PS/MU/EP/NOTE 82-13
RB/gm - 14.10.1982

ELECTRON YIELD FROM p-N COLLISIONS

(A study with KASPRO-EGS program)

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I. Introduction

The aim of this study was to calculate the electron (positron) yield resulting from proton-nucleus collisions. Protons of 24 GeV/c hit a target and initiate a hadronic cascade. The predominant production of electrons (positrons)is due to pair creation of the γ's from the π^0 decay. The electrons and positrons initiate in the target an electromagnetic cascade. Two cases are considered: a target of medium Z and a target combined of one material with low Z and a much shorter γ-electron converter of large Z. As tool for these calculations we used two existing programs: 1) KASPRO and 2) EGS.

EGS (see Ref. 1) calculates the electromagnetic cascade and the various interactions, as annihilation, Bhabba scattering, Møller scattering, bremsstrahlung, multiple elastic scattering of $e^{\pm}$, pair production, Compton scattering, photo effect etc. EGS is well documented in Reference 1 and available at CERN.

KASPRO calculates the hadronic cascade and is described in Refs. 2, 3, 4, but there is only a short write-up for the use of the program.

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A combination of both programs was already applied by J. Ranft and W.R. Nelson, Refs. 5, 6, 7, but no documentation or write-up - how to use it - is available.

Both programs use a weighted Monte-Carlo simulation of all the processes.

II. Tests and calculations

1. Test of KASPRO with SPUKJ

We used KASPRO for the simulation of the π^+ production from a copper target. The target was a copper cylinder (radius 1 cm, length 7,77 cm). About 10^6 incident protons (24 GeV/c) were used for the calculation in runs with and without Coulomb interaction. The bins in angle were 10 mrad. The output is compared with the particle production of the program SPUKJ, Ref. 8. The results from the two programs were in agreement and no significant difference was found except KASPRO runs yield in larger statistical fluctuations. In Figure 1a we show the results for the bin 0-10 mrad, in Figure 1b the bins 40-50 mrad. In KASPRO less statistical fluctuations occur at larger production angles due to the corresponding larger space angle*. The test proved that KASPRO is applicable for calculations using production targets**.

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* The bin size $\Delta\Theta$ of the opening angle Θ can be chosen by the input in KASPRO, but all bins correspond then to the same $\Delta\Theta$.

** The value BFR (the weighted forward-backward ratio, see input) was 0,05. One run with BFR = 20 shows no significant difference. The cut PTHR was 0,5 GeV/c (threshold momentum).

2. Run with KASPRO-EGS

The combined version KASPRO-EGS was used to calculate the electron yields of a target of one material as well as a target-converter combination*. The first target** consisted of a cylindrical Be-target of 9,7 cm length and a W-converter of 0,3 cm length. A second run was done with 19,7 cm Be and 0,3 cm W. In a third run with KASPRO-EGS a 10 cm long copper target (without converter) was used, characteristics of the target materials are given in Table 1. In the EGS part we applied an energy cut of 500 MeV, in the KASPRO part one of 600 MeV. The radius of the targets was set to 0,5 cm. This dimension was still large compared to the "beam size" at the exit of the target. We used $5 \cdot 10^3$ incident protons of 24 GeV/c momentum.

TABLE 1

Characteristics of target and converter material

from: Review of particle properties, Rev. of Mod. Physics 52, 2, 1980

Z	A	λ_c Collision length	λ_a absorption length	λ_R Radiation length
Be 4	9,01	30 cm	36,7 cm	35,3
Al 13	26,98	25,5 cm	37,2 cm	8,9
Cu 29	63,54	9,3 cm	14,8 cm	1,43
W 74	183,85	5,6 cm	10,3 cm	0,35

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* The hadronic cascade using KASPRO can be calculated in one material only, but the calculation of the electromagnetic cascade in EGS allows to use different materials for target and converter. Therefore the interaction length λ_a (hadronic cascade) in the converter has to be small compared to the interaction length λ_a in the target.

** A target length of about 10 cm corresponds to the length of targets, used in the present beams of the PS areas.

III. Results of the calculations

The yield of electrons and positrons from p-nucleus collisions are shown in Fig. 2 for two production angles (angular bins 0-10 mrad and 50-60 mrad for the 9,7 cm Be-target + W-converter). In Figs. 3a and 3b the $(e^{+}+e^{-})$-yield* from the various targets are shown. A larger yield of $e^{\pm}$ is obtained from the Be-target with W-converter (compared to the Cu-target of the same length), especially for the higher $e^{\pm}$-momenta. This can be understood: a) the total length (10 cm) of the Cu-target corresponds to 7 radiation lengths (the mean $e^{\pm}$-energies are too much degraded); b) the W-converter (high Z) at the end of the Be-target is efficient since $e^{\pm}$ pair creation is proportional to Z^2.

The smaller production rate of π^{o} in low Z targets is of minor importance compared to the $e^{\pm}$-yield increase due to a γ-converter (1 radiation length of a material with high Z).

In Fig. 4 the result of calculation of the e^{-}-rate in a "negative beam" is shown. π^{-}-spectra from SPUKJ are used and properly normalized to be compared with $e^{\pm}$-production from KASPRO-EGS. The statistical accuracy is poor for momenta in the range of 5 to 10 GeV/c, however, the general trend is confirmed by various measurements in the test beams c_{13} and t_6 (Ref. 10).

Note that the population of e^{+} and e^{-} in the momentum bin 0 to 1 GeV/c may be larger in reality, since in the calculations a momentum cut at 0.6 GeV/c is applied.

In conclusion: Targets of light material (small Z) followed by a thin converter (large Z) are preferable compared to medium Z targets to obtain large $e^{\pm}$-yields. There is still a gain in $e^{\pm}$-yield by using rather long targets of light material ($\sim$ 2/3 of an absorption length or even more).

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* In the Figs. 2 and 3 the yield $N(e^{+}+e^{-})$ is plotted as a function of $e^{\pm}$ momentum. No significant variation is expected for e^{+} and e^{-} distributions at the e^{+} or e^{-} momenta of our interest (> 1 GeV/c).

For very short targets ($\lesssim$ 1 cm) the $e^\pm$-rate in a secondary beam may increase with heavier target material (larger Z), but obviously the yields are low. This is suggested by measurements, Ref. 9.

Finally it should be remarked that the yield of $e^\pm$-production in p-N collisions is strongly dependent on the $(e^\pm)$ secondary momentum and on the momentum of the primary protons. The yield for a not too large range of $e^\pm$-momenta may be optimized by the choice of the target size and material.

Acknowledgement

The author would like to thank L. Hoffmann for continuous support and many stimulating discussions. The help of P. Aarnio and G.R. Stevenson with the program KASPRO is gratefully acknowledged, as well as the comments and corrections to Annex 1 by J. Ranft.

Finally, I would like to thank for the hospitality at CERN during the time of my visit.

