Central collisions of 800-GeV protons with Ag/Br nuclei in nuclear emulsion

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Central collisions of 800-GeV protons with the heavy components of nuclear emulsion, ^{107}Ag and ^{80}Br, have been investigated to determine the characteristics of small-impact-parameter collisions and, by comparison with the analysis of inclusive proton-emulsion inelastic interactions and inelastic proton-nucleon collisions, to study the dependence of the interaction process on the mean number of intranuclear collisions $\langle \nu \rangle$. The data are also compared with the results obtained in proton-emulsion collisions, both central and inclusive, at 200 GeV. The variations in the secondary-particle multiplicities and the normalized pseudorapidity density correlate with $\langle \nu \rangle$ and demonstrate that proton-nucleus interactions, both central and inclusive, can be described adequately by the incoherent superposition of proton-nucleon collisions.

I. INTRODUCTION

Investigations of high-energy hadron-nucleus central collisions are of great importance both for understanding the hadron-nucleus interaction and as a basis for studies of particle production by heavy ions interacting in nuclear targets. Recently, heavy-ion collisions have been investigated extensively in the energy range up to 200 GeV/nucleon,[1] following the suggestion that, as the result of the high energy densities achieved in the collision, new physical phenomena, such as the formation of a quark-gluon plasma, may occur.[2] Alternatively, nucleus-nucleus collisions may be explained as a superposition of many hadron-nucleus interactions, and this possibility requires detailed knowledge of hadron-nucleus phenomena.

Results of various experiments,[3–5] including work at 800 GeV (Refs. 6–8), have shown that the particle production in inclusive (all impact parameters) hadron-nucleus interactions can be described by models that assume a superposition of successive, independent collisions of the projectile with the nucleons of the target nucleus.[3–11] Although these superposition models satisfactorily explain the inclusive data, it is not clear whether or not they can also describe central collisions, i.e., collisions with a small impact parameter. This paper reports a study of such central collisions for 800-GeV protons, the highest fixed-target energy currently available, with the Ag and Br elements in nuclear emulsion.

The analysis of interactions restricted to those collisions having small impact parameter, and correspondingly a large excitation of the target nucleus, is compared with both the inclusive proton-emulsion data[6–8] and with proton-nucleon collisions at the same primary energy.[12] In addition, the dependence of the results on the incident energy of the protons is investigated by comparing the 800-GeV data with previous data at 200 GeV (Ref. 13).

The basic parameter in all models describing particle production on nuclei as an incoherent superposition of hadron-nucleon interactions is the number of intranuclear collisions ν of the projectile, which measures the thickness of nuclear matter as viewed by the impinging hadron. In this paper we address the general question of whether the differences in particle production observed in inclusive and central collisions at the highest accelerator energy may be attributed only to the different numbers of intranuclear collisions which characterize these two samples. To answer this question, the angular distributions of fragments emitted from the struck nucleus, the average multiplicities of particles produced, and the relative densities of secondary particles in different rapidity regions are investigated.

II. EXPERIMENTAL MATERIAL

Several emulsion stacks composed of GOSNIIHIM-FOTOPROEKT BR2 nuclear emulsion pellicles of dimensions 10 cm×20 cm×600 μm thick were exposed to the 800-GeV proton beam at the Fermi National Accelerator Laboratory (experiment No. E508). Along-the-track microscope scanning was performed to select the data sample which consisted of 1749 inelastic interactions (excluding coherent events). The general characteristics of these inclusive interactions have been described elsewhere.[6-8]

The tracks emanating from each interaction were classified according to the commonly accepted emulsion-experiment terminology, based upon their appearance in the microscope, as follows: *s*, shower tracks; *g*, gray tracks; and *b*, black tracks. The shower tracks correspond to the produced, singly charged, relativistic particles ($\beta \geq 0.7$), whereas gray and black tracks are formed by slower particles ($\beta < 0.7$) emitted from the target nucleus. Gray tracks are mostly recoil protons with momenta 0.2–1.0 GeV/*c*, with less than a few percent admixture of low-momentum pions. The black tracks are produced by low-energy target fragments. The numbers of particles are denoted n_s, N_g, and N_b, respectively. The gray and black tracks together are usually called *h* tracks ($N_h = N_g + N_b$), where *h* stands for heavily ionizing.

