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DISCLAIMER

Wide-Angle High-Energy Proton Spectra
by 800 MeV/A C, Ne, and Ar Beams

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ABSTRACT

Inclusive proton spectra, as well as two-particle correlations, have been measured in collisions of C on C and Pb, Ne on NaF and Pb, and Ar on KCl and Pb, at 800 MeV/A beam energy. A magnetic spectrometer and three sets of counter telescopes were used to measure over a wide range of fragment energies and angles. Protons associated with large momentum transfers show exponential energy distributions having a characteristic decay constant about (70-90 MeV)$^{-1}$. For light-mass targets a strong two-particle correlation has been observed, which is kinematically consistent with quasi-elastic proton-proton scattering.

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Recently there has been a growing interest in studying central collisions between relativistic heavy ions.[1] Since central collisions are violent and tend to involve large momentum transfers between projectile and target, we expect that such collisions will be the dominant source of high-energy fragments emitted at large laboratory angles.

Previous experimental studies of large-angle fragmentation involved mainly measurements of relatively low-energy particles,[2,3,4] typically protons with energies less than 200 MeV. In the present experiment we measured light-fragment energy spectra up to a few GeV over a wide range of laboratory angles, from 10° to 145°, and tried to learn more about the general features of central collisions. Among the various fragments observed, the yield of protons was dominant. In this paper we restrict ourselves to results pertaining to the proton spectra only.

As to the theoretical aspects of central collisions, several models based on a thermal equilibriated system[2,3,5,6,7] and some based on nucleon-nucleon scatterings[8-13] have recently been proposed. We will compare our inclusive data with these models. A crucial test of the assumption of thermal equilibrium can be made by measuring two- (or more-) particle correlations.[14] At the end of this paper we report some two-particle correlation results.

Projectiles and targets studied in the present measurements were C on C and Pb, Ne on NaF and Pb, and Ar on KCl and Pb, at 800 MeV/A beam energies. Some preliminary data were already reported in Ref. 15.

A magnetic spectrometer was used to measure energy spectra. A total of 9 planes of multiwire proportional chambers (MWPC) placed before and after the spectrometer magnet determined the particle trajectory. Momentum, charge, and mass of each fragment were determined from three independent quantities, time-of-flight, dE/dx and the trajectory. Particle separation between different fragments was excellent, and the typical momentum resolution, $\Delta p/p$, was a few percent. The beam intensity was monitored by an ion chamber and several sets of monitor telescopes, with which the absolute beam intensity was determined to ±5%. In order to cover a wide momentum range (.3-3 GeV/c) we normally took data at two different sets of magnetic fields. Still, overall uncertainty in the present absolute cross sections is about (20-30)%, most of which is due to MWPC efficiency, spectrometer acceptance, and orbit tracing.

Typical results[16] for inclusive spectra are shown in Fig. 1. Shown there are two examples, Ar on KCl and Ar on Pb, where the kinematics of the former case corresponds closely to those for equal-mass collisions, whereas the latter corresponds to the case of heavier-mass target. Data are presented in the plane of two Lorentz-invariant variables, y and p_T/m_pc, where y is the rapidity defined by $y = (1/2)\{\log (E + p_{/\!/})/(E - p_{/\!/})\}$ and p_T is the transverse momentum. Each contour line connects the same invariant cross sections, $\sigma_I \equiv (E/p^2)(d^2\sigma/dpd\Omega)$, and two adjacent thick solid curves differ by one order of magnitude in cross section. The projectile and target rapidities are indicated by y_P (=1.23) and y_T (=0), respectively. The line $(y_P + y_T)/2$ (=0.61) corresponds to 90° in the nucleon-nucleon CM frame, and y_{CM} is the rapidity of the CM frame of the total nucleus system. According to a naive fireball model[2,3] protons are emitted isotropically in the effective CM frame of the fireball even in the case of different mass combinations between projectile and target. The rapidity of such an effective fireball CM frame is indicated by y_{FB}.[17]

In the small p_T region we expect that proton emission is highly influenced by projectile and target fragmentation for which two peaks at $y = y_P$ and y_T are expected. When the target is heavier than the projectile, we further expect more low-p_T fragments from the target than from the projectile. In the case of Ar on Pb we clearly observe such effects.

