ANL-HEP-CP--86-54

DE87 001501

ANL-HEP-CP-86-54

IUHEE-383

UM HE 86-10

PU-86-567

June 1986

MULTIPLICITY DISTRIBUTIONS IN e^+e^- ANNIHILATION AT 29 GeV: A COMPARISON WITH HADRONIC DATA

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The charged particle multiplicity distributions for single jets in e^+e^- annihilation at 29 GeV have been measured using the High Resolution Spectrometer at PEP. The shape of the distribution agrees well with a Poisson distribution. No correlation is observed between the multiplicities in the two jets of an event. For fixed values of the prong number of the total event, the multiplicity sharing between the two jets is in good agreement with a binomial distribution. These observations are contrasted to the results from soft hadronic collisions and conclusions are drawn about the nature of clusters.

Submitted to XXIII International Conference on High Energy Physics, July 16-23, 1986, Berkeley California, by M. Derrick, Argonne National Laboratory.

Following the completion of Fermilab and the CERN Intersecting Storage Rings, there were many studies of charged particle multiplicity distributions and correlations in soft hadronic collisions.[1,2] All of the data could be encompassed by the phenomenological idea that the reactions proceed through the independent emission of clusters.[3] To fit the data, the clusters had to be typically 1 GeV in mass and decay to a few stable particles, such as pions, that were subsequently observed.

In this paper we present new results on multiplicity distributions in e^+e^- annihilation at 29 GeV. The data are quite different from the hadronic results and cast new light on the nature of clusters. The experiment, which corresponds to an integrated luminosity of 185 pb^{-1}, was done using the High Resolution Spectrometer (HRS) at the e^+e^- storage ring, PEP. The storage ring was operated at a center of mass energy of 29 GeV.

The HRS[4] is a solenoidal spectrometer that measures charged particles and electromagnetic energy over 90% of the solid angle. The tracking system consists of a vertex chamber, a central drift chamber, and an outer drift chamber. The central drift chamber has 15 layers of cylindrical drift planes, eight of which have stereo wires (±60 mrad) in order to measure the position along the e^+e^- beam direction. The momentum of a charged particle in the 1.62 T magnetic field is measured with a resolution of 3% at 14.5 GeV. The minimum momentum for detecting tracks with good efficiency is about 200 MeV/c. The 40-module barrel shower counter system provides electromagnetic calorimetry over 62% of the solid angle with energy resolution of $\sigma_E/E = 0.16/\sqrt{E\ (\mathrm{GeV})}$.

The beam pipe and the inner wall of the central drift chamber are made of beryllium so as to minimize the conversion of photons into electron-positron pairs; the total material between the interaction point and the central drift chamber is less than 0.02 radiation lengths.

To ensure good tracking efficiency, the thrust axis of the event was selected to be within 30° of the equatorial plane of the detector, and each track had to have an angle with respect to the e^+e^- beam direction of more than 24° and had to register in more than one-half of the drift chamber layers traversed. With these selections, the reconstruction efficiency for isolated tracks was greater than 99%. For a typical annihilation event, with several close neighboring tracks, the reconstruction efficiency was 80% or better.

In order to compare with the hadronic data, a two-jet data sample was selected using the sphericity (S) and aplanarity (A) variables, where the S and A values were set by the eigenvalues of the momentum tensor. The collimated ($S < 0.25$) and planar ($A < 0.10$) events are called two jet since these selections remove the events with hard gluon radiation. This data sample contains 24,553 events.

The true multiplicity distribution was determined from the observed data by means of a matrix unfolding technique. If N_m^0 is the number of events observed with m tracks and N_N^T is the true number of events with N tracks (N even), we define M_{Nm} such that

$$N_N^T = \sum_m M_{Nm} N_m^0 \quad .$$

The matr.x M_{Nm} was determined from a Monte Carlo simulation of the experiment, which includes the effects of the experimental cuts as well as the tracking inefficiencies.[(5)]

In the initial data selection, events with $m < 5$ were removed in order to exclude tau pair events. The numbers of events with $N = 0$, 2 and 4 charged particles were estimated from the data themselves assuming independent fragmentation of the two jets in the event.