For each shower particle and each heavily ionizing particle emitted in an interaction, the particle coordinates are measured under high magnification in an optical microscope and used to determine the emission angle θ (the polar angle of the particle with respect to the direction of the incident proton). Then the pseudorapidity $\eta \equiv \ln \tan(\theta/2)$ is derived. Depending upon the angle, the measurements were performed at different distances downstream from the interaction vertex in order to keep the uncertainty in η constant at $\Delta\eta \sim 0.1$ unit.

In our investigation, an interaction was assumed to be a central collision of the proton with the Ag or Br component of the nuclear emulsion if the number N_h of target fragments was greater than 27. There is a correlation between N_h and ν (Refs. 14–18) which implies that large values of N_h will sample large ν collisions. Further, it has been shown[19] that $N_h > 27$ provides a sample of interactions in which complete disintegration of the Ag or Br target nucleus occurs, i.e., the target nucleus evaporates into only protons and alpha particles with no residual nucleus observed. Events characterized by $N_h > 27$ constitute less than 3% of the inclusive data, so an additional "area scanning" of the emulsion plates was performed to increase the statistics. Area scanning is essentially 100% efficient in locating interactions accompanied by large numbers of N_h tracks. Altogether 197 central collisions have been collected, and their analysis is the basis of this report.

In order to compare the characteristics of both inclusive and central proton-nucleus interactions with those of proton-nucleon collisions, an additional along-the-track scan was performed to locate 1156 events satisfying the criteria for interactions on free, or quasifree, nucleons in the emulsion. For this data sample, events with no evaporation fragments from the target nucleus ($N_b = 0$) and no more than one proton in the momentum range 0.2–1.0 GeV/*c* emitted in the forward hemisphere were accepted.

The dependence of the results on primary energy is investigated using 200-GeV proton-emulsion data collected by the Kracow Emulsion Group.[13] This data set consists of 2595 inclusive interactions and 124 central collisions satisfying the same criterion as applied to the 800-GeV data: i.e., $N_h > 27$.

III. NUMBER OF INTRANUCLEAR COLLISIONS AND PARTICLE MULTIPLICITIES

The probability distribution $P(\nu)$ and the mean number $\langle \nu \rangle$, of proton-nucleon collisions inside a target nucleus can be calculated once the impact-parameter distribution is known. For the inclusive *p*-emulsion data, $P(\nu)$ was obtained from Glauber-model calculations averaged over all impact parameters.[20] For the central collision data, however, the range of impact parameters is not known *a priori*, and so a phenomenological model must be used. Previous work on nuclear interactions in emulsion has shown that the number of gray tracks emitted from an interaction can be related to the number of intranuclear collisions experienced by the projectile, and a series of models have been proposed.[14-18] The model of Andersson, Otterlund, and Stenlund[14] employed here predicts the distribution function $P(\nu, N_g)$, which gives the probability of finding an event with ν intranuclear collisions and N_g gray particles. The probability distribution $P(\nu)$ for central interactions was calculated with this function and the measured N_g distribution. Figure 1 compares the N_g distributions measured for the inclusive and the central collision data samples at 800 GeV, and Fig. 2 compares the calculated $P(\nu)$ distributions for the two data sets. The average number of intranuclear collisions $\langle \nu \rangle$ for the distributions presented in Fig. 2 are 2.6 and 5.7, respectively, for the inclusive and the central-collision data sets.

For an incident projectile energy of 800 GeV, the measured multiplicity distributions of shower particles are compared in Fig. 3 for inclusive and central collisions.

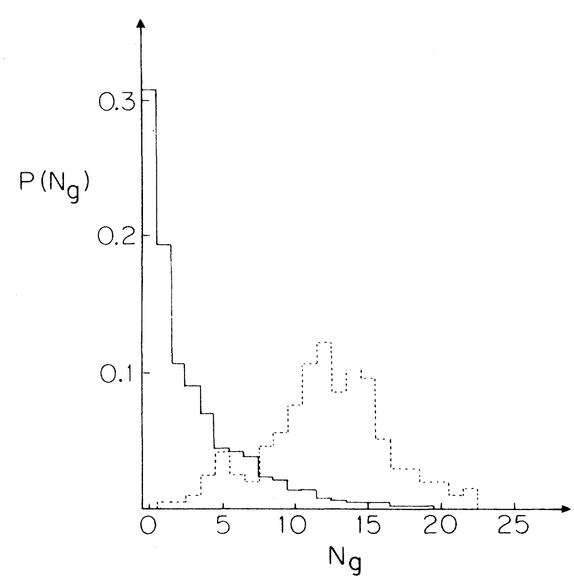

FIG. 1. Distributions of the number of gray particles. The solid (dashed) histogram represents the inclusive (central) data set.