Data points far from $(y,p_T/m_pc) = (y_P,0)$ and $(y_T,0)$ are mainly due to high momentum transfers between projectile and target. In these regions Fig. 1 shows that contributions from projectile and target can no longer be cleanly separated. There we observe the following features of the angular distributions. For Ar on KCl they show forward and backward peaking in the CM frame. Isotropic distributions in the CM frame are indicated by dotted lines in Fig. 1(a). In the case of Ar on Pb, they tend to approach symmetry about 90° in the nucleon-nucleon CM frame as we go to higher momentum transfers; namely they approach more closely the angular distributions for the Ar on KCl case, implying that projectile and target nucleons tend to contribute more equally to produce high energy proton fragments.

In Fig. 2 the distributions of proton kinetic energy, E_K, along the line $y = (y_P + y_T)/2$ are plotted. In the case of identical nucleus collisions the plot corresponds to the energy distributions at 90° in the CM frame. Two significant features are observed:

(1) Invariant cross sections approach $\exp(-E_K/E_0)$ at high proton energies with slope factor E_0 being about 70-90 MeV.

(2) For low energy protons the cross sections deviate substantially from an exponential shape.

A slight increase of the slope factor as we increase projectile or target masses implies that we can pump more energy into the heavier system.

In the simplest fireball model,[2,3] where the total available energy in the overlap region between projectile and target is completely thermalized, the calculated temperature is about 120 MeV for identical nucleus collisions and about 110 MeV for Ar + Pb, both of which are much higher than the observed slope factor. Recently several modifications of the fireball model, such as the firestreak model,[5,6] have been proposed. These modifications have succeeded in reproducing our present data much better than the original fireball model did, as shown in Fig. 2. However, if we look in more detail at the data, the firestreak model (or any of the thermal models) is in disagreement with our low energy proton results. In all cases the experimental yield there is much less than the theoretical value. Further modifications of the thermal model toward a partial thermalization are now in progress.[18,19] For example, Siemens[19] pointed out that an explosion mechanism may explain the observed flattening at low energies.

At another extreme are explanations of the present results in terms of nucleon-nucleon scattering. Hatch and Koonin[9] have modified the theory of Schmidt and Blankenbecler[8] and have obtained reasonably good agreement with our observations, as shown in Fig. 2. They assumed a momentum distribution of the form $(p/p_0)(\sinh p/p_0)$ for the nucleons inside the nucleus. More extensive cascade calculations[12,13] give even better fits to the data.

The fact that most of these models succeed in reproducing at least the main features of the data indicates that it may be difficult to choose between them on the basis of inclusive proton spectra only. In order to clarify the situation one step further we studied two-particle correlations.

To measure two-particle correlations we prepared 3 sets of additional counter telescopes ("tag telescopes"), as shown in Fig. 3(a). As viewed along the beam direction, these telescopes were set above and below ($\phi = \pm 90°$) and to the right-hand side ($\phi = 180°$). The spectrometer was on the left-hand side ($\phi = 0°$) of the beam. We define the following ratio, C, as

$$C(\theta_{SP}, \theta_{TAG}) \equiv 2 \frac{(SP\cdot R)/R}{(SP\cdot U)/U + (SP\cdot D)/D}$$

where SP refers to the spectrometer and R, U and D refer to right-, up- and down-telescopes. θ_{SP} and θ_{TAG} are polar angles with respect to the beam direction (all 3 telescopes were set at the same θ_{TAG}). (SP•R) indicates the coincidence counts between SP and R, and R in the above equation shows the single counts of the right telescope. We call the above ratio C the "degree of coplanarity." If $C > 1$, coplanar-type emission is favored. In a thermal equilibrium situation we expect $C \simeq 1$. With the 3 telescopes relatively high-energy fragments, typically $E_{proton} > 200$ MeV, were detected, and the ratios C were measured as a function of θ_{SP}.

A typical result is shown in Fig. 3(b). The absolute scale of the ratio C is reliable within an error of ±0.1. It is sensitive to the polar angles of 3 telescopes, and they were uncertain by a few degrees. Nevertheless, in the case of C + C we observe that $C > 1$. In addition, the ratio C peaks at around $\theta_{SP} = 40°$. When we moved θ_{TAG} to smaller angles than 40°, we observed that such a peak in C was shifted toward larger angles in θ_{SP}. These observations strongly suggest that such a peak is due to proton-proton quasi-elastic scatterings.

