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INTERSECTING STORAGE RINGS COMMITTEE

A Proposal for an Experiment

THE FLUX AND ENERGY SPECTRUM OF γ-RAYS RESULTING FROM p-p COLLISIONS IN THE INTERSECTING STORAGE RING AT CERN

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A Proposal to Study the Flux and Energy Spectrum of Gamma Rays at Various Angles in p-p Collisions From ISR at CERN

Experimental Group	:	The Tata Institute of Fundamental Research, Colaba, Bombay 5, India
Spokesmen	:	Dr. R.R. Daniel and Dr. P.K. Malhotra
Beams	:	28 GeV ISR (colliding beams)
Intensity	:	Interaction rate between 10^4 and 1.6×10^5 $\sec^{-1}$ is acceptable.
Emulsions	:	Ten stacks each of 10-G5 pellicles of dimensions 10 cm x 10 cm x 0.06 cm to be exposed at angles ranging from 5° to 90°.

1. MAIN OBJECTIVES

1.1 Experimental

In this experiment it is proposed to study in great detail, gamma rays emitted from interactions arising from the ISR colliding beams. Measurements will be made of the flux and energy spectra of the gamma rays at angles varying from about 5° to 90° with respect to one of the beams. Nuclear emulsions will be used as the detector in this experiment. As special advantages of using nuclear emulsions here, we would like to enumerate and emphasise the following: (a) In the region of gamma ray energies we deal with in this experiment, namely, about a hundred MeV to a few GeV, a simple measurement of the opening angle of the electron-positron pair will yield reliable and sufficiently accurate estimates of the gamma ray energy. Wherever necessary, these measurements can be supplemented by multiple Coulomb scattering measurements, which again are reliable in this energy range; (b) The direction of the gamma ray can be determined with high precision with respect to the high energy charged particle secondaries, also recorded in the emulsions; (c) Because of the high emulsion density of about 3. 8 g. cm^{-3} and the small conversion length of about 3. 7 cm in emulsion, sufficient number of gamma rays can materialise in a small volume of the detector; (d) The machine time required is relatively small and the general lay out for the experiment is simple.

While it is true that, in general, the role of nuclear emulsion as a detector in accelerator work is on the decline, the present proposal is one where it can be used with very definite advantage. The simplicity of the general layout, the small machine time required and the favourable energy region of the gamma rays where the emulsions are most well suited are factors in favour of using nuclear emulsions for this experiment. Also, the experiment can be carried out during the early period when the ISR comes into operation.

1. 2 Interpretative

Measurements of the type described above can lead to considerable amount of interesting physics, because of the detailed knowledge we will be able to gather about the intensity and spectrum of γ-rays as a function of emission angle. We expect that sophisticated electronic instrumentation will be used by others to determine the composition, energy spectrum etc., of the charged particle secondaries. The results from these two kinds of experiments when brought together will considerably help in our understanding of particle production at these high C.M. energies. In particular, we will refer to the following: (i) The energy spectra of gamma rays at different angles of emission provide a good testing ground for particle production models at high energies, such as the thermodynamic model of Hagedorn and Ranft(1), the fire ball model and that of Pal and Peters(2); (ii) Together with information on the composition of charged particles and energy spectra of $\pi^{\pm}$ at various angles, one should be able to deduce vital information on the relative importance of possible sources of gamma rays other than neutral pions, such as η, η' etc.; (iii) It can yield information on the relative importance of isobars and the 'fire ball'; (iv) There are indications that the flux of secondary cosmic ray gamma rays of $E > 30$ GeV at balloon altitudes is about twice as large as that predicted by the model of Pal and Peters(2) which has been found to explain rather well a number of features concerning the propagation of cosmic rays in the atmosphere. This observation, if confirmed, would suggest an additional source of gamma rays besides the neutral pion. Since the C.M. energies in this case and that of the ISR are comparable, we have an opportunity of looking into this problem under controlled conditions.