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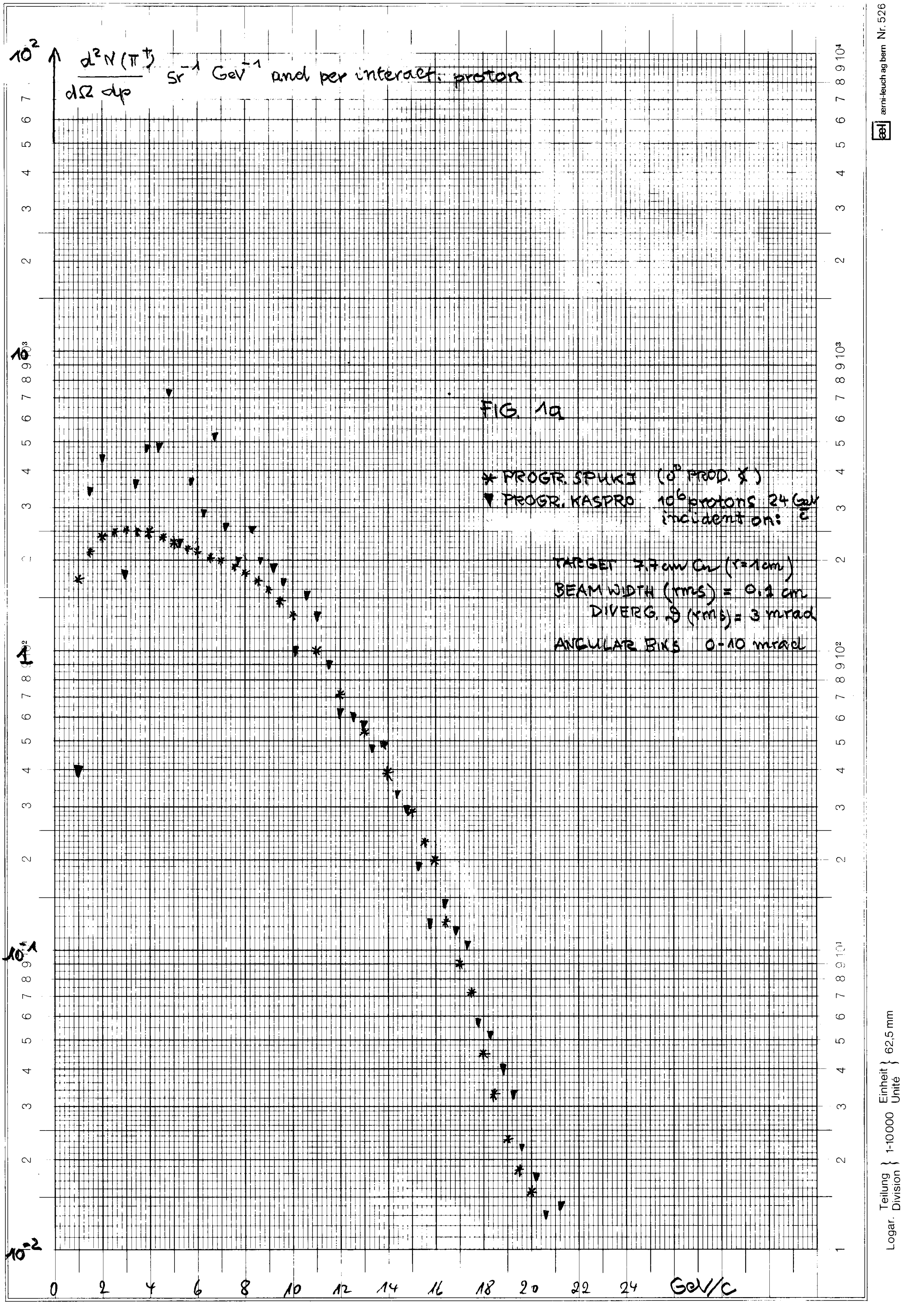

FIG. 1a

10^2
$\frac{d^2N(\pi^+)}{d\Omega\, dp}$ sr^{-1} GeV^{-1} and per interact. proton
10
1
10^{-1}
10^{-2}
0
2
4
6
8
10
12
14
16
18
20
22
24
GeV/c
* PROGR. SPUKI (0° PROD. γ)
▼ PROGR. KASPRO
10^6 protons 24 GeV/c incident on:
TARGET 7.7 cm Cu (r=1cm)
BEAM WIDTH (rms) = 0.1 cm
DIVERG. ϑ (rms) = 3 mrad
ANGULAR BINS 0-10 mrad