Further support for this interpretation comes from the analysis of the proton energy spectra at the peak position. In the case of $\theta_{TAG} = 40°$ and $\theta_{SP} = 40°$ we observed an enhancement of about 60% in the proton yield at $E_{proton}(\mathrm{lab}) \simeq 400$ MeV when the spectrometer event was in coincidence with the R-telescope. A similar correlation was also observed for Ne + NaF and Ar + KCl cases. Therefore we conclude that direct proton emission is taking place in these collisions and that the assumption of thermal equilibrium is not tenable for such processes.

In the case of C on Pb we have not observed such correlations. In this case the ratio C is even smaller than 1. In heavy nuclei the expected higher average multiplicities as well as multiple scatterings will have the effect of causing the value C to approach 1 even if quasi-elastic scattering takes place. Furthermore, nuclear shadowing can cause $C < 1$. We are now making a systematic analysis of two-particle correlations in order to determine the fraction of direct emission and also to study the shadowing effect, as a function of projectile mass, energy, and target mass.

In conclusion, we learned that high energy proton inclusive spectra are characterized by exponential slopes which various theoretical models explain quite well. Deviations from exponentials for low-energy protons in the CM frame are still open to further studies. In two particle correlations the data show non-thermal behavior at least for light nuclei.

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REFERENCES

1. For recent reviews of relativistic heavy-ion physics see H. Steiner, in Proc. VIIth Int. Conf. on High-Energy Physics and Nuclear Structure, Zurich, 1977, M. P. Locher, ed. (Birkhauser Verlag, Basel and Stuttgart, 1977), p. 261; A. M. Poskanzer, in Proc. Int. Conf. Nuclear Structure, Tokyo, 1977, J. Phys. Soc. Japan 44 (1978), Suppl. p. 760. Also see A. S. Goldhaber and H. H. Heckman, Ann. Rev. Nucl. Sci. 27 (in press).
2. G. D. Westfall, J. Gosset, P. J. Johansen, A. M. Poskanzer, W. G. Meyer, H. H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. 37, 1202 (1976).
3. J. Gosset, H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall, Phys. Rev. C16, 629 (1977).
4. H. H. Heckman, H. J. Crawford, D. E. Greiner, P. J. Lindstrom, and Lance W. Wilson, Phys. Rev. C17, 1651 (1978).
5. W. D. Myers, Nucl. Phys. A296, 177 (1978).
6. J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C (in press).
7. Y. Kitazoe and M. Sano, Proc. Int. Conf. Nuclear Structure, Tokyo, 1977, J. Phys. Soc. Japan 44 (1978), Suppl. p. 386.
8. I. A. Schmidt and R. Blankenbecler, Phys. Rev. D15, 3321 (1977).
9. R. L. Hatch and S. E. Koonin, Caltech preprint (1978).
10. J. Randrup, Phys. Lett. B (in press).
11. H. J. Pirner and B. Schürmann, Saclay preprint (1978).
12. R. K. Smith and M. Danos, private communication (1978).
13. Z. Fraenkel, private communication (1977).
14. S. E. Koonin, Phys. Rev. Lett. 39, 680 (1977).

15. S. Nagamiya, I. Tanihata, S. Schnetzer, L. Anderson, W. Brückner, O. Chamberlain, G. Shapiro, and H. Steiner, Proc. Int. Conf. Nuclear Structure, Tokyo, 1977, J. Phys. Soc. Japan 44 (1978), Suppl. p. 378.

16. Cross section values for all the cases plotted in the laboratory frame as well as those plotted in the y-p_T/m_pc plane will be available in an LBL report in the near future.