The main features of the hadronic data that gave rise to the cluster model were:

(i) A non-Poissonian multiplicity distribution with a tail at the higher N values.[(6)]

(ii) A linear correlation between the mean number of neutral pions and the number of negative prongs.[(7)]

(iii) A long-range multiplicity correlation[(8)] described by the equation

$$\langle n \rangle_B = a + bn_F \tag{1}$$

where n_B and n_F are the numbers of charged particles in the two jets of the event, arbitrarily called forward (F) and backward (B). At ISR energies, the b values are typically ~ 0.2.

(iv) Charge transfer distributions inconsistent with independent emission of single pions.[9]

(v) Rapidity gap distributions that show a break at a gap size (r) of about 1.4 units.[10] The distribution of large gaps is consistent with an exponential $P(r) = \rho \exp(-\rho r)$ with $\rho = 1$. Since the charged particle density is about 2 particle per unit of rapidity, this data was interpreted as giving a cluster multiplicity of two.

(vi) Strong two-particle correlations in rapidity[11] with a typical range of one unit.

All of these observations could be understood if the observed hadrons result from the decay of low mass clusters. The clusters were later identified with resonances, such as the ρ^0 meson, that were found to be copiously produced in the central region of high energy collisions.[12]

More recently, these ideas have received confirmation from the measurements of 546 GeV $\bar{p}p$ collisions made by the UA5 collaboration.[13] These data show a strong F:B correlation ($b = 0.57 \pm 0.01$ in Eq. (1)), a growth of the high N tail well above that expected from scaling the lower energy data and an F:B split at fixed N which agrees with a binomial distribution of pairs.

All of the hadronic multiplicity data are also represented by the negative binomial distribution:

$$P(N, \langle N \rangle, k) = \frac{k(k+1)\ \ldots\ (k+N-1)}{N!} \left(\frac{\langle N \rangle/k}{1 + \langle N \rangle/k}\right)^N \left(1 + \frac{\langle N \rangle}{k}\right)^k \tag{2}$$

and various interpretations of meaning of the parameter k again lead to the idea of clusters.(14)

We now compare these observations with our e^+e^- data. If the events are divided into two jets by a plane perpendicular to the thrust axis, the single jet charged particle multiplicity distribution shown as the histogram in Fig. 1(a) is obtained. This distribution has a mean value $\langle n \rangle = 6.26 \pm 0.02 \pm 0.15$, a dispersion, $D_2 = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2} = 2.45 \pm 0.02 \pm 0.12$ and an f_2 moment, $f_2 = \langle n(n-1) \rangle - \langle n \rangle^2 = -0.26 \pm 0.03 \pm 0.13$: the first error is statistical and the second systematic. The full line in Fig. 1 connects values of a Poisson distribution $P(n) = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$ calculated with $\langle n \rangle = 6.26$. It agrees well with the data, as expected from the value of the f_2 moment which should be zero for such a distribution. The dashed line shows a Poisson in n/2, which might be more appropriate if pairs of oppositely charged particles were emitted.(15) This curve clearly does not agree with the data histogram.

The multiplicity distribution for the total event is shown in Fig. 1(b). Again, the line connects points on a Poisson distribution with the same mean value. This data has $\langle N \rangle = 2\langle n \rangle$ by definition and a dispersion $D_2 = 3.48 \pm 0.02 \pm 0.17$ which is $\sqrt{2}$ times larger than $D_2 = 2.45 \pm 0.02 \pm 0.12$ measured for the single jets.

The variation of $\langle n \rangle_B$ with n_F, shown in Fig. 2, is flat. The slight rise at low n_F values comes from the cut at m = 5 that excludes the low multiplicity events. The line shows the result of a simple calculation using the measured $\langle N \rangle$ values for (u,d,s), c and b quarks,(16) as well as the effect of the cut at m = 5. A fit to the data of Fig. 2(a) with $n_F > 6$ to Eq. (1) gives $b = -0.001 \pm 0.015$. Figures 2(b) and 2(c) show the data with the rapidity selections listed; again there is no F:B correlation.