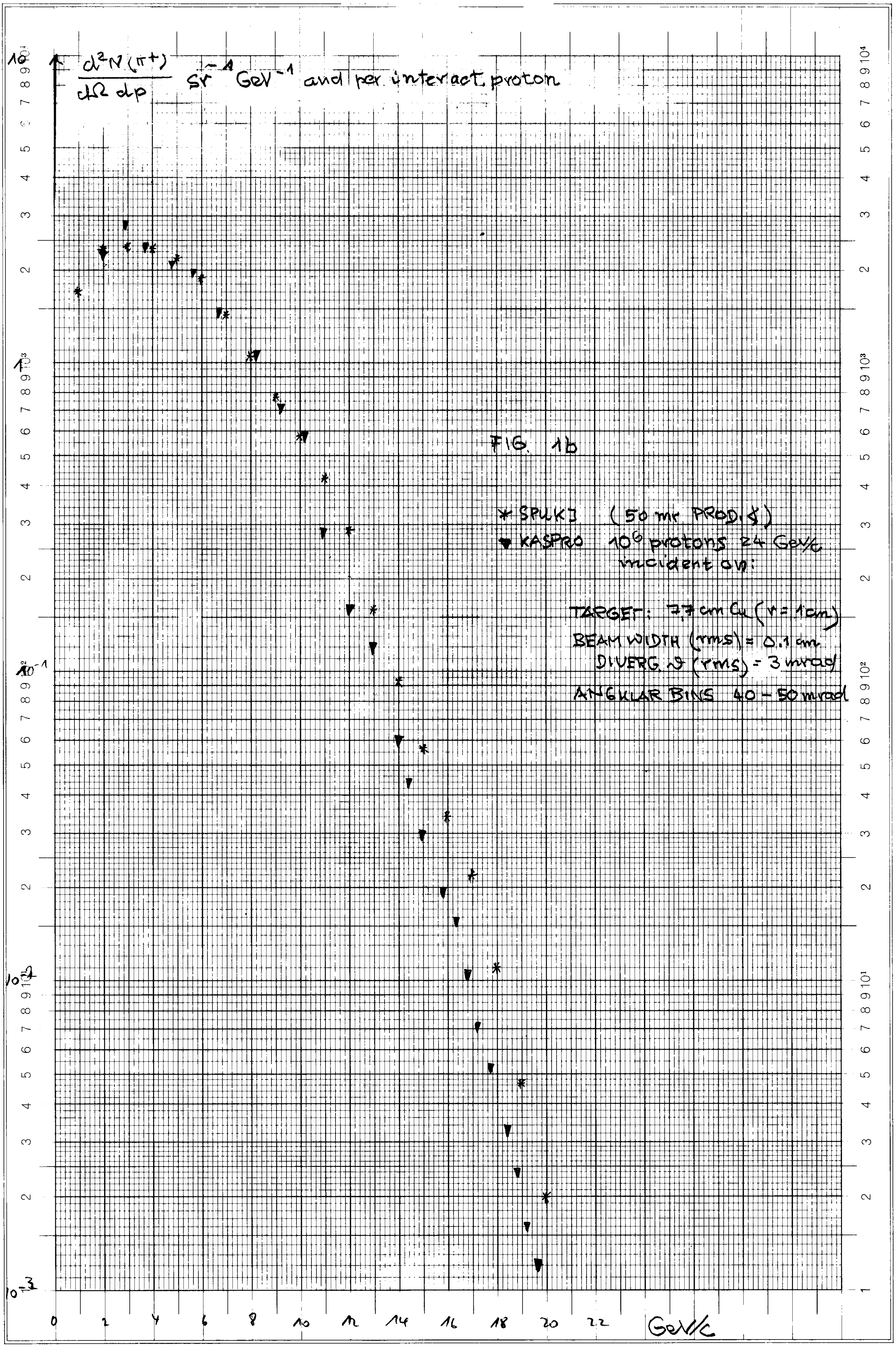

FIG. 1b

* SPUKI (50 mr PROD. ∢)
▼ KASPRO 10^6 protons 24 GeV/c incident on:

TARGET: 7,7 cm Cu (r = 1 cm)
BEAM WIDTH (rms) = 0.1 cm
DIVERG. ϑ (rms) = 3 mrad

ANGULAR BINS 40 – 50 mrad

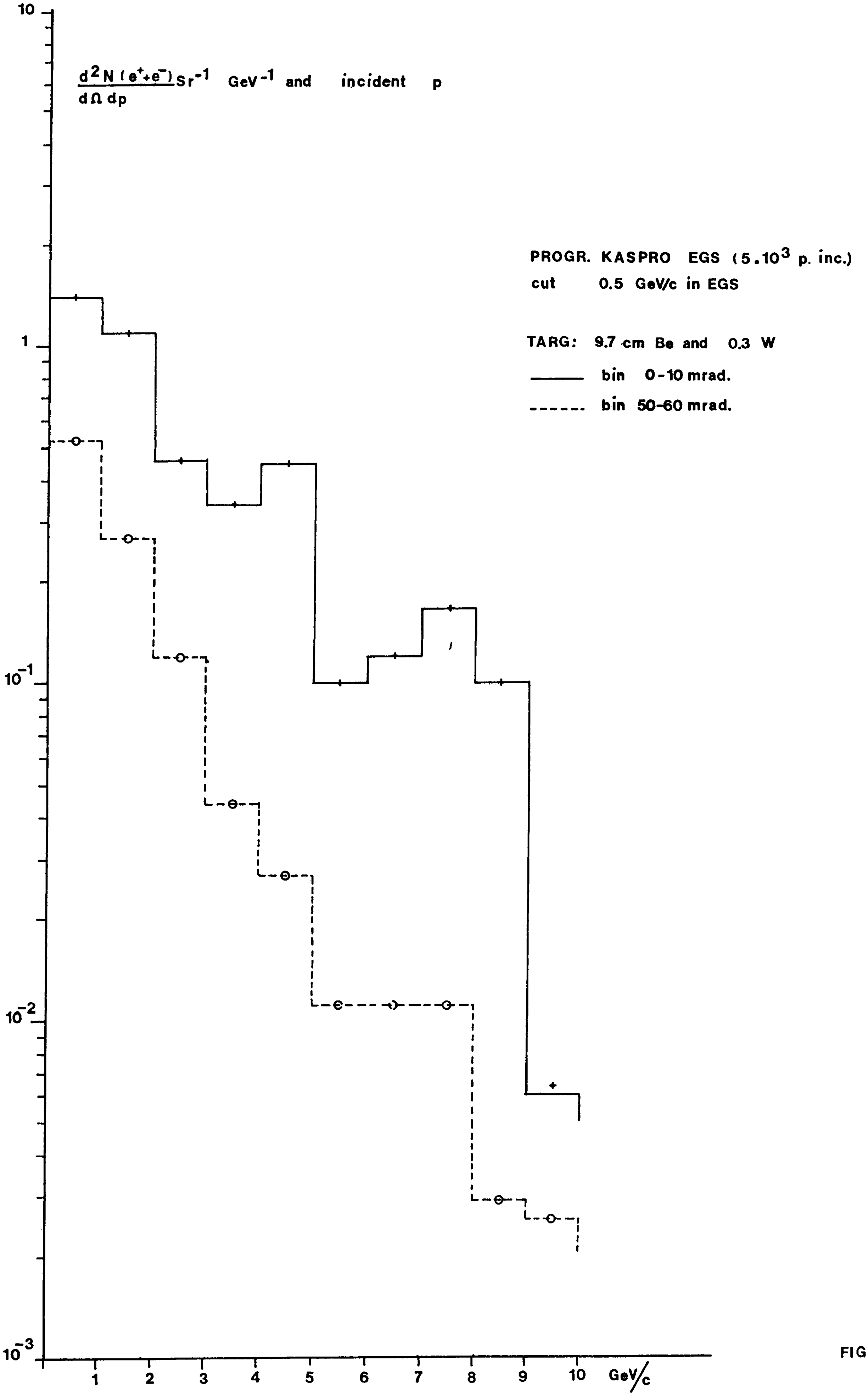
10
1
10^{-1}
10^{-2}
10^{-3}
$\frac{d^2N(e^+ + e^-)}{d\Omega\, dp}$ Sr^{-1} GeV^{-1} and incident p
PROGR. KASPRO EGS ($5 \cdot 10^3$ p. inc.)
cut 0.5 GeV/c in EGS
TARG: 9.7 cm Be and 0.3 W
bin 0-10 mrad.
bin 50-60 mrad.
1
2
3
4
5
6
7
8
9
10
GeV/c

