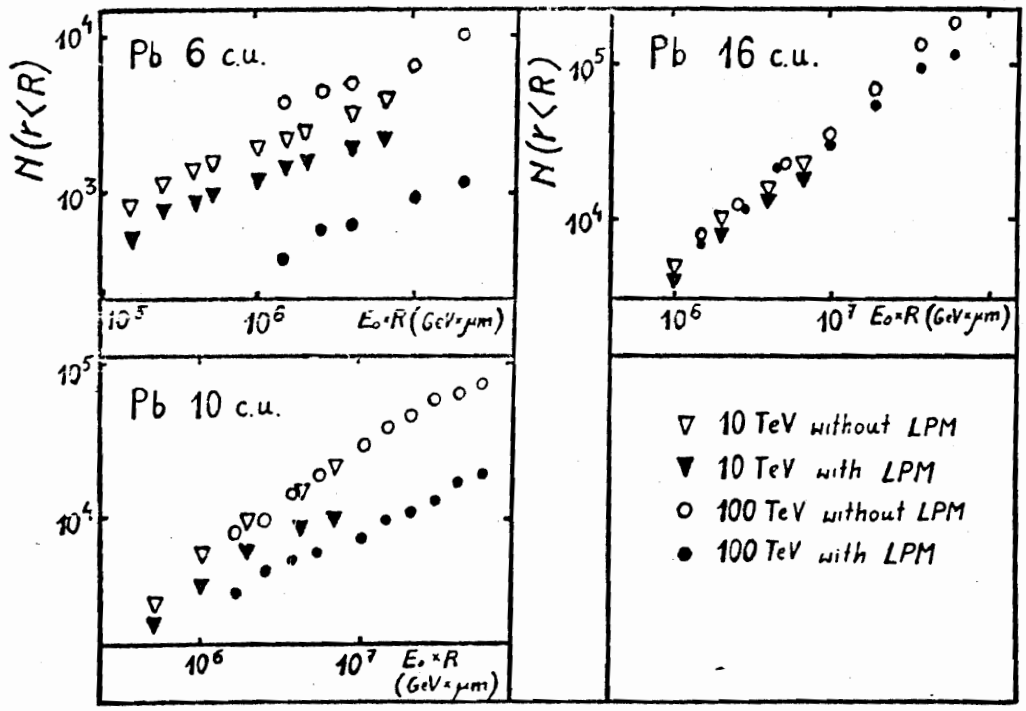

Fig.6 The electron numbers in cascades calculated for lead with and without LPM effect for different energies and depths against $E_o r$ parameter.

Fig.7 is on the next page.

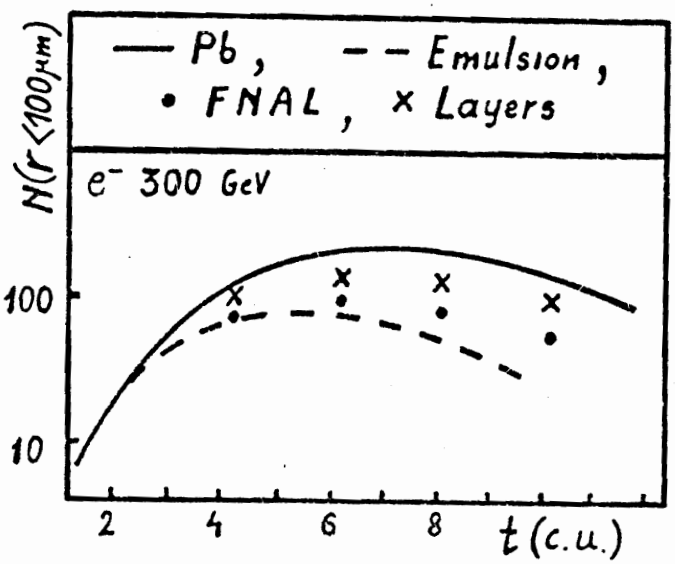

Fig.8 Cascade curves of electrons in electron initiated showers for radii 100 μm /for lead, layers, FNAL and emulsion/.

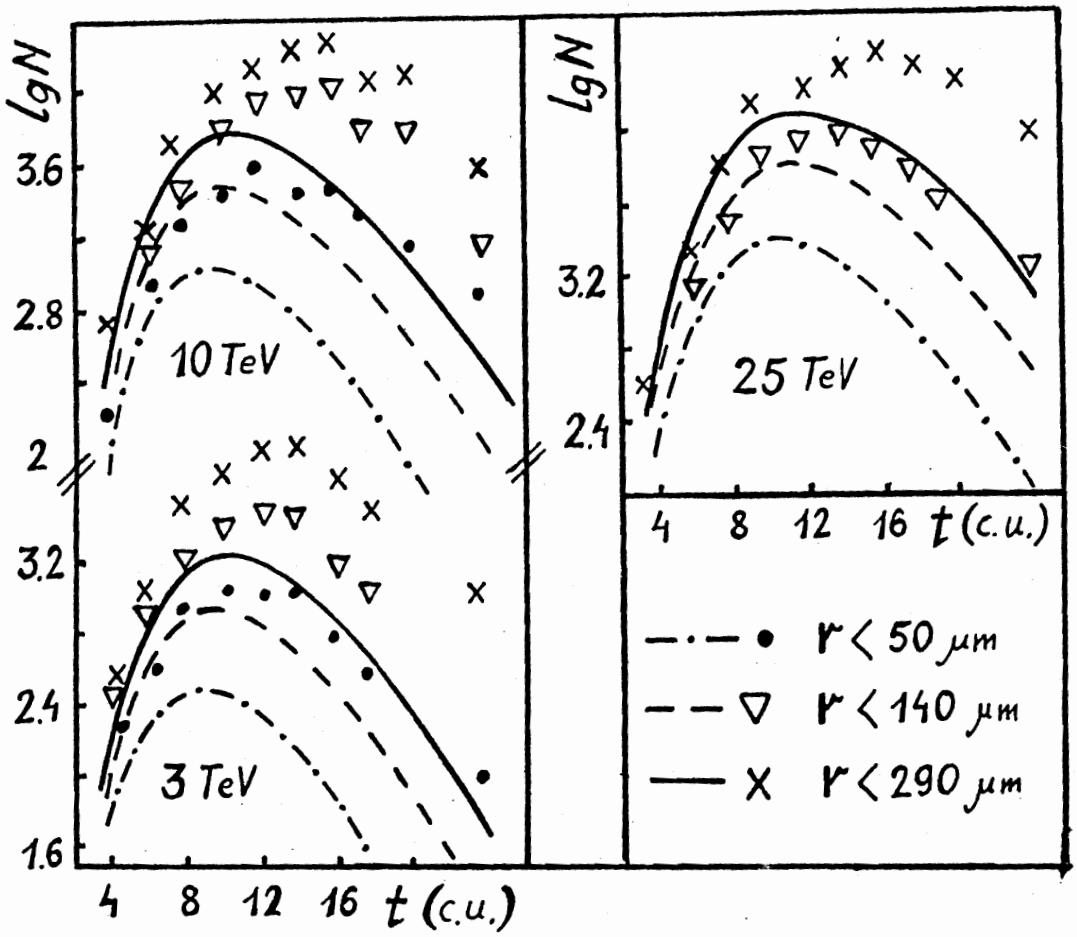

Fig.7 The comparison of our simulated data with Ivanenko's curves for number of electrons within a circle of radius r for shower initiated by photon in lead.

Fig. 8 is in the previous page..