The Poisson multiplicity distribution for single jets, the $\sqrt{2}$ difference between of the widths of the single jet and complete multiplicity distributions, and the lack of an F:B correlation support the idea of independent jet fragmentation to individual hadrons. This can be further investigated by looking at the F:B split for fixed total multiplicity N.

These data for N = 6 to N = 18 are shown as the histograms of Fig. 3. The lines, which connect the points on binomial distributions,

$$P_n(n_F) = \frac{N!}{n_B!\; n_F!} \left(\frac{1}{2}\right)^{n_B} \left(\frac{1}{2}\right)^{n_F} \quad . \tag{3}$$

represent the histograms reasonably well, although the data tends to be narrower. For the binomial distribution (Eq. (3)), the dispersion is given by $D_2^2 = \frac{N}{4}$ so that $4\langle n_F^2 \rangle = N(N+1)$. Figure 4 shows the variation of $\langle n_F^2 \rangle$ with N(N+ 1): the line, which is drawn with a slope of 1/4, agrees remarkably well with the data points.(17)

The dashed histograms in Fig. 3 for N = 12, 14, 16 show the results of the UA5 experiment.(13) These distributions are clearly wider than the e^+e^- data, and are well represented by the dashed lines, which correspond to binomial distributions of pairs. These hadronic distribution have been interpreted as due to charge conservation(15,18), or to the dominance of the reactions by charge neutral clusters.(19) Since charge conservation also holds for e^+e^- annnihilation, it seems unlikely that the differences in the F:B distributions at fixed N for e^+e^- and hadronic collisions arises from these effects.

The e^+e^- data given here support the simplest picture of independent emission of single charged particles from the uncorrelated fragmentation of the two jets of the event. However, the e^+e^- final states, in common with the hadronic reactions, include many resonances(20) such as ρ^o, $K^*(890)$, f^o, $K^*(1420)$, etc. In pp interactions at a center of mass energy of 19.6 GeV, the ρ^o/π^- ratio is 0.13 ± 0.02,(12) in good agreement with the value of 0.13 ± 0.01 for ρ^o/negative particles measured in the present e^+e^- experiment.(20) In addition, 40% of the e^+e^- events have two mesons or baryons containing the heavy quarks, c and b. These heavy quark states decay to several π and K mesons.

We conclude that the neutral clusters that provide a useful description of many phenomena seen in the hadronic data cannot be identified with resonances.(21) One obvious possibility is that the effects in the hadronic data are a manifestation of multiple parton (gluon) interactions within a given hadronic collision. Why the resonances that are present in the e^+e^- final states are not manifest in the multiplicity correlations presented in this paper is a subject for further investigation.

This work was supported in part by the U.S. Department of Energy under Contracts No. W-31-109-ENG-38, DE-AC02-76ER01112, DE-AC03-76SF000998, DE-AC02-76ER01428, and DE-AC02-84-ER40125. We thank the PEP operations group for providing the luminosity on which these results are based.

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The latter authors show that the multiplicity distribution, when interpreted with the negative binomial distribution, gives the cluster multiplicity $\langle n \rangle_c$. The result is:

$$\langle n \rangle_c = \frac{B}{B-1} \frac{1}{\ln(1-B)} \quad ,$$

where $B = \frac{\langle n \rangle}{\langle n \rangle + k}$. This equation gives $\langle n \rangle_c$ values close to one for our data.

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between the mesons. We further note that the rapidity gap distribution for our data presented by Valdata-Nappi shows no break near $r = 1.4$, and a slope $\rho = 2$ consistent with the charged particle density in rapidity, and so a "cluster" multiplicity of one.