17. For this calculation the authors would like to thank J. Gosset and G. D. Westfall.

18. S. Das Gupta, Lawrence Berkeley Laboratory Report LBL-7749 (1978).

19. P. Siemens, private communication (1978).

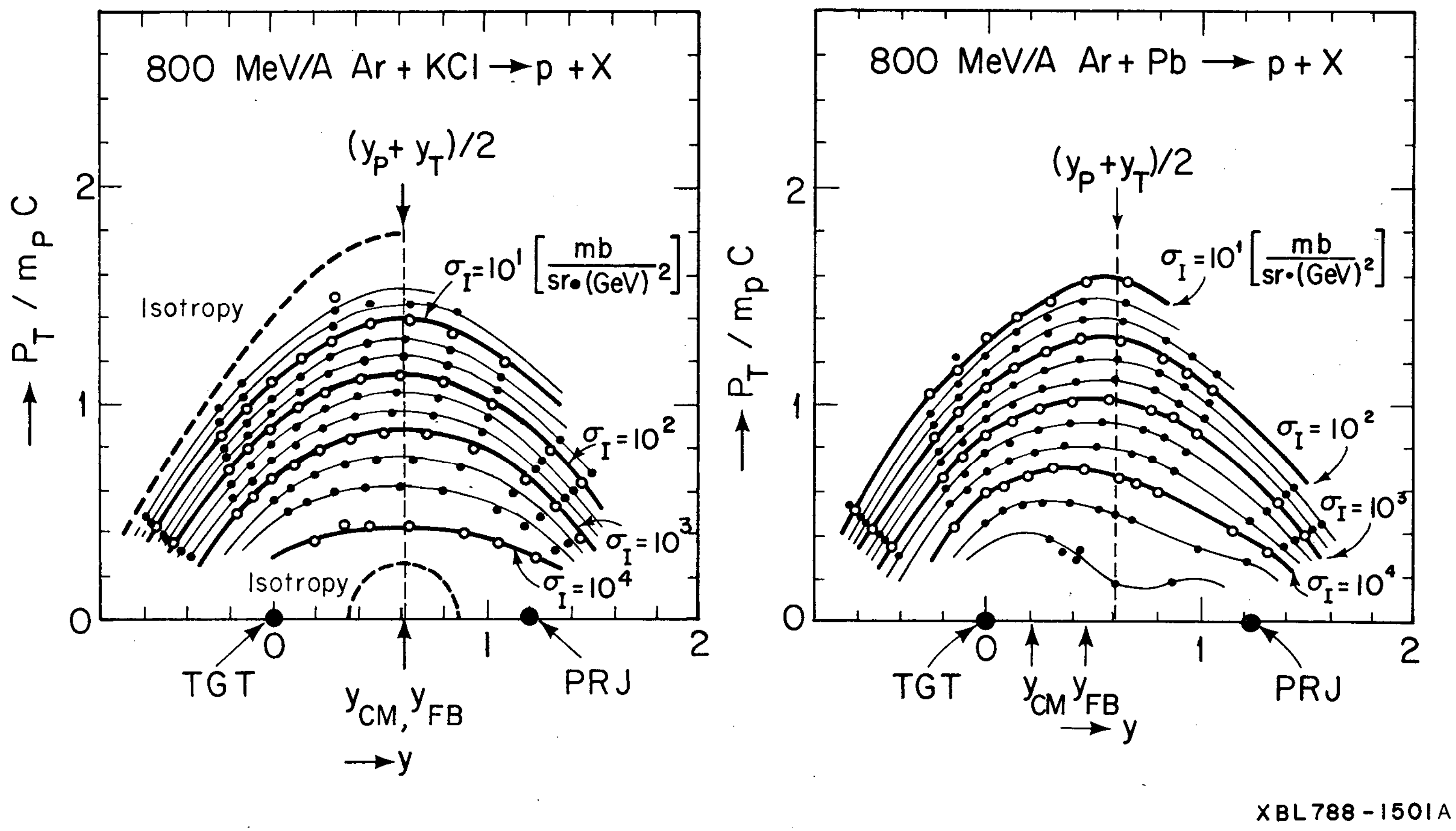
FIGURE CAPTIONS

FIG. 1. Contour plots of cross sections in the rapidity - p_T/m_pc plane for (a) 800 MeV/A Ar + KCl → p + X (left) and (b) 800 MeV/A Ar + Pb → p + X (right).

FIG. 2. Proton energy distributions along $y = (y_P + y_T)/2$ in the nucleon-nucleon CM frame. High-energy protons are approximately described by $\sigma_0 \cdot \exp(-E_K/E_0)$. The slope factor E_0 shown here has an error of ±5 MeV. Two theoretical models are compared with the data: the firestreak model of Ref. 6 and the hard-scattering model of Ref. 9.

FIG. 3. (a) Experimental configuration for two-particle correlation measurements.

(b) Degree of coplanarity C for all charged particle emission plotted as a function of the spectrometer angle θ_{SP}. Absolute scale of vertical axix is reliable within an error of ±0.1.