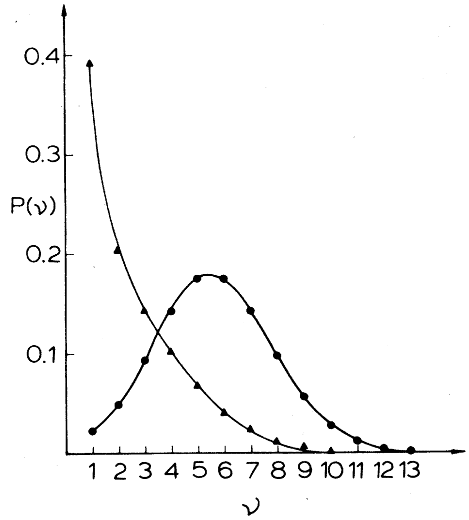

FIG. 2. Distributions of the number of intranuclear collisions in inclusive p-emulsion (▲) and central p-Ag/Br (●) interactions.

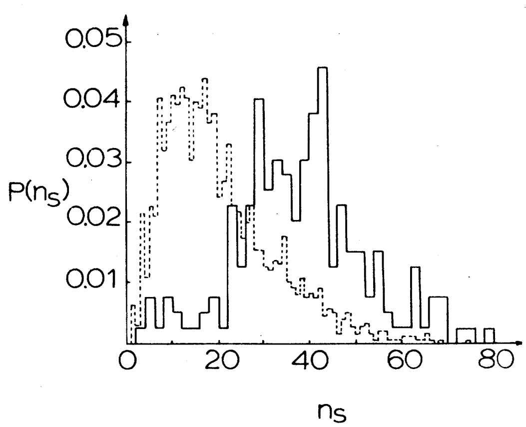

FIG. 3. Distributions of the number of shower particles for inclusive (dashed) and central (solid) collisions.

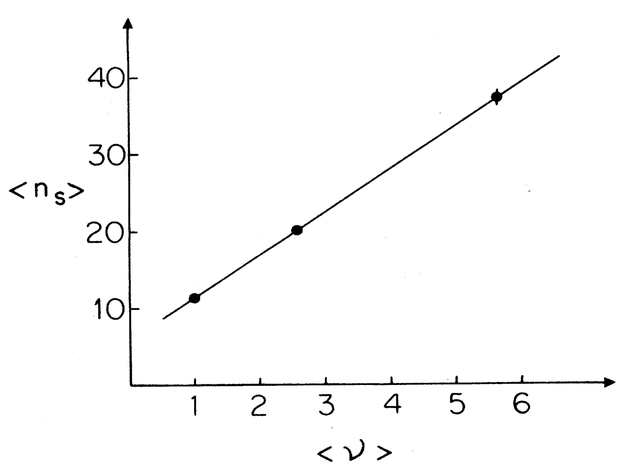

FIG. 4. The dependence of the average multiplicity of shower particles on the average number of intranuclear proton-nucleon collisions. The line is a guide for the eye.

The mean multiplicities for these two distributions, as well as for proton-nucleon interactions measured in our experiment, are 11.2±0.2 for proton-nucleon interactions, 19.8±0.3 for inclusive proton-emulsion interactions,[7] and 37.5±1.0 for the central proton-Ag/Br collisions. These mean multiplicities are plotted versus the average number of intranuclear collisions in Fig. 4, which shows a linear relation between $\langle n_s \rangle$ and $\langle \nu \rangle$, and this is the behavior expected from superposition models.[9–11]

IV. ANGULAR DISTRIBUTIONS OF THE TARGET FRAGMENTS

The superposition models assume that each collision of the projectile in the target nucleus yields the same distribution of gray particles, irrespective of the incident energy, and that consecutive collisions contribute independently to the final N_g distribution. Thus, the angular distribution of gray particles should not depend on either primary energy or the number of intranuclear collisions. Figures 5(a) and 5(b) compare the angular distributions of gray particles in inclusive and central collisions at two primary energies, demonstrating the energy independence.