It may also be emphasised, that as a fall out of this experiment, we will be able to get information on the flux and composition of charged secondary particles. For example, it will be possible to obtain the angular dependence of the momentum spectra of charged particles in the low momentum region, which is primarily determined by the emulsion stack dimensions. Table I summarises the momentum regions in which charged particles can be unambiguously identified by measurements of residual range-ionisation supplemented by decay characteristics for stopping particles, and multiple scattering-ionisation measurements for faster particles. Thus, for instance, a simple measurement of range will give us the momentum distribution of $\pi^{\pm}$ - below about 200 MeV/c (for 10 cm x 10 cm x 0.6 cm stack size). This can be extended to about 1 GeV/c by multiple scattering and ionisation measurements. The latter technique also enables us to obtain $\pi^{\pm}$ momentum spectrum between 3.5 - 15 GeV/c; in the region between 1.0 - 3.5 GeV/c definite identification is not possible because the g.d.- $p\beta$ curves for $\pi^{\pm}$ cross those of $K^{\pm}$ and p.

2. EXPERIMENTAL DETAILS AND EXPOSURE REQUIREMENTS

One can cover a broad range of angles by sampling at, say, 10 different positions ranging from a few degrees to around 90°. From practical considerations we assume the smallest angle to be 5°. We would thus like to have exposures at 5°, 10°, 15°, 20°, 30°, 40°, 50°, 75° and 90°.

Ten stacks of G5 emulsion, each consisting of 10 pellicles, 10 cm x 10 cm, 600 μm thick, will be used. Fig. 1 shows the exposure arrangement. In order to avoid duplication in the requirements of different experiments, we have revised this proposal keeping in mind the possibility of our using the vacuum chamber and the emulsion stands proposed by Cracow Group(4).

Table 1. Regions of momentum in which various charged particles can be identified and the momentum spectra accurately determined.

Particle	Momentum covered in residual range-ion. measurements (MeV/c)	Momentum covered in $p\beta$-ion. measurements (GeV/c)
$\pi^{\pm}$	< 200	< 1.0 (and 3.5-15)
$K^{\pm}$	< 400	< 1.1
p	< 650	< 1.7 (and 3.5-15)
$\Sigma^{\pm}$	< 750	-

The rate of γ-rays incident on a unit area of the stack is given by

$$F_{\gamma}(\theta) = \frac{dN_{\gamma}(\theta)}{d\Omega} \cdot \frac{\Delta\Omega}{A} \cdot R_{pp}$$

where, $dN_{\gamma}(\theta)/d\Omega$ is the differential angular distribution of γ-rays produced at 50 GeV C.M. energy.

$\Delta\Omega = A/r^2$ is the solid angle subtended by the stack with face area A and at a distance r from the intersection region.

R_{pp} is the rate of pp interactions in the colliding beams.

Regarding the angular distributions of γ-rays at about 50 GeV C.M. energy, the best one can do at this stage is to use the predictions of the thermodynamic model of Hagedorn and Ranft(1). The number* of γ-rays per steradian

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[*] We are grateful to Dr. C. Daum of CERN and Dr. S. N. Ganguli for supplying these numbers to us.

per pp interaction is shown in Fig. 2 as well as given in Table 2 for each angle at which exposure is required.

Table 2. The flux (cm^{-2} hr^{-1}) of γ-rays at a distance of 2 meters from the interaction region on the basis of Hagedorn and Ranft's model, and the resulting exposures times for a constant density of $e^{\pm}$-pairs corresponding to a passage of 3×10^3 γ-rays/cm^2 through each stack. These have been worked out for two different values of pp interaction rate.

θ	$\frac{dN_\gamma}{d\Omega}$ $sterad^{-1}$	F_γ $cm^{-2}.hr^{-1}$		Exposure Time hr	
		$R_{pp} = 1.6 \times 10^5$ sec^{-1}	$R_{pp} = 10^4$ sec^{-1}	$R_{pp} = 1.6 \times 10^5$ sec^{-1}	$R_{pp} = 10^4$ sec^{-1}
5°	16.5	2.4×10^5	1.5×10^4	0.013	0.2
10°	7.2	1.1×10^5	6.9×10^3	0.030	0.5
15°	3.6	5.1×10^4	3.2×10^3	0.062	1.0
20°	1.9	1.8×10^4	1.1×10^3	0.16	2.5
30°	0.80	1.2×10^4	7.5×10^2	0.17	2.8
40°	0.61	8.4×10^3	5.2×10^2	0.37	5.9
50°	0.50	6.6×10^3	4.1×10^2	0.47	7.5
60°	0.42	6.0×10^3	3.8×10^2	0.52	8.3
75°	0.37	5.5×10^3	3.4×10^2	0.57	9.1
90°	0.35	5.1×10^3	3.2×10^2	0.62	9.9
5°-40°	-	-	-	0.16	2.5
50°-90°	-	-	-	0.50	8.0

The choice of the distance (r) from the interaction region depends on the p-p interaction rate, the reasonability of the exposure times required for acceptable density of pairs in the stacks, and for small angles the proximity of the edge of the stand holding the emulsion stacks to the beam line. In this revised version of the proposal we have chosen r = 2m because of the possibility of our using the same vacuum chamber and the emulsion stands as suggested by the Cracow Emulsion Group in their revised proposal(4).

