CERN/PSCC/80-140
PSCC/P 35
December 19, 1980

PROPOSAL

_TUDY OF $\bar{p}$-NUCLEUS INTERACTION WITH A HIGH RESOLUTION MAGNETIC SPECTROMETER

E. Aslanides[2], O. Bing[2], P. Birien[1], G. Bruge[1], H. Catz[1], A. Chaumeaux[1], J.M. Durand[1], D. Garreta[1], B. Mayer[1], J. Mougey[1] and A.I. Yavin[3]

We propose to use the high resolution, large solid angle and large momentum acceptance magnetic spectrometer SPES II to study the interaction between $\bar{p}$ and complex nuclei in the following experiments :

1) $A(\bar{p}, \bar{p})A$. Angular distribution of $\bar{p}$ elastically scattered from ^{12}C, ^{40}Ca, ^{90}Zr and ^{208}Pb.

2) $A(\bar{p}, \bar{p}')A^{*}$. Excitation energy spectra and some angular distributions of $\bar{p}$ inelastically scattered from ^{12}C, ^{40}Ca, ^{90}Zr and ^{208}Pb up to an excitation energy of $\simeq$100 MeV.

3) $A(\bar{p},p)A_{Z-1,\bar{p}}$. Excitation energy spectra for knock out reaction on ^{6}Li, ^{45}Sc, ^{123}Sb and ^{209}Bi at several angles.

4) Analysing power for elastic scattering of $\bar{p}$ from ^{12}C, ^{40}Ca, ^{90}Zr and ^{208}Pb at small angles.

5) Total cross section for $\bar{p}$ interaction with the targets mentioned above, by the usual transmission technique.

Any beam momentum between 600 MeV/c and 800 MeV/c will be suitable for this experiment.

DPh-N/ME - Saclay 1)
CRN - Strasbourg 2)
Tel Aviv University 3)

I. INTRODUCTION

$\bar{p}$ interaction with nuclei is largely unknown. Since the early Berkeley experiments of 1957[1] in which a few total, annihilation and reaction cross sections were measured, no data have been published. The lack of experimental work is evidently due to the low intensity and poor quality of available antiproton beams. The advent of LEAR will drastically change this situation in such a way that $\bar{p}$ could eventually be used as a nuclear probe. In this respect the situation with LEAR will be similar to that of pion beams a decade ago.

Antiprotons have the distinctive property of annihilation in the nucleus with an energy deposit of approximately 2 GeV, a characteristic that classical probes lack. It was therefore suggested[2] that antiprotons be used to study the properties of hadronic matter at high temperature. Here we propose, instead, to use antiprotons in a more conventionnal way, by investigating elastic, inelastic and some other reaction processes. The interest of these exploratory measurements can be stressed at different levels :

1) They can provide information on the elementary $\bar{N}$-N interaction, complementary to that obtained from direct $\bar{N}$-N experiments.

2) The specificity of $\bar{N}$-N interaction can provide new information on nuclear structure.

3) Unexpected phenomena may come out in this entirely new field.

II. PHYSICS MOTIVATIONS

The description of a reaction between an "elementary particle" probe and a complex nucleus usually involves three ingredients :

- The structure of the nucleus.
- The reaction mechanism.
- The elementary scattering amplitude of the probe by nucleons.

When the reaction mechanism and the elementary amplitudes are well known, fruitful information on nuclear structure can be extracted. The following examples will illustrate this point :

- Charge distribution (and therefore proton density distribution) of nuclei have been deduced from electron scattering experiments[3].

- From intermediate energy proton scattering[4], matter density distributions of nuclei have been determined, by means of Glauber or Kerman - Mac-Manus - Thaler (KMT) type calculations in treating the reaction mechanism.

- More recently, K^+ mesons[5], characterized by their long mean free path in nuclear matter, have been used because of their ability to probe the inner part of matter distribution.

We feel that the reaction mechanism is well understood for the above mentioned hadronic probes. For instance, in a KMT calculation, we have obtained equaly good fit with the same nuclear density for 1.7 GeV/c protons and 0.8 GeV/c K^+ as shown in fig. 1.