In Fig. 6 the cosθ distributions of gray particles from

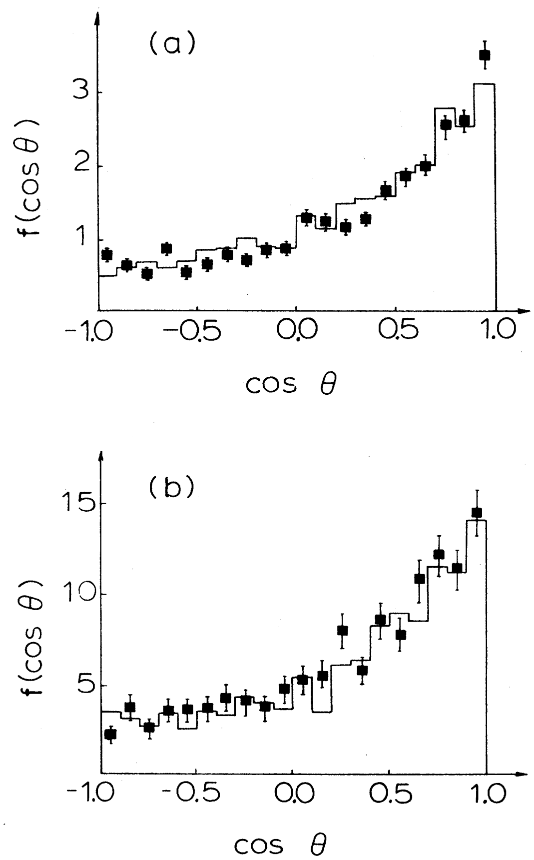

FIG. 5. Comparison of the angular distributions of gray tracks from inclusive (a) and central (b) p-emulsion collisions at two energies: 200 (■) and 800 GeV (solid histogram). On the vertical axis, $f(\cos\theta) = (1/N_{ev}) dN_g / d(\cos\theta)$ is plotted.

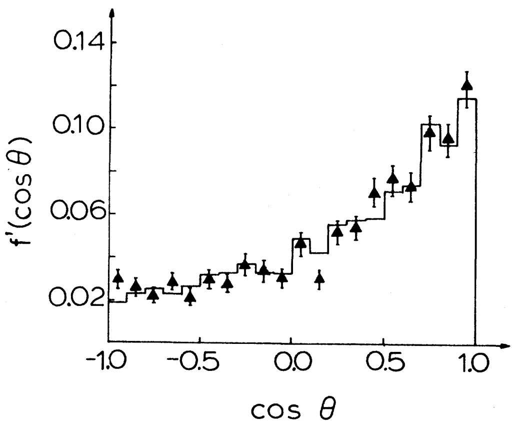

FIG. 6. Comparison of the angular distributions of gray tracks for inclusive (solid histogram) and central (▲) p-emulsion collisions at 800 GeV. Distributions are normalized to the equal areas, $f'(\cos\theta)=(1/\langle N_g \rangle)(1/N_{ev})dN_g/d(\cos\theta)$.

the inclusive data and central interactions at 800 GeV are presented. The distributions are normalized to equal areas. Although the mean number $\langle \nu \rangle$ of projectile collisions inside the target nucleus changes from 2.6 to 5.7 between inclusive and central collisions, the N_g angular distributions agree within the statistical uncertainty. These results are consistent with the expectation from superposition models and thereby provide additional support for the $N_g - \langle \nu \rangle$ correlation based originally on the observed energy independence of the multiplicity distribution of gray particles. The results also justify the applicability of $N_g - \langle \nu \rangle$ relation to *central* hadron-nucleus collisions.

V. PSEUDORAPIDITY DISTRIBUTIONS OF SHOWER PARTICLES

The angular distributions of shower particles, normalized to the average multiplicity $\langle n_s \rangle$, are shown in Fig. 7 as a function of the pseudorapidity for the three data sets characterized by different numbers of intranuclear collisions. A rapid multiplicity increase is observed at low η values, but not for $\eta > 6$. The largest values are observed for the central collision data set which corresponds to the largest value of $\langle \nu \rangle$.