The stack offers a useful irradiation area of $8 \times 0.6 = 4.8$ cm^2. This results in a solid angle of $\Delta\Omega = 1.2 \times 10^{-4}$ steradian.

In order to minimise the background contribution due to secondary interactions in the emulsion, we propose to restrict the scanning to $e^{\pm}$-pairs to within 1 cm from the entry. This corresponds to a conversion probability of 0.23.

From our previous experience of work with γ-rays from p-carbon interactions at 24 GeV and π^--carbon interactions at 16 GeV, and taking into account the density of charged secondaries as also the general stray background(5), we feel that a comfortable density of $e^{\pm}$-pairs is about one per 25 fields, 0.03 cm x 0.03 cm, or equivalently one pair in an emulsion volume of 1.3×10^{-3} cm^3. This leads to a total of 3.5×10^3 pairs in a useful scanning volume of 4.8 cm^3 for each angle. Thus, if the exposure is designed to correspond to these considerations, we should have enough pairs, at each angle, to carry out the experiment, even if our exposure estimates are under by a factor of 2 or 3.

The above number of pairs result from a total of 1.5×10^4 incident γ-rays on an area of 4.8 cm^2 at a distance $r = 2m$. This corresponds to 3×10^3 γ-rays/cm^2. Thus, the overall consideration in arriving at the exposure times needed is to match this requirement of the γ-rays that should pass through the stack.

In order to calculate the exposure times, one needs to know the interaction rate. The design value of luminosity of the ISR for beam-beam interactions is 4×10^{30} cm^{-2} sec^{-1}, which, for $\sigma_{pp} = 40$ mb, corresponds to an interaction rate of $R_{pp} = 1.6 \times 10^5$ sec^{-1}. We have assumed this value in our calculations. However, it is possible that this design value may not be achieved in the initial stage of the commissioning of ISR. We have, therefore, also done the calculations using a nominal figure of 10^4 sec^{-1} for the interaction rate.

2.1 Exposure Times Required

The exposure times so obtained are given in Table 2 for the two assumed values of the interaction rate. It is clear that since the exposure times vary by a factor of 50 between 5° and 90°, it is not advisable to have one exposure time for all the angles. It may, however, be adequate to have two exposures, one for the 6 stacks, 5° to 40°, and the other for the 4 stacks, 50° to 90°. These are also listed in the last two rows of the Table 2, for the two assumed values of the interaction rates. Thus, if $R_{pp} = 1.6 \times 10^{+5}$ sec^{-1} we would like to have about 10 min exposure for the 6 smallest angle stacks and 30 min for the 4 largest angles. However, if $R_{pp} = 10^4$ sec^{-1} then the corresponding two values of the exposure times are 2.5 hr and 8 hr respectively.

It is not clear to us whether the vacuum chamber, designed for experiments such as these, will be suitable for the 5° and 10° exposures also. If for some reason this is not possible then perhaps another way could be found to take these two exposures. In that case it would be better to have $r \geqslant 4$m, so that exposure times are not too short.

3. BACKGROUND

There are mainly two types of background which are likely to affect an experiment such as proposed here.

The first type of background is the general radiation which causes the overall blackening of emulsion. This is chiefly due to particles produced, (i) in beam-gas collisions outside the interaction region, (ii) in collisions of the outer fringes of the beam with the walls of the vacuum chamber and (iii) as a result of induced radioactivity in the general vicinity. All or most of this background can be distinguished from the 'signal' by a simple measurement of the direction of the particle. However, as this background leads to general blackening of emulsion it makes scanning difficult and tortuous, if its level is very large. It is difficult to estimate the intensity of this kind of background. It is therefore, important to determine this by carrying out a test exposure prior to the actual exposure. One can, however, get some idea about this kind of background from the preliminary experimental studies due to Agoritsas et al(5). According to their results, we may expect an intensity of roughly 10^4 particles

$cm^{-2} hr^{-1}$. While this level is not serious, it would be highly desirable to reduce it further by installing adequate shielding close to the vacuum chamber as suggested by the Cracow Group(4).