FIG. 2

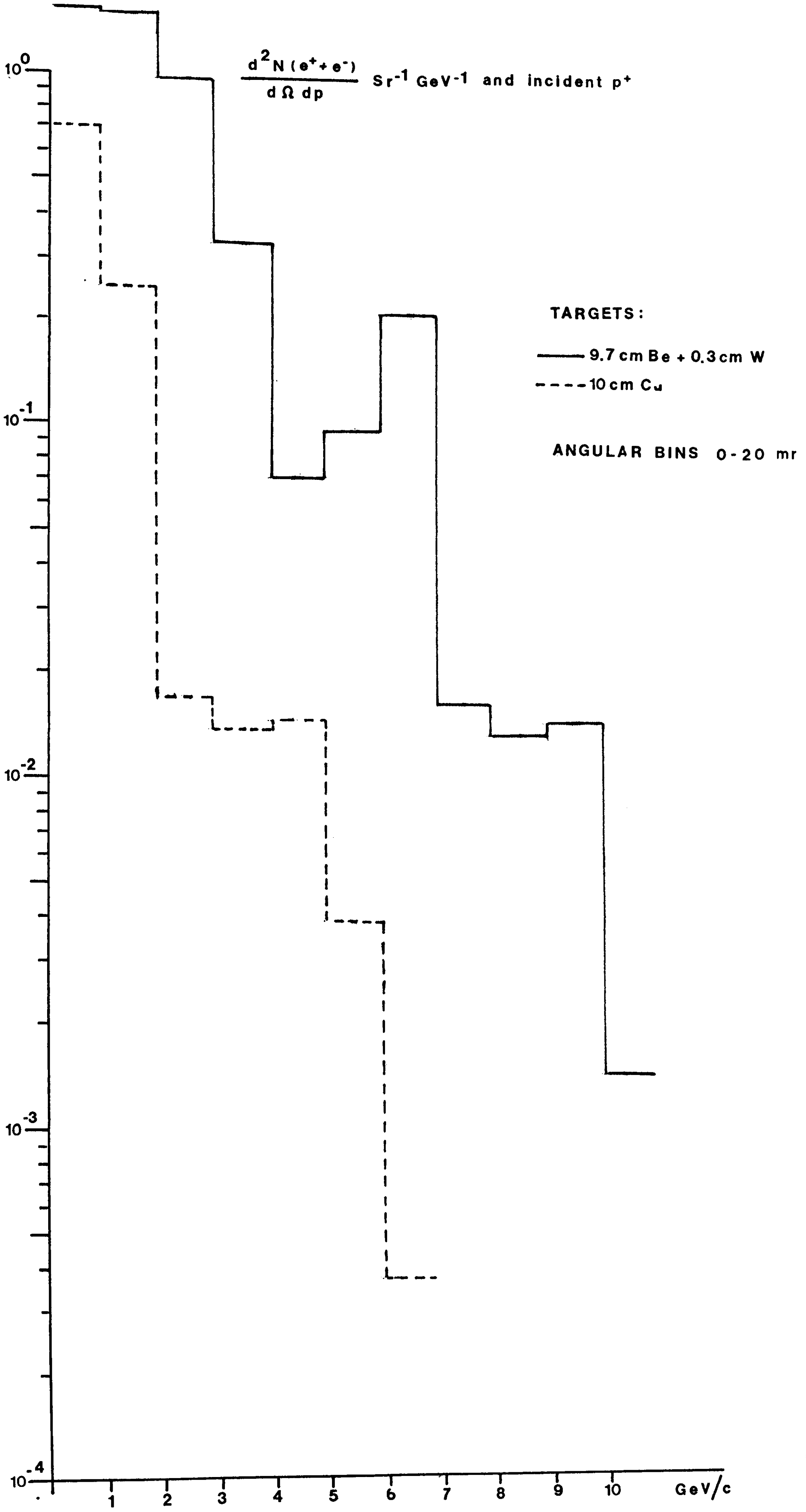
$\frac{d^2N(e^+ + e^-)}{d\Omega\, dp}$ Sr^{-1} GeV^{-1} and incident p$^+$
TARGETS:
9.7 cm Be + 0.3 cm W
10 cm Cu
ANGULAR BINS 0-20 mr
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
2
3
4
5
6
7
8
9
10
GeV/c

FIG.3a

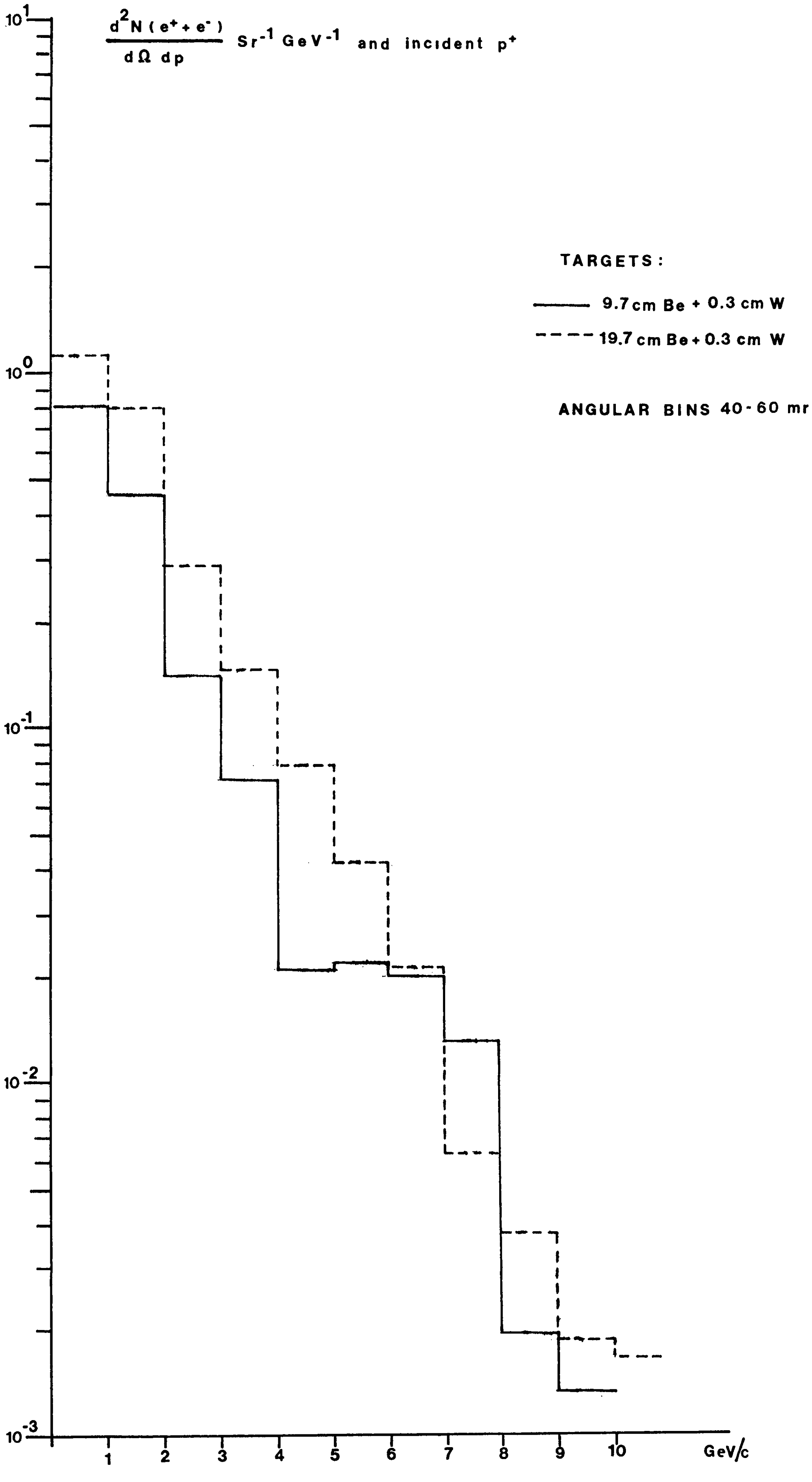
$\frac{d^2N(e^+ + e^-)}{d\Omega\, dp}$ Sr^{-1} GeV^{-1} and incident p^+
TARGETS:
9.7 cm Be + 0.3 cm W
19.7 cm Be + 0.3 cm W
ANGULAR BINS 40-60 mr
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
1
2
3
4
5
6
7
8
9
10
GeV/c