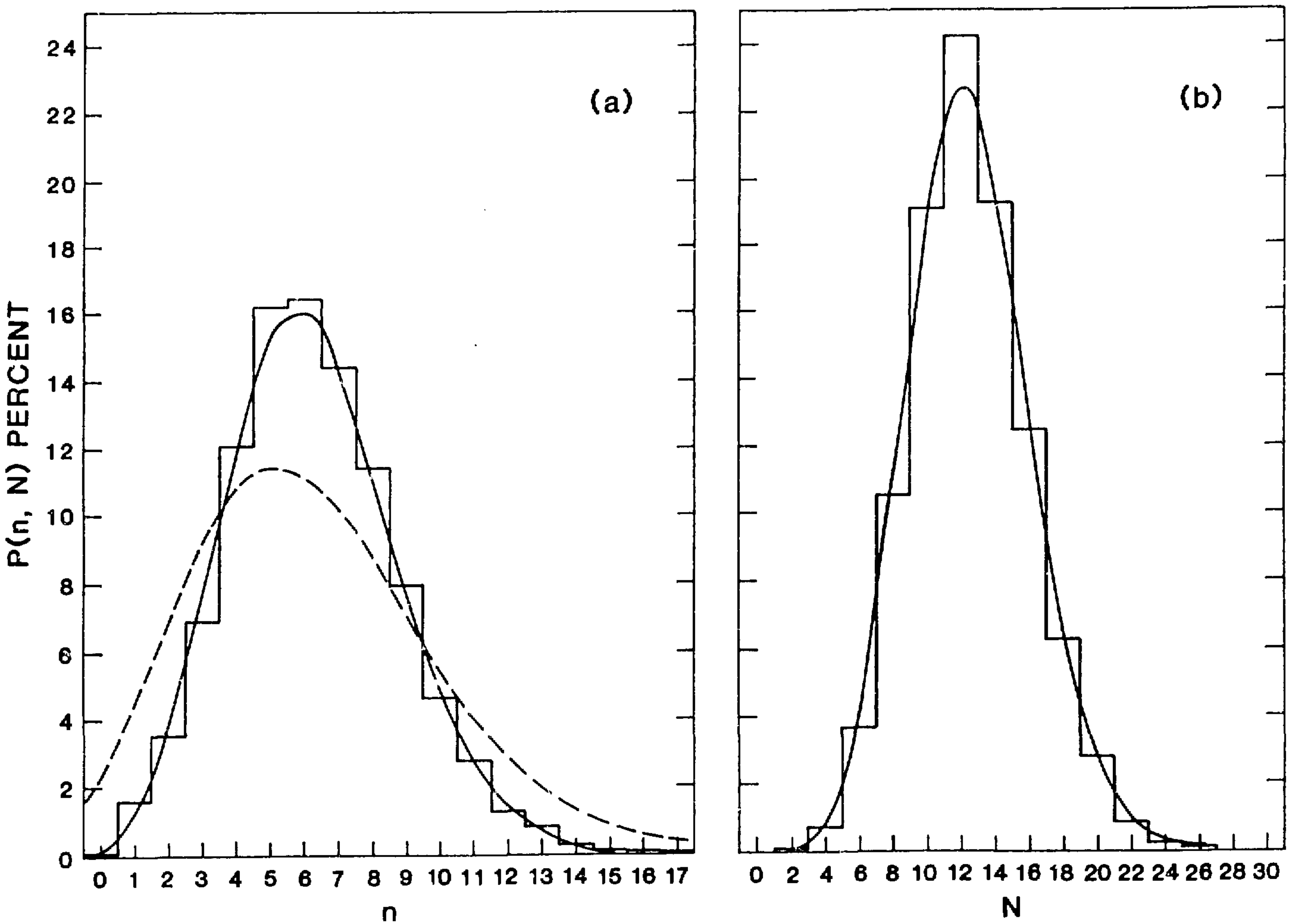
Figure Captions

1. The histograms show the charged particle multiplicity distributions for two-jet events: (a) single jet, (b) whole event. The full lines connect points on a Poisson distribution with the same mean values. The dashed line in (a) shows a Poisson distribution of pairs.