The second kind of background is more serious as it cannot be distinguished from the 'signal'. This is due to the photons produced in beam-gas collisions in the interaction region. We have estimated this contribution in the following way.

We assume the angular distribution of the photons to be the same as that of charged shower particles as experimentally obtained by Winzeler(6) in a study of p-p collisions at 24 GeV. We reduce this to absolute flux by noting that the shower particle multiplicity is 4.0 and $n_\gamma \approx n_{\pi^\pm} = 3.0$. The angular distribution of photons so obtained is shown in Fig. 2.

We have carried out these calculations for three different sets of parameters, given in Table 3. We have assumed(7) that the composition of gas is 97% H_2 and 3% CO and have considered two values of pressure, 10^{-11} torr and 3×10^{-11} torr, in the interaction region.

Table 3

Set	Pressure torr	Composition of gas (%)		N_p
		H_2	CO	
A	10^{-11}	97	3	4×10^{14}
B	3.10^{-11}	97	3	4×10^{14}
C	3.10^{-11}	97	3	10^{14}

As in beam-beam interactions we have used two figures for the number of protons circulating, viz. $N_p = 4 \times 10^{14}$ and 10^{14} corresponding to beam-beam interaction rates of 1.6×10^5 $\sec^{-1}$ and 10^4 $\sec^{-1}$, respectively. We assume $\sigma_{pp} = 40$ mb and the average of σ_{p-C} and $\sigma_{p-O} = 380$ mb.

The calculations for each angle, are done only for contribution of gas in the respective visible length of the beam, i. e., corresponding to the projection of beam-beam region.

Because of the steepness of the angular distribution, at small angles with one of the beams, the contribution is only due to that beam, while for angles greater than about 60° it is important to take the contribution of the other beam also into account.

Table 4 summarises the results of these calculations for three different sets of parameters listed in Table 3. N_γ (b-g) is the intensity of γ-rays per cm^2 per hr, due to b-g interactions due to both the beams at the stack position 2 m from the centre of the intersection region. For comparison, we have also listed the intensity of γ-rays due to beam-beam interactions. It is clear from this table that, as far as this experiment is concerned, the background due to beam-gas interactions is not going to be important for the range of parameters considered here. This is also true, except perhaps for exposure at $\theta = 5^\circ$, even if the pressure of gas in the intersection region is as low as 10^{-10} torr, provided the number of protons circulating in each beam is not far less than 10^{14} and that the residual gas is essentially hydrogen.

Table 4. Comparison of background due to b-g collisions with the signal due to b-b interactions.

Angle	N_γ (b-g) $cm^{-2} . hr^{-1}$			N_γ (b-b) $cm^{-2} . hr^{-1}$			$\frac{N_\gamma \text{ (b-g)}}{N_\gamma \text{ (b-b)}}$ (percent)		
	A	B	C	A	B	C	A	B	C
5°	920	2800	700	2.4×10^5	2.4×10^5	1.5×10^4	0.4	1.2	4.6
10°	230	700	175	1.1×10^5	1.1×10^5	0.7×10^3	0.21	0.64	2.5
15°	85	260	65	5.1×10^4	5.1×10^4	3.2×10^3	0.17	0.51	2.0
30°	13	37	9	1.2×10^4	1.2×10^4	7.5×10^2	0.11	0.32	1.2
60°	1.7	5.1	1.3	6.0×10^3	6.0×10^3	3.8×10^2	0.03	0.09	0.3
90°	0.7	2.2	0.6	5.1×10^3	5.1×10^3	3.2×10^2	0.014	0.04	0.2

4. SCIENTIFIC AND TECHNICAL COMPETENCE

The Tata Institute of Fundamental Research has been carrying on extensive work on high energy physics using nuclear emulsions for a long time. Therefore adequate competence and facilities exist for all phases of this proposal such as design of experiment, processing of emulsions, scanning and data reduction, and interpretation.

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CAPTIONS TO THE FIGURES

1. The exposure arrangement. Two exposures are required, one for the six stacks, 5° to 40°, and the other for the 4 stacks, 50° to 90°.