FIG.3b

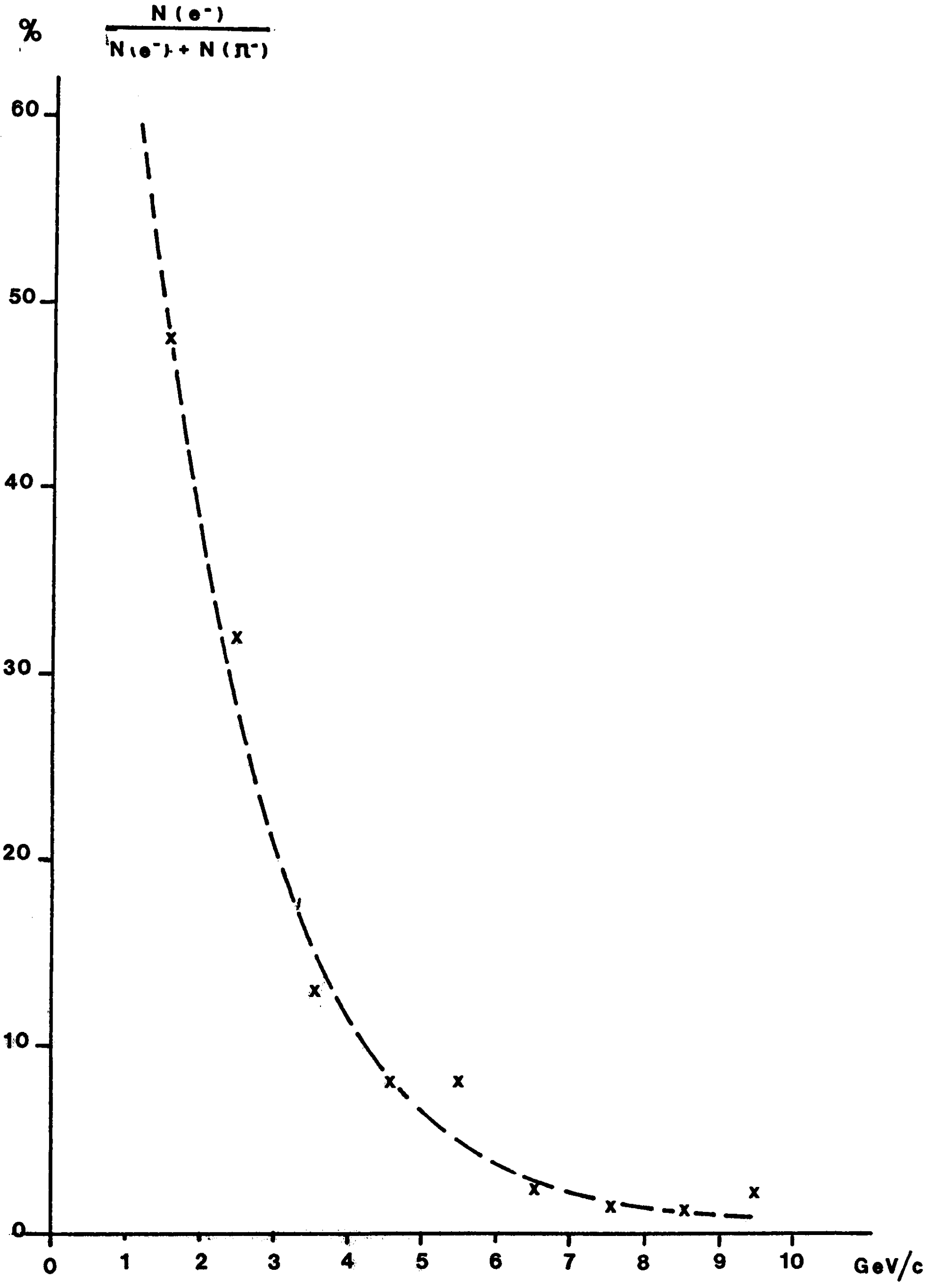

FIG. 4

Percentage of e^- in a negative beam calculated with KASPRO-EGS.
$N(\pi^-)$ from SPUKJ (normalised to incident protons).
Primary beam: 24 GeV/c protons.
Target: 19.7 cm Be + 0.3 cm W.
Production angle: 0-20 mr.

ANNEX I

CALCULATIONS WITH KASPRO AND KASPRO-EGS

1. Input

The input options are different in KASPRO and KASPRO-EGS. Those of KASPRO can be found in "a short write-up (see Ref. 2 and Annex II) for the KASPRO program". The input data of KASPRO-EGS are:

Data card 1 Title Format (20A4)
same as in KASPRO.

Data card 2 E0, DIX, DEX, PTHR Format (4F10.4) *)
meaning of the variables is the same as in KASPRO.

Data card 3 DEL, DD, DP Format (3F10.4)
DEL same as in KASPRO.
DD same as in KASPRO.
DP momentum bin (default DP = E0/50) in GeV.

In KASPRO DP cannot be changed. It always has the value E0/50.

Data card 4 NZTAR, ZMSS, RHO Format (I10,2F10.2)
same as in KASPRO.

Data card 5 (IOPT(I), I = 1,21) Format (21I1)
The options IOPT differ from those of KASPRO

IOPT(1) star densities are printed.

IOPT(2) distributions are printed (see output).

IOPT(3) distributions are plotted.

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*) The sign Ø is set for zero in cases of doubt.

IOPT(4)	Coulomb scattering is considered.
IOPT(5)	particles of the hadron cascade are printed.
IOPT(6)	1 = tables are calculated and written onto file KASPRO DATA. 0 = tables are read from file KASPRO DATA.
IOPT(7)	the program calculates the fluxes IOPT(13) to IOPT(21).
IOPT(8)	the incoming particles are pions.
IOPT(9)	energy deposition and star densities.
IOPT(10)	the incoming particles are neutrons.
IOPT(11), IOPT(12)	number of incoming particles: IOPT(11)*10**IOPT(12)
Remark:	In KASPRO-EGS there is no check whether there is enough time left for printing or not, contrary to KASPRO.
IOPT(13).....IOPT(21)	same as in KASPRO. If IOPT(18) (considers π^0 only) is set to "1" the electromagnetic cascade is initiated once there is a pi-zero created in 'KASPRO' (see page A4).
Remark:	only <u>one</u> option of IOPT(13 to 21) can be set 1; obviously, for KASPRO-EGS IOPT(18) has to be used.
Data card 6	R, RA, RDWN Format (3F10.2) R, RA same in KASPRO and KASPRO-EGS RDWN (donwstream length, e.g. "converter") If one choses a target consisting of two materials, RDWN is the length of the "downstream" material. The first material then has a length of (R-RDWN), so R is the total length. The difference of the material is only taken into account for the EGS-part of the program. The hadronic shower uses only the first material whose properties are defined in data card 4.
Remark:	therefore it should be: RDWN << R and small compared to the collision length in the "downstream" material.

Data card 7 BS, CS Format (2F10.6)

BS and CS same as in KASPRO

Remark: There is no way to change BFR. BFR is set to 1/20 which is the default value of KASPRO.