To investigate these features in more detail, we define the normalized pseudorapidity density $R(\eta)$ as

$$R(\eta)=\rho_{pA}(\eta)/\rho_{pN}(\eta) , \quad (1)$$

where $\rho(\eta)=(1/N)(dn_s/d\eta)$ is the shower particle density determined from N proton interactions on nuclear (ρ_{pA}) or nucleon (ρ_{pN}) targets. The term ρ_{pA} may denote the pseudorapidity density in either central or inclusive collisions. The normalized pseudorapidity densities at 800 GeV are shown in Fig. 8 for both the inclusive p-emulsion and the central p-Ag/Br data samples. The variation of $R(\eta)$ throughout the pseudorapidity range is basically similar for the two data sets.

In the projectile fragmentation region ($\eta > 6$), the nor-

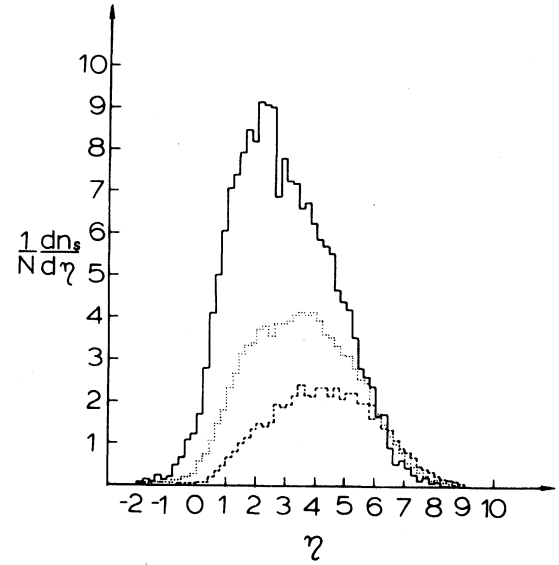

FIG. 7. The pseudorapidity distributions for proton-nucleon (dashed), inclusive proton-emulsion (dotted), and central p-Ag/Br (solid) collisions at 800 GeV.

malized pseudorapidity density $R(\eta)$ is less than unity for both sets of data. In many superposition models this effect is explained as the result of energy conservation since the additional particles produced in consecutive intranuclear collisions carry away some of the energy of the incident proton thereby reducing its momentum, compared to the nucleon-nucleon case.

For $\eta \gtrsim 2$ the $R(\eta)$ values do not exceed the mean number of projectile collisions for each sample, i.e., $R(\eta) < 2.6$ and < 5.7, respectively, for inclusive and central collisions. This indicates that no secondary interactions of the produced particles occur inside the target nucleus in this η region. However for $\eta \lesssim 2$, $R(\eta)$ increases rapidly. This behavior may be explained by the formation zone hypothesis,[21,22] which assumes that some time is needed in the particle's rest frame for its creation.

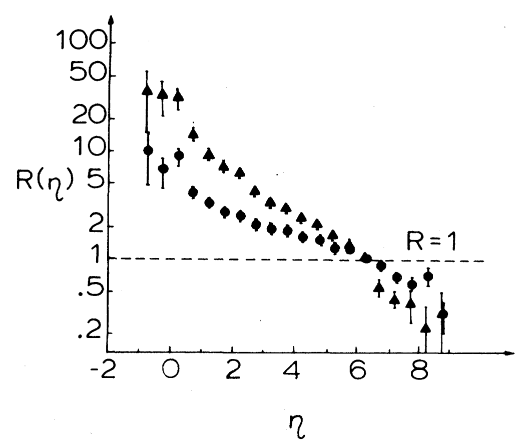

FIG. 8. The normalized pseudorapidity densities $R(\eta)$ for inclusive (●) and central (▲) proton-nucleus collisions at 800 GeV.