800 MeV/A Ar + KCl → p + X
$(y_P + y_T)/2$
$\sigma_I = 10^1$ $\left[\frac{mb}{sr \cdot (GeV)^2}\right]$
$\sigma_I = 10^2$
$\sigma_I = 10^3$
$\sigma_I = 10^4$
Isotropy
Isotropy
$\rightarrow P_T / m_P C$
0
1
2
0
1
2
TGT
PRJ
y_{CM}, y_{FB}
$\rightarrow y$
800 MeV/A Ar + Pb → p + X
$(y_P + y_T)/2$
$\sigma_I = 10^1$ $\left[\frac{mb}{sr \cdot (GeV)^2}\right]$
$\sigma_I = 10^2$
$\sigma_I = 10^3$
$\sigma_I = 10^4$
$\rightarrow P_T / m_P C$
0
1
2
0
1
2
TGT
y_{CM}
y_{FB}
$\rightarrow y$
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XBL788-1501A

Fig. 1

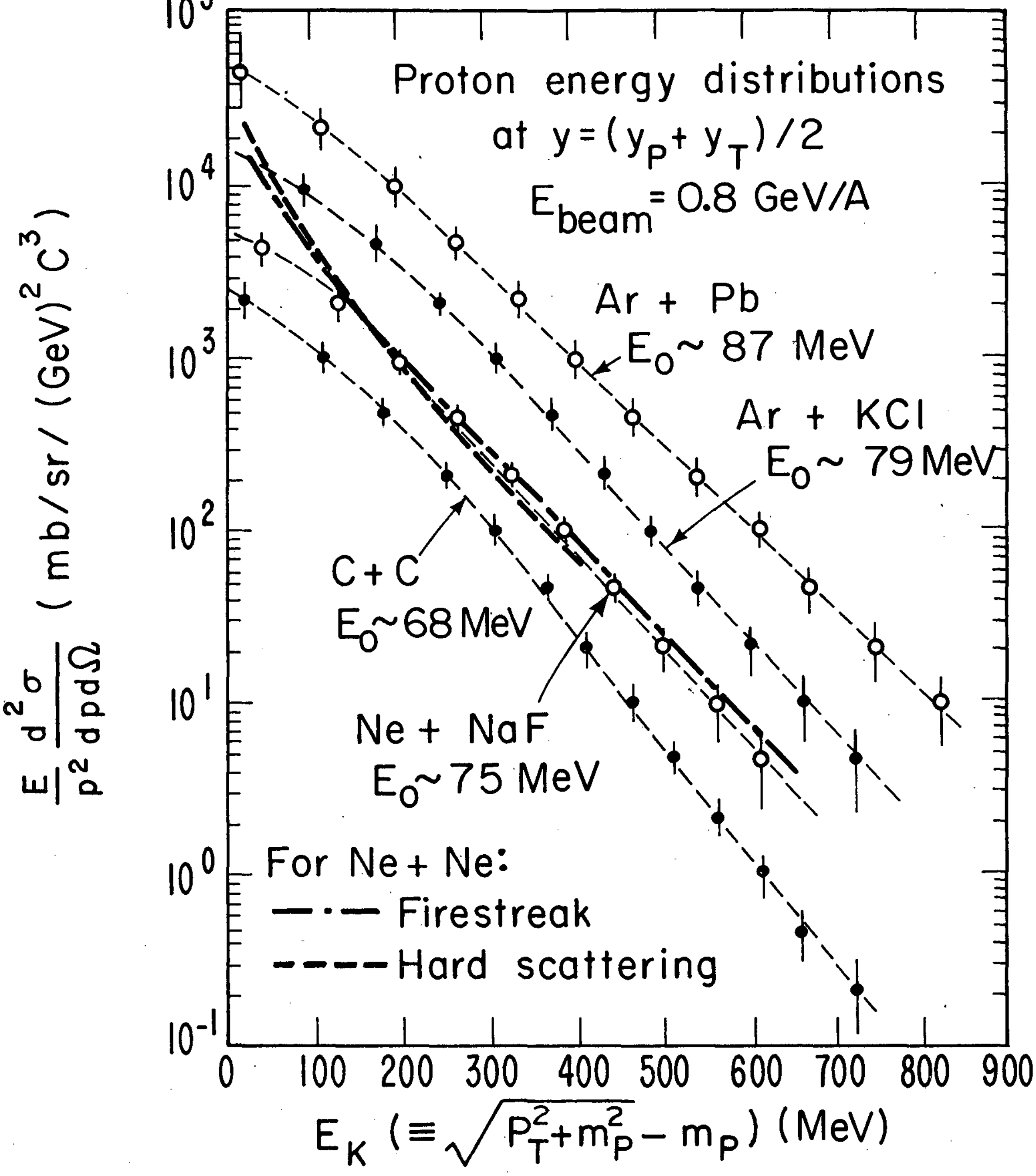

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Fig. 2

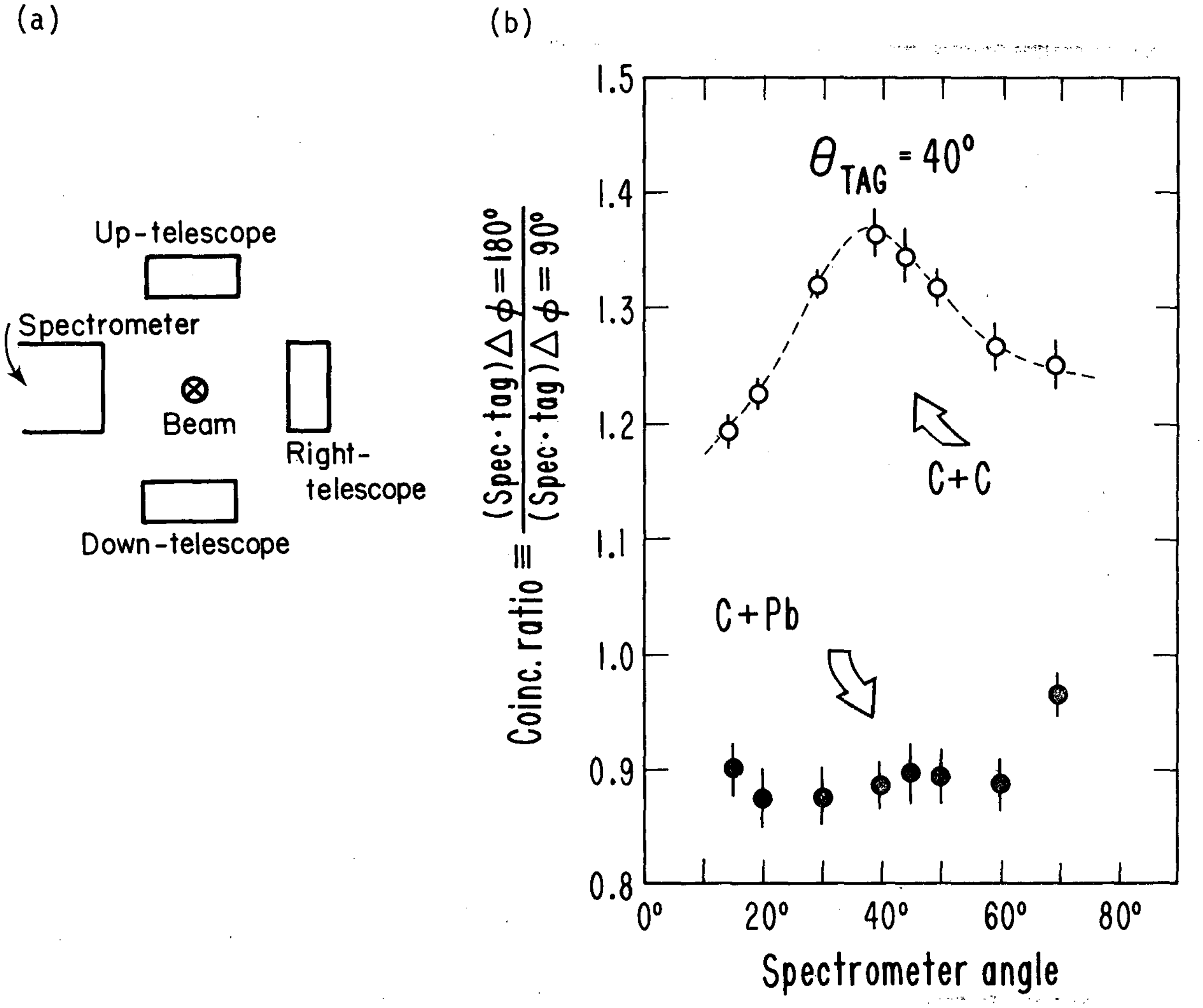

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Fig. 3

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