2. Angular distribution of photons at 50 GeV C. M. energy as predicted by the thermodynamic model of Hagedorn and Ranft. Also shown is the angular distribution of photons, assumed to be the same as that of charged shower particles as experimentally obtained by Winzeler in a study of p-p collisions at a laboratory energy of 24 GeV.

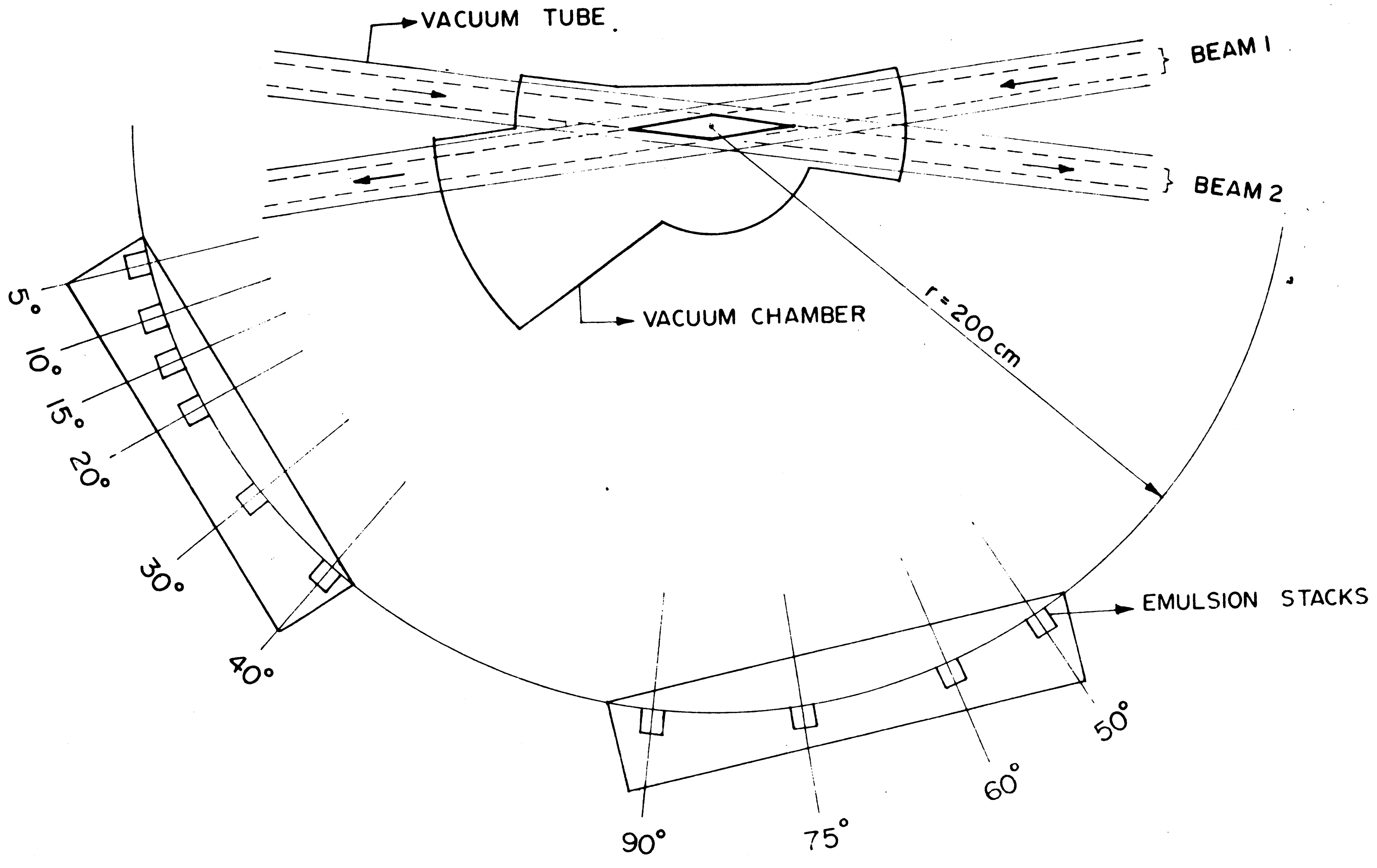
VACUUM TUBE.
BEAM 1
BEAM 2
VACUUM CHAMBER
r = 200 cm
EMULSION STACKS
5°
10°
15°
20°
30°
40°
90°
75°
60°
50°