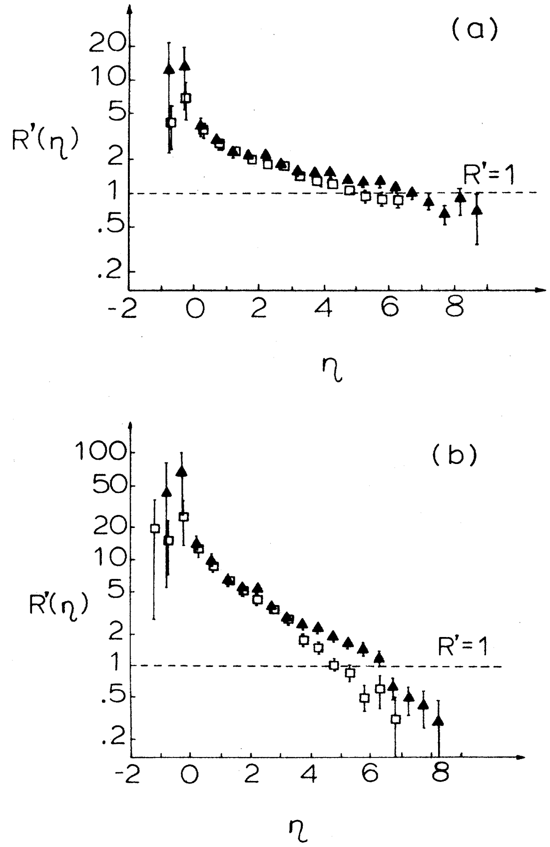

FIG. 9. The normalized pseudorapidity distribution $R'(\eta)$ for inclusive (a) and central (b) collisions at two energies: 200 (□) and 800 GeV (▲).

Consequently, because of time dilation in the laboratory frame, the fast particles ($\eta \geq 2$) are hadronized outside the nucleus and only slow secondaries can reinteract inside the target. This explains the rapid increase of $R(\eta)$ at low η values. To investigate the energy dependence of $R(\eta)$, we compare in Fig. 9 the normalized pseudorapidity distributions at 200 and 800 GeV both for inclusive and central interactions. A purely p-nucleon data set is not available at 200 GeV, but the comparison can be made using

$$R'(\eta)=\rho_{pA}(\eta)/\rho_{N_h=0,1}(\eta) , \quad (2)$$

where the denominator is the set of interactions showing very little target excitation ($N_h=0,1$), i.e., interactions with single nucleons or with peripheral nucleons in the emulsion nuclei. The quantity $\rho_{N_h=0,1}(\eta)$ differs only slightly from $\rho_{pN}(\eta)$ in Eq. (1). It is seen in Fig. 9 that the normalized pseudorapidity distributions $R'(\eta)$ show no energy dependence in the target fragmentation region, both for inclusive and central collisions.

VI. DISCUSSION AND CONCLUSION

The central collisions of 800-GeV protons with Ag and Br nuclei in nuclear emulsion have been compared both to inclusive proton-emulsion and to proton-nucleon interactions at the same energy, providing a comparison for interactions that vary in $\langle \nu \rangle$ from about 1 to 6. To investigate the energy dependence the inclusive and central collisions at 200 and 800 GeV have been compared. Taken together these data sets provide stringent constraints to be met by superposition models.

(1) The angular distributions of the target fragments are independent of the mean number of intranuclear collisions and of the energy of the projectile.

(2) The average multiplicity of produced particles increases linearly with the number of intranuclear collisions.

(3) The normalized shower-particle pseudorapidity density $R(\eta)$ shows a similar variation with η throughout the pseudorapidity range for both central p-Ag/Br and inclusive p-emulsion interactions. The difference in the absolute values of $R(\eta)$ at a given η can be attributed to the different values of $\langle \nu \rangle$.

(4) The particle densities $R'(\eta)$ investigated at two primary energies show no energy dependence in the target fragmentation region both for inclusive and central collisions.

The high values of the normalized particle densities in the target fragmentation region (low η) can be explained by the existence of some cascading effects inside the target nucleus due to the secondary interactions of the lower-energy pions produced in this η region.

Central collision events are those most likely to show collective phenomena if any exist for p-nucleus interactions. The conclusion from the particle multiplicities, the target fragment angular distribution and the $R(\eta)$ behavior for the highest-energy fixed target data set currently available is that the superposition models can describe the results adequately. The differences observed among the inclusive and central collisions appear to be explained quite well by the difference in the mean number of intranuclear collisions. No collective effects are observed in the present results, and evidence for such effects will have to be sought elsewhere, e.g., in the fluctuations in the pseudorapidity distributions or in different types of correlations among the secondary particles.

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