Summary of input data cards KASPRO-EGS:

Card	Variabls	Format
1	TITLE	20A4
2	E0, DIX, DEX, PTHR	4F10.4
3	DEL, DD, DP	3F10.4
4	MZTAR, ZMSS, RHO	I10,2F10.2
5	(IOPT(I), I = 1,21)	21I1
6	R, RA, RDWN	3F10.2
7	BS, CS	2F10.6

2. Output (of interest for this note)

The output of KASPRO is described in "a short write-up for the KASPRO program", (Ref. 2).

The output of KASPRO-EGS (if one uses the example COOLCU)*) is:

1. Copy of the input data and the table of inelasticities which are used.
2. From subroutine 'AUSGAB' (Ref. 1) 100 direction cosines of the protons.
3. Sum of weights for primary and secondary particles.
4. Sum of weights *EKIN as 3.

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*) on permanent file

5. List of the following variables

SWE1	sum of weight 1st generation
SWEE1	sum of weight *EKIN 1st generation
QSWE1	SWE1/M
QSWEE1	SWEE1/M
IEV	number of all interactions
IEV1	number of all interactions of primaries
WLI $\equiv$ SWE1/IEV1	average weight
WLE $\equiv$ SWEE1/IEV1	average (weight *EKIN)
WLO(ILO)	sum of weights of particle type ILO created by a proton
ISTOP	number of particles with P0 $\leq$ PTHR (stopped particles), PTHR (threshold, see Annex 2)
IWETHR	number of particles with WE $\leq$ WETHR (= 10^{-12}) cut for too small weights
IPIO	number of created π^o
ISPUK	number of particles created in 1st generation
ISPEK	number of generated particles leaving the target

Further output tables see Annex II.

Remark: KY = 1 $e^{\pm}$-spectra or γ-spectrum*
KY = 2 first generation π^o-spectrum
(not properly normalized, printed for 'diagnostic')