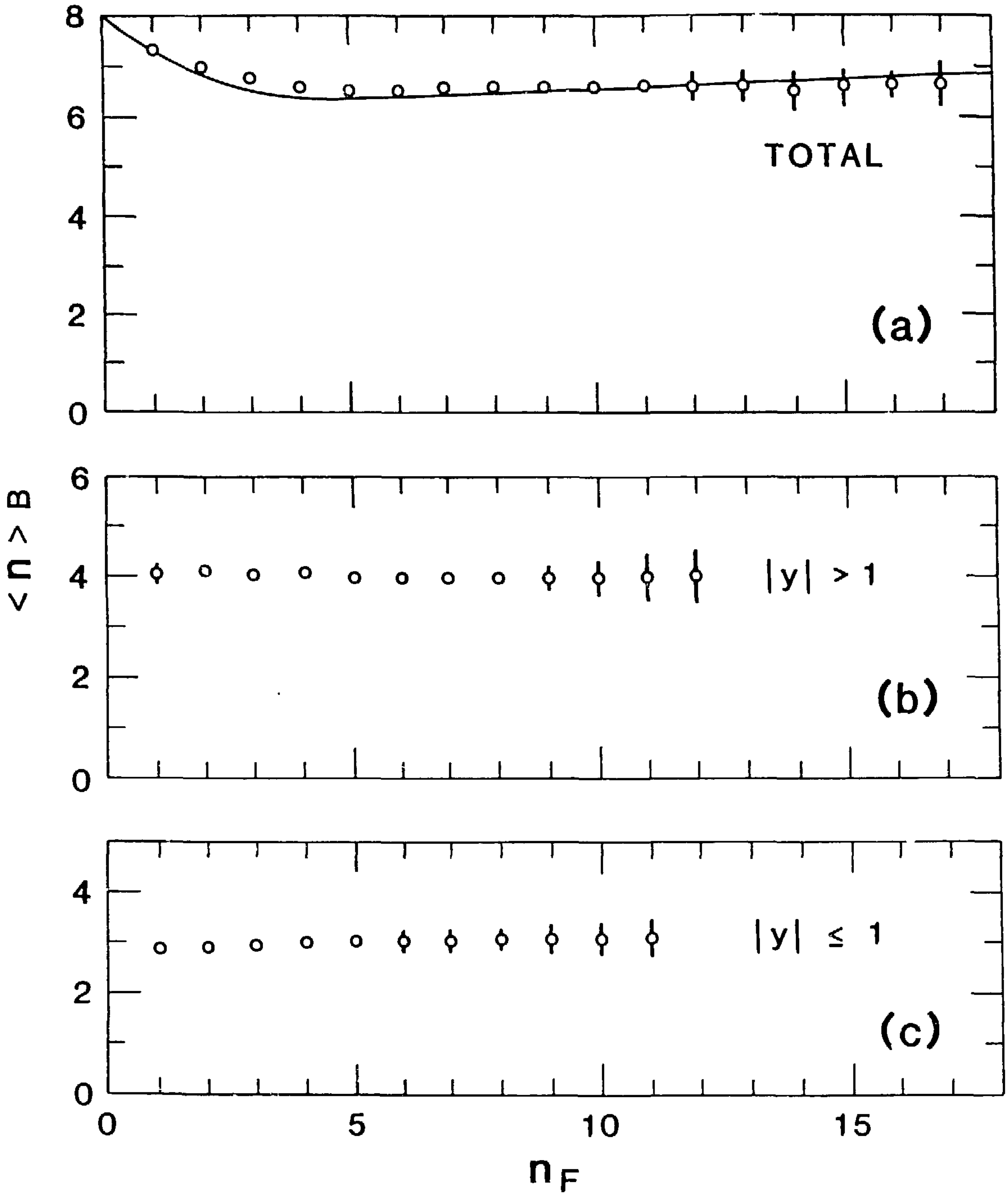
2. Forward:backward multiplicity correlations for (a) full rapidity span, (b) tracks with $|Y| < 1.0$ removed, (c) tracks in the region $|Y| < 1.0$. The errors shown are dominated by the systematic uncertainties. The line shows the result of the simple calculation described in the text.

3. The full histograms show the forward:backward charged particle multiplicity splits for fixed total multiplicity (N) for N = 6 to N = 18. The full lines connect points on a binomial distribution. For N = 12,14,16, the dashed histograms show the results of the UA5 experiment (Ref. 13). The dashed lines, which agree with the dashed histograms, correspond to a binomial distribution of pairs of charged particles.