FIG. 1

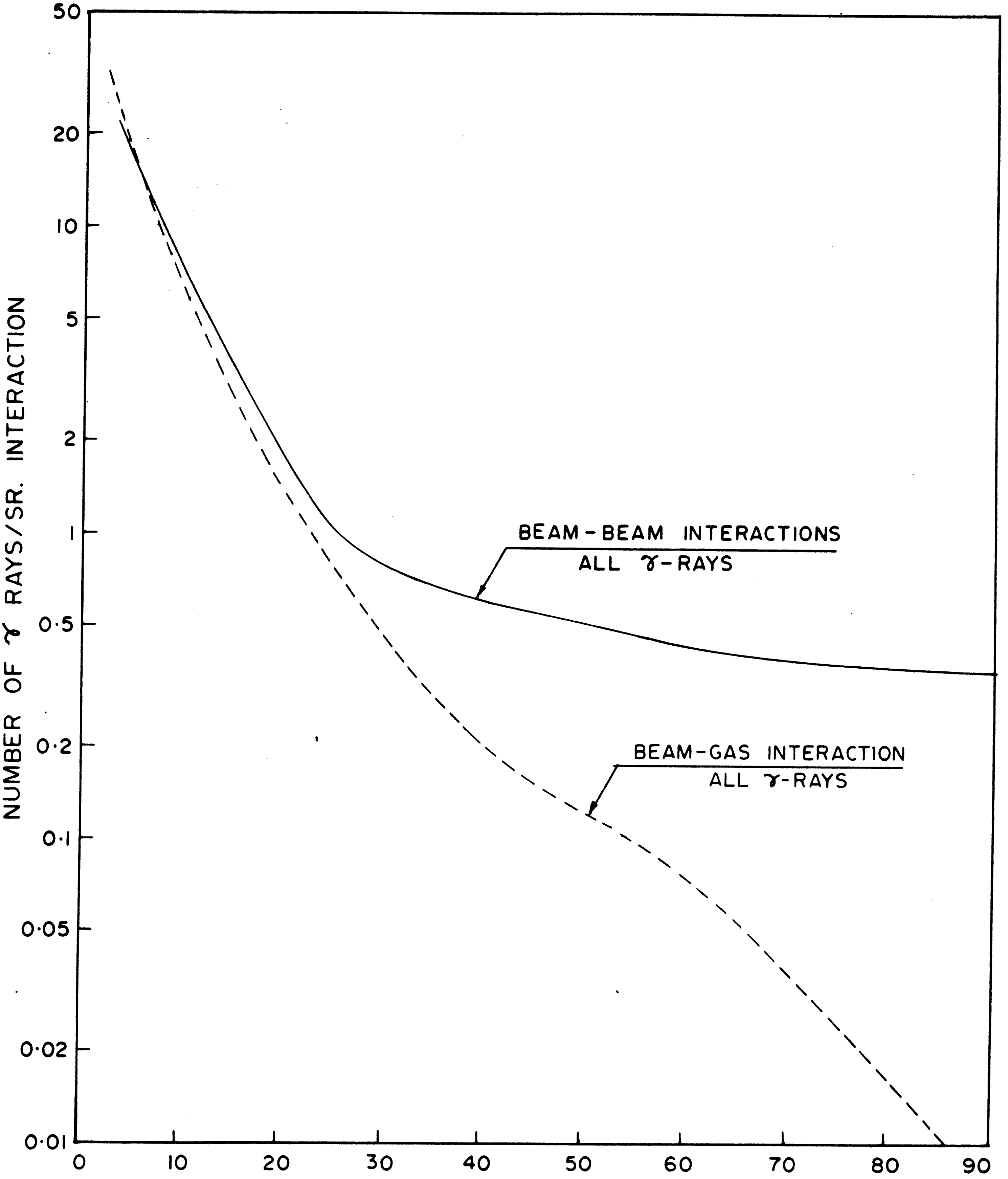
50
20
10
5
2
1
0·5
0·2
0·1
0·05
0·02
0·01
NUMBER OF γ RAYS/SR. INTERACTION
0
10
20
30
40
50
60
70
80
90
θ (DEGREES)
BEAM - BEAM INTERACTIONS
ALL γ - RAYS
BEAM-GAS INTERACTION
ALL γ - RAYS

FIG 2