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KASPRO-EGS PROGRAMME
IF (IOPT(18).EQ.1) FLUX OF ELECTRONS AND POSITRONS
IF (IOPT(18).EQ.2) FLUX OF POSITRONS
IF IOPT(18).EQ.3) FLUX OF ELECTRONS
IF (IOPT(18).EQ.4) FLUX OF PHOTONS
```

3. Production of hadrons and their contribution to the distributions (KASPRO)

3.1 Selection of particle type produced in the interaction

It is assumed that the incoming primary reacts with one nucleon of the target nuclei. So the necessary kinematical relations (CM-energy) are calculated in the system primary nucleon.

The subroutine PEDEWE (in KASPRO and KASPRO-EGS) selects with the help of subroutine IRND the particle type of the secondary, its kinetic energy in the CM-system (as defined above) and the weight factor GNM, with which it contributes to the distributions.

3.2 Longitudinal and transverse momentum PL, PT of produced particles

Then the subroutine SELECT (called from PEDEWE) produces two random values PL and PT, which afterwards are the corresponding values for the longitudinal and the transversal CMS-momenta. These two momenta are drawn from the distribution (see Annex II)

$$f(PT,\ PL) = e^{\left(-BS\,\frac{PL}{E} - CS\ PT^2\right)} \qquad (E = \text{total CM-energy})$$

BS and CS are parameters which can be defined in the input. It is in this point that the assumption of the factorization of $d^2n/dPLdPT$ into two functions $f_1(PL)$ and $f_2(PT)$ enters. For kinematical reasons the CMS-momentum $p = \sqrt{PL^2 + PT^2}$ may not be larger than a limiting value PM. This is taken into account by first choosing PL and afterwards not allowing PT to be larger than $\sqrt{PM^2 - PL^2}$.

The weight of the secondary is calculated as described in Section 6. This weight is multiplied by WBACKW if PL < 0 and by WFORW if PL > 0. Here WBACKW = (1+BFR)/2*BFR and WFORW = (1+BFR)/2, (Section 1, Input).

4. Angular and momentum bins

4.1 Calculation of azimuthal angle ν

The angle between PL and PT is equal to Θ (in spherical coordinates), because the direction of the beam is parallel to the z-axis.

Θ = ATAN2 (PT/PE, PLLA/PE); PLLA is the value of PL in the LAB system. PT is the same value in CMS and LAB system. PE is the total momentum in the LAB. These values are calculated by subroutine PEDEWE. Subroutine SFECFE (SFE; CFE) selects an angle θ (in spherical coordinates). SFE and CFE are the sine and cosine of θ: SFE = sin θ, CFE = cos θ. Subroutine TRANS calculates the direction cosines out of SFE, CFE and Θ.

4.2 Determination of bins corresponding to PE and Θ

The calculation of the corresponding bins in PE and Θ is done in subroutines SPE2 and SPU2. SPU2 corresponds to the first generation (π^0), SPE2 to all secondaries $e^{\pm}$ and γ. In SPE2 the arrays DIS, DIINT and DISS of COMMON-block /O/ are calculated, in SPU2 the arrays DIE, DIENT and DIEE, as primaries and secondaries, respectively

DIS, DIE : $\frac{d^2n}{dpd}$

DISS, DIEE : $\frac{dN}{d\Omega}(\Theta)$

DIINT, DIENT: $\frac{dN}{dp}(P)$.

From the direction cosines x_D, y_D, z_D the angle Θ is calculated via $\tan\Theta = \sqrt{(x_D^2+y_D^2)}z_D$. Then the corresponding Θ-bin is found. If this bin is not in the allowed range, i.e. $[0,...50*DD]$ the event is dropped. An analogue procedure is done for PE. After finding the corresponding bin the event contributes with weight WE/DP to DIENT (DIINT), with WE/(OP*DOME) to DIE(DIS) and with WE/DOME to DIEE(DISS);
DOME = $2\pi(\cos\Theta_i - \cos\Theta_{i+1})$.

4.3 The connection between KASPRO and EGS

Every time when a π^o is created there is a call to EGS. The π^o immediately decays into two gammas, each of them creating an electromagnetic cascade. To use KASPRO-EGS one has to choose the option that only π^o are considered. The program EGS calls SPE2 of KASPRO to get electron or positron yields.

5. The tables

There are the following tables which are read from a file or calculated by the program and afterwards written onto a file:

ANMULT, TMULT, AMULT, BMULT, GNMULT, TGNM, SNORMF, GINT, EMI.

The reading or writing is done by subroutine TABM.

Each of these variables represents an array of size (25,5,6) *). The first variable corresponds to an energy, the second to the primary, the third one to the secondary. The tables are valid for the CM-energy of the primary and the hit target nucleus. It is considered that the primary hits only one nucleon of the nucleus. The energy bins in the CM-system are: ECM = 10**(-2+K*0,2)+M1+MIJ; K = 1,25, where M1 is the mass of a nucleon, MIJ the mass of the incident primary.

The variables AMULT and BMULT correlate to $d^2N/dPLdPT$.

The variables ANMULT and GNMULT correspond to the inelasticities, ANMULT to the array AINEL (the correct inelasticities), GNMULT to the array ART (the normalized inelasticity). If one chooses a special secondary particle, i.e. one is only interested in the yield of a special secondary, the correct inelasticities of this particle is set to 0,5. All the others are reduced correspondingly.

The other tables are used for normalization.

5.1 Definitions of the arrays

$$5.1.1 \quad \mathrm{AMULT(K,IJ,ILO)} = \int_{-PM}^{PM} \left(\int_{\Theta}^{\Theta_1} \mathrm{VLT(PT)\,dPT} \right) d\Theta L$$

AMULT is the average multiplicity of secondaries of type ILO created by primaries IJ.

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*) except TMULT and TGUN which are of size (25,5)

5.1.2 $$\mathrm{BMULT(K,IJ,ILO)} = \int_{-PM}^{PM} \left(\int_{\Theta}^{\Theta_2} \mathrm{VLT(PT)} \sqrt{PT^2+PL^2+PM^2}\, dPT \right) dPL$$

BMULT is the average energy of secondaries of type ILO created by primaries IJ.

5.1.3 ANMULT(K,IJ,ILO) = EINEL*ECM*AMULT/BMULT

where EINEL = 1,005*AINEL+1E-15 if ILO = $p, n, \pi^+, \pi^-, \pi^o$

or EINEL = value of table if ILO = $\bar{p}$.

5.1.4 $$\mathrm{TMULT} = \sum_{ILO} \mathrm{ANMULT(KI,IJ,ILO)}$$

average multiplicity for all secondaries created by primary ILO.

5.1.5 GINT = GINN/SNORMF

where

$$\mathrm{GINN} = \int_{-PM}^{PM} \left(\int_{\Theta}^{\Theta_3} \mathrm{EXP}\left(-BS \frac{PL}{ECM} - CS\ PT^2\right) \sqrt{PL^2+PT^2+M(ILO)}\, dPT \right) dPL*C$$

$$C \equiv \frac{CS*BS}{2*ECM(1-\mathrm{EXP}(-CSPM^2))(1-\mathrm{EXP}(-\frac{BS*PM}{ECM}))} .$$

5.1.6 $$\mathrm{SNORMF} = \int_{-PM}^{PM} \left(\int_{\Theta}^{\Theta_4} \mathrm{EXP}\left(-BS \frac{PL}{ECM} - CSPM^2\right) dPT\ dPL*C\right.$$

5.1.7 GNMULT = RRT*ECM*TMULT/(BAK*GINT)

This array is used for selection of particle type in IRND

RRT = 1,005*ART+1E-15,

where ART is the array of the renormalized inelasticities

$$\mathrm{BAK} = \sum_{ILO} ((RRT*ECM)/GINT) .$$

5.1.8 $$\mathrm{TGNM}(K1,IJ) = \sum_{ILO} \mathrm{GNMULT}(K1,IJ,ILO)$$

The upper limits of the integrals are

$$O_1 = \min\,(3, \sqrt{PM^2-PL^2})$$

$$O_2 = \min\,(1.5, \sqrt{PM^2+PL^2})$$

$$O_3 = \begin{array}{ll} PM^2-PL^2 & \text{if } (PM^2-PL^2)*CS \geq 45 \\ 45/CS & \text{otherwise} \end{array}$$

$$O_4 = \begin{array}{ll} PM^2-PL^2 & \text{if } (PM^2-PL^2)*CS \geq 10 \\ 10/CS & \text{otherwise} \end{array} \quad .$$

Choosing a special particle type changes the array ART because the inelasticities are changed in such a way that the chosen particle type has inelasticity ½.

Which arrays are changed if CS or BS are changed one sees immediately checking the fomulae.

The change of target material changes the parameters in the production formulae, so that BMULT, AMULT, ANMULT and TMULT are changed.

The change of the variable BFR does not change any of the tables.

6. Calculation of the weights

The weight WE(MO) of the secondary particle is connected to the weight WE(LO) of the primary by the relation:

WE(MO) = WE(LO)*WEE where

WEE = VFN*ANM*TML/(SCN*GNM).

VFN, ANM, TML are calculated in CNMULT
SCN is calculated in SNMULT
GNM is calculated in IRND.

SCN = SSFUN(PL,PT,ECM,PM,EM)/SN (energy EM corresponds to the momentum PM)

SCN takes into account the selection of PT and PL out of the distribution

$$e^{(-CSPT^2-BS\,\frac{PL}{ECM})} .$$

SN is an interpolation of the tables SNORM (interpolation in energy).

SSFUN is given by

$$SSFUN = \frac{BS*CS*(EXP(-\frac{BS*PL}{ECM} - CSPT^2)}{2+ECM*(1-EXP(-BS*PM)/ECM)*(1-EXP(-CS*PM**2))} .$$

PM is the maximum value of PL or PT.

IJ is the primary particle type.

ILO is the secondary particle type.

VFN = VPLPT(IJ,ILO,ECM,PL,PT,KK) (KK lower limit of energy bin)

= VLT(PT)/(AMT).

VLT(PT) is equal to ($d^2N/dPLdPT$) as given in Table 1 of HS-RP/JR/77-16, page 11. It takes into account the production formula

AMT = (AMULT+AKORR) is the interpolated value of AMULT
ANM is the interpolated value of ANMULT
TML is the interpolated value of TMULT
GNM is the interpolated value of GNMULT.

The tables are calculated if one chooses the corresponding option, otherwise they are read from a file (IOPT(6) = 0,1 in KASPRO-EGS, IOPT(8) = 0,1 in KASPRO).

7. Remarks to using the program