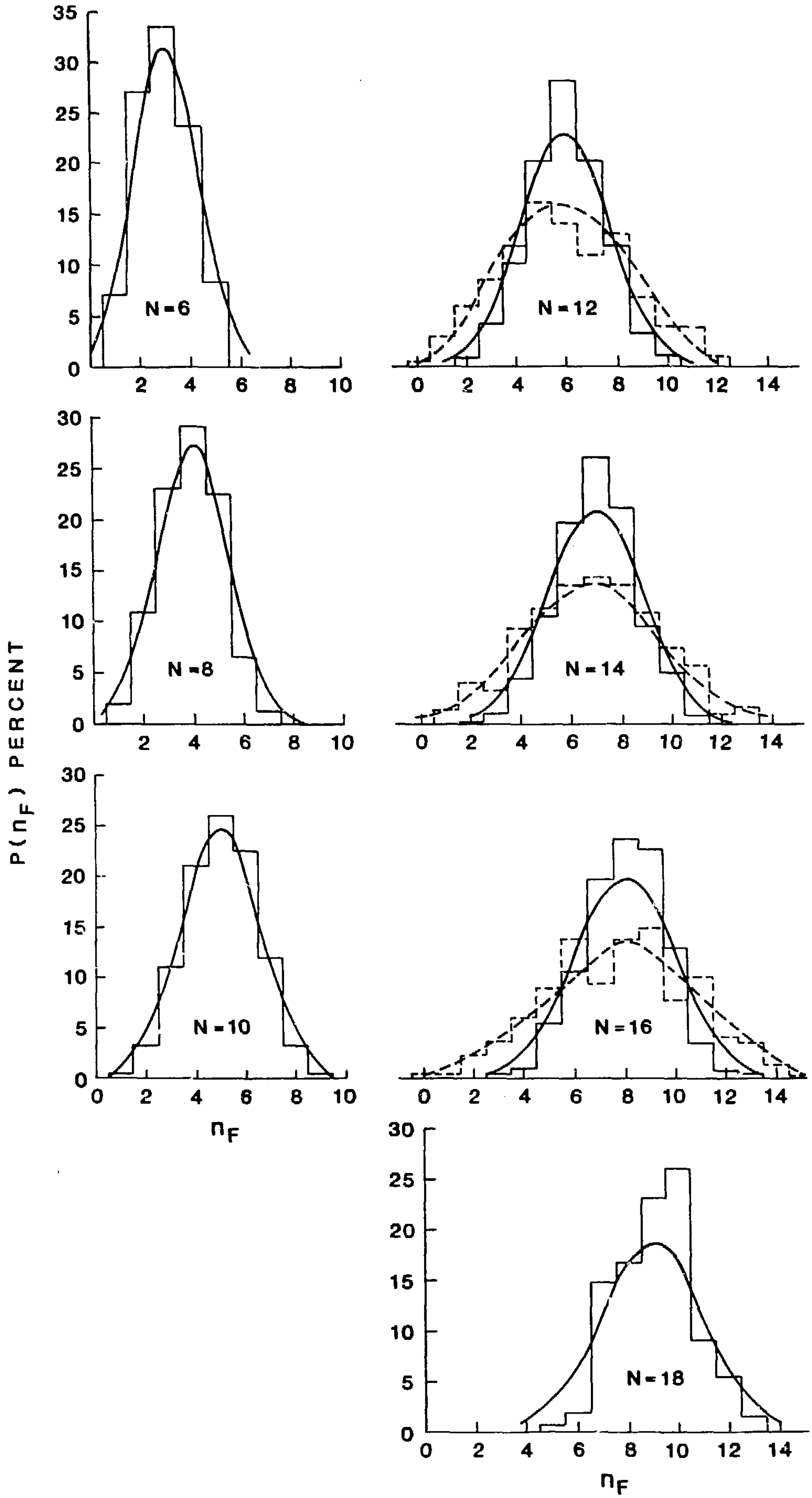
4. Variation of $\langle n_F^2 \rangle$ with $N(N + 1)$. The line is drawn with a slope of 0.25.