a) As said in Chapter 5 the change of the targaet material, the values CS and BS in the selection formula for PT and PL and/or the selection of a special particle type requires a new calculation of all the tables which are used for the weight function.

b) The bin size should not be used too small because then too many particles are rejected so the statistics gets very poor. On the other hand, the bin size should not be too large because then all events fall in too few channels. A bin size of the opening angles of 10 mrad seems to be adequate for the region of our interest ($e^{\pm}$-yields at 0^{o} and small production angles).

c) One needs a large number of primaries (and rather long CPU time) to get satisfying statistics. Typically $5 \cdot 10^{3}$ incident particles were used for KASPRO-EGS. A not too small cut-off energy is important to reduce computer time (.6 GeV/c for EGS in our case). The CPU time on the IBM 370/168 used for 1 run was about 30 minutes.

ANNEX 2

(from Ref. 2)

Input and options for KASPRO

Data card 1 TITLE FORMAT(20A4)

gives the heading for the case and is reproduced in the output.

Data card 2 EO,DIX,DEX,PTHR FORMAT(4F10.2)

EO	(GeV/c) = the primary particle momentum, p_0.
DIX	(cm) = Δr, the sigma of the projections of the beam distribution on the vertical and horizontal planes X and Y (assumed to be Gaussian). The program only considers particles from this distribution which are incident on the front face of the target (see data card 6).
DEX	(radians) = $\Delta\phi$, the rms angular divergence of the projections of the beam on the X and Y planes The program accepts all angles from this distribution ie. there is no cut in ϕ as there is in radial position.
PTHR	(GeV/c) = Pthr, the lower threshold momentum. Pthr should be larger than or equal to 0.3 GeV/c. The program stops all particle with momenta below Pthr.

Data card 3 DEL,DD FORMAT(2F10.2)

DEL	is a parameter which should be equal to 1.0 for the particle flux options and for the star density options for blocks whose length is smaller than 8 to 10 interaction lengths λabs. For larger blocks DEL should be set to (block length)/(10 x λabs). This helps to improve statistics in deep penetration problems.
DD	(radians) give the bin size $\Delta\Theta$ for plotting the histograms of $d^2N/dp.d\Omega$ in the particle flux option. The momentum bins Δp are fixed as $\Delta p = p_0/50$.

Data card 4 NZTAR,ZMSS,RHO FORMAT(I10,FF10.2)

NZTAR	gives the atomic number of the material.
ZMSS	gives the atomic weight of the material.
RHO	(g/cm^3) gives the density of the material.

Data card 5 (IOPT(I),I=1,21) FORMAT(21I1)

IOPT selects the options for the program. Unless otherwise stated setting IOPT=1 activates the option, otherwise IOPT should be set to 0.

IOPT(1) sets the normalization of the program.
=0, normalization to incoming particles,
=1, normalization to interacting particles.

IOPT(2) sets the primary particle type.
=0, proton,
=1, neutron,
=2, pi-plus,
=3, pi-minus.

IOPT(3) requests plots of the star densities.
=0, no plots,
=1, plots of energy deposition and all stars only,
=2, all types of star densities.

IOPT(4) requests tables of the star densities.
=0, no tables,
=1, tables of energy deposition and all stars only,
=2, all types of star densities.

NB. IOPTs (3) and (4) constitute the "star density" options and should only be used with the "all-particles" option IOPT(21) set to 1.

IOPT(5) requests plots of particle fluxes.
=0, no plots,
=1, plots of total particle flux from the target,
=2, plots of first-generation particles also given.

IOPT(6) requests tables of particle fluxes.
=0, no tables,
=1, tables of total particle flux from the target,
=2, tables of first-generation particles also given.

IOPT(7) The particle flux can be plotted and printed as a function of the emittance.

IOPTs 5-7 constitute the "particle flux" options which can be used with any one (but only one) of the options 13-21.

IOPT(8) The program will calculate the tables needed for the selection of the secondary particles. This takes about 100 secs of CPU time on the CDC7600. The tables are written to TAPE20 in binary form in the CDC version or to file 21 in 5E16.8 format in the IBM version so that they can be used for future runs of the program. This option must be used whenever a new material is chosen, whenever the flux of a new secondary particle type is required (see options 13 to 21) or whenever new weighting parameters are chosen for the selection functions (see data card 7).

	If IOPT(8) is 0, the program expects to read the selection tables from TAPE20 (CDC version) or file 21 (IBM version) in the formats described above.
IOPT(9)	Multiple Coulomb scattering of primary and secondary particles is considered. This option should be used for the particle flux options if the beam divergence is small.
IOPT(10)	The random number generator is called IOPT(10) times before the program starts.
IOPT(11) IOPT(12)	The number of primary particles is IOPT(11)*10**IOPT(12). For the particle flux options, depending on the length of the target, 5x10^4 to 2x10^5 particles should be considered. For the star density options between 10^3 and 10^4 particles should normally be sufficient.
IOPTs 13	to 21 select the kind of secondary particles for which the selection functions are optimised and for which the outputs fluxes are calculated. Note that a change in one of these options requires new selection tables to be calculated (IOPT(8)). For the star density options IOPT(21) must be used so that the selection inelasticities coincide with the natural inelasticities.
IOPT(13)	protons.
IOPT(14)	neutrons.
IOPT(15)	pi-plus.
IOPT(16)	pi-minus.
IOPT(17)	antiprotons.
IOPT(18)	pi-zero.
IOPT(19)	protons and neutrons.
IOPT(20)	charged pions.
IOPT(21)	all particles.
	NB. Only one of these options 13 to 21 can be used in a single run. In the plots and tables of the flux options the secondary particle is characterized by a parameter IT where IT = IOPT-12; thus for pi-plus IT = 15-12 = 3.

Data card 6 R,RA,DUX,DUW,DPP FORMAT(5F10.2)

R	(cm) gives the total length of the cylindrical block or target.
RA	(cm) gives the total radius of the cylindrical block or target.
DUX	(cm) is the step size in x (spatial dimension) for the emittance ellipses.
DUW	(radians) is the step size in angle for the emittance ellipses.
DPP	(GeV/c) is the bin size in momentum for the dN/(dp/p) versus emittance plots.

DUX,DUW and DPP need only be specified if IOPT(7) is equal to 1.

Data card 7 BS,CS,BFR FORMAT(3F10.2)

BS,CS

BS and CS are parameters in the function from which the secondary particles are chosen. This selection function is defined in a nucleon - nucleon cms:

$$S^{*}(p^{*}_{\parallel},p_{\perp},\sqrt{s}) = \exp(-BS.\frac{p^{*}_{\parallel}}{\sqrt{s}} - CS.p_{\perp}^{2})$$

$\sqrt{s}$ is the total cms energy, $p^{*}_{\parallel}$ is the longitudinal momentum of the secondary particle in the cms and $p_{\perp}$ is the transverse momentum. With an appropriate choice of BS and CS one can enhance the proportion of particles generated in the phase space region of interest. For instance a large value of CS will suppress particles with large $p_{\perp}$ and so should be used for small angle production problems. BS = 2.0 and CS = 1.0 are suitable general purpose parameters. Note that any change in BS or CS requires new selection tables to be calculated (see IOPT(8)).

BFR

is a parameter which allows particles to be preferentially selected in the backward or forward direction; BFR is the backward to forward ratio of selection in the cms. If BFR is not given a value (ie left blank), it is set to the default value of 1/20.

The combination of these three parameters BS, CS and BFR allows preferential selection of particles in the momentum and angular region of interest. Care should be taken in choosing these values and some trials may be necessary to ensure optimum statistics in the region of interest.

Table 1

Summary of input data cards for KASPRO

Card	Variables	Format
1	TITLE	20A4
2	EO,DIX,DEX,PTHR	4F10.2
3	DEL,DD	2F10.2
4	NZTAR,ZMSS,RHO	I10,2F10.2
5	(IOPT(I),I=1,21)	21I1
6	R,RA,DUX,DUW,DPP	5F10.2
7	BS,CS,BFR	3F10.2

Output

General Output

On the first four pages the program prints general output which allows the identification of the problem and of the options selected. In detail this output contains the following

- a copy of the input data,
- the parameters in the particle production formulae used,
- the inelasticities for particle production as used in three different primary momentum intervals, below the pi-production threshold, betweeen the pi-production and antiproton - production thresholds and above the antiproton - production threshold,
- inelasticities for the selection of secondaries which differ from the production inelasticities for the options IOPT(13) to IOPT(20),
- a summary of the meaning of the options and the status of each option,
- a description of the beam and the cylindrical target,
- about one page of output summarizing details of the Monte Carlo calculations.