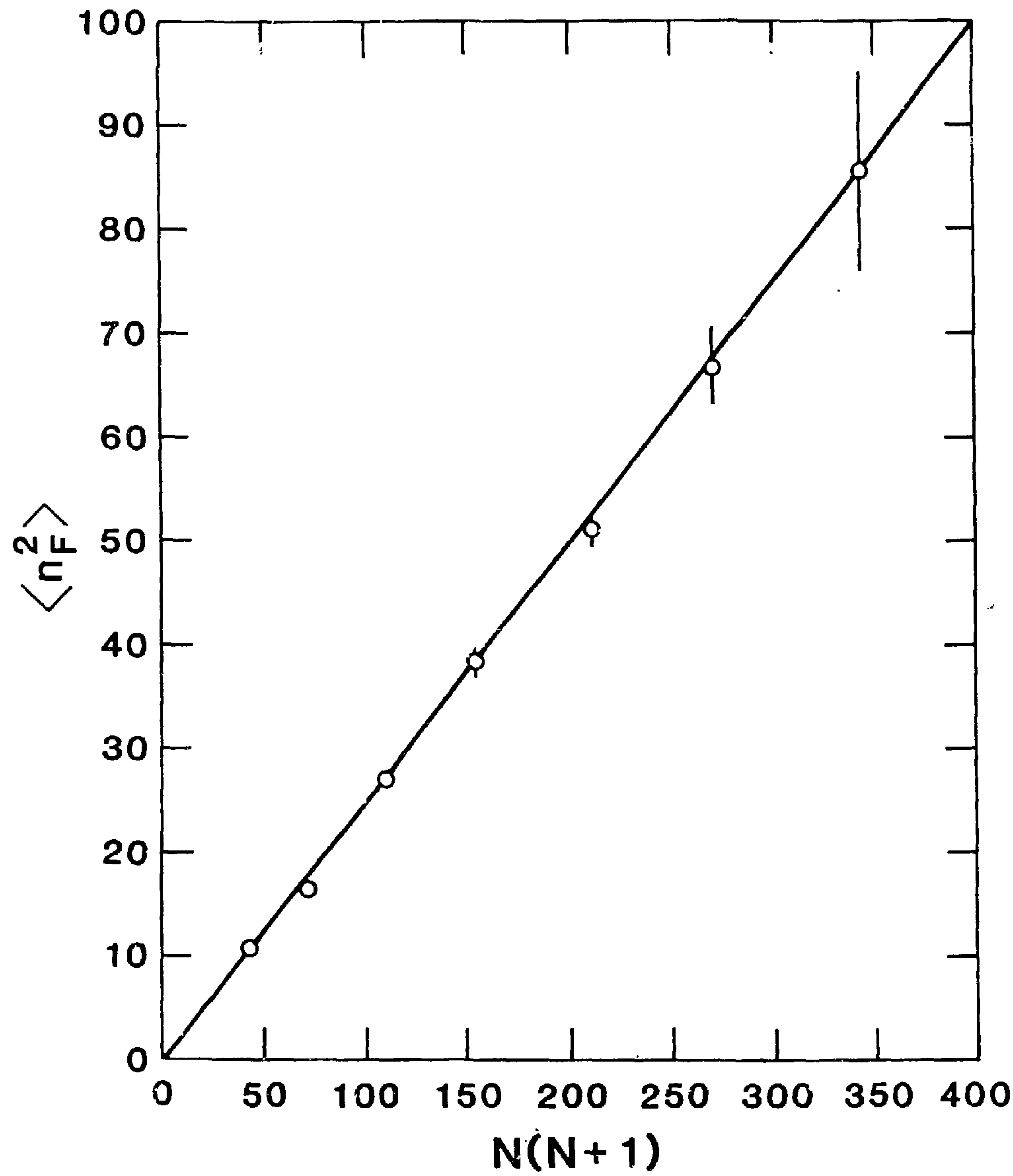
(a)
(b)
P(n, N) PERCENT
0
2
4
6
8
10
12
14
16
18
20
22
24
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
n
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
N



TOTAL
(a)
|y| > 1
(b)
|y| ≤ 1
(c)
< n > B
n F



P(n_F) PERCENT
N = 6
N = 8
N = 10
N = 12
N = 14
N = 16
N = 18
n_F
n_F



100
90
80
70
60
50
40
30
20
10
0
$\langle n_F^2 \rangle$
0
50
100
150
200
250
300
350
400
N(N+1)

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