- Pion scattering[6], in the energy region of the Δ resonance, has provided interesting information about proton and neutron wave function components of nuclei, because of the difference between the $\pi^{\pm}p$ and $\pi^{\pm}n$ interactions.

Antiproton scattering is characterized by strong absorption, due to large annihilation. The average annihilation cross section for $\bar{p}p$ and $\bar{p}n$ is of the order of 100 mb at 600 MeV/c. The range of antiproton in nuclear matter is, therefore of the order of 0.7 fm. This can lead to interesting surface properties of the interaction but also makes the theoretical predictions difficult[7].

a) Elastic scattering of $\bar{p}$ from nuclei will give information about the $\bar{p}$ - nucleus interaction. It will be complementary to that obtained from antiprotonic atom experiments. In addition its sensitivity to the elementary amplitudes will provide information on the $\bar{p}$ - neutron amplitudes which cannot be obtained directly.

We have performed a calculation for elastic scattering of $\bar{p}$ from ^{40}Ca at 730 MeV/c, using the elementary amplitude of Grein[8] adjusted to produce σ_{tot}=138 mb[9]. The result is presented in fig. 2, where the dashed curves show the sensitivity to different parameters of the elementary amplitude. No definite conclusion about this amplitude can be drawn from data on a single nucleus. The information on the elementary amplitude will however be considered as reliable if one is able to fit angular distributions of $\bar{p}$ scattering from several nuclei. Therefore, we think that a systematic survey of elastic scattering of $\bar{p}$ from a set of nuclei can provide information on the elementary amplitude. Moreover some features of the $\bar{p}$ - nucleon interaction, to which direct $\bar{p}$ - nucleon scattering experiments are insensitive, can be tested with nuclei : Fig. 3 shows the sensitivity of elastic scattering cross section for ^{40}Ca to the q-dependence of the elementary amplitude phase.

b) C.B. Dover[7] considers the possibility for the real part of the $\bar{p}$ - nucleus optical potential to have longer range than the imaginary part. This characteristic feature, combined with the centrifugal barrier, can create an attractive "pocket" where the absorption is relatively weak. It may lead to resonant effects in the high partial waves of $\bar{p}$ - nucleus elastic scattering.

c) Polarization in $\bar{p}$ - ^{12}C small angle elastic scattering at 0.91 GeV/c has been calculated by G. Alberi et al.[10] It is not very large but could be appreciably different from zero (.15 at $\theta = 10°$). On the other hand, C.B. Dover[7] expects small polarizations in $\bar{p}$ - nucleus scattering so that even the sign of them is difficult to predict, because of annihilation. Measurements of the $\bar{p}$ - nucleus polarization would shed some light on this question. In addition, polarization measurements will be useful for future design of $\bar{p}$ polarimeters.

d) Total cross section measurements will be an useful complement to elastic scattering in determining optical potentials for $\bar{p}$ - nucleus elastic interaction.

e) The possible existence of exotic antiprotonic nuclei, speculative as this idea might be, is of great interest. The short mean free path of $\bar{p}$ in nuclei makes this possibility doubtful but one could not rule it out entirely on the basis of this argument. In fact, conditions should be sought in which such nuclei, if they exist, could be produced.

Dover's idea[7], for instance, of an attractive pocket for the real potential, in which the absorption would be weak, suggests that such nuclei might exist. We would like to search for such nuclei by means of the $A_Z(\bar{p},p)A_{Z-1,\bar{p}}$ reaction where the knocked-out proton is detected at forward angle in order to get small momentum transfer. The antiproton is then expected to replace a proton of an outer shell. Nuclei like ^{6}Li, ^{45}Sc, ^{123}Sb and ^{209}Bi, with a single proton outside a closed proton shell, would be good candidates for such reactions. Most favorable, but contradictory conditions, are that the residual (capturing) nucleus be small and that the single proton have a large orbital angular momentum and therefore feel a large centrifugal barrier.

Unfortunately those two conditions change in opposite ways when we proceed in the above list of possible targets from ^{6}Li to ^{209}Bi. Observing the recoil proton at forward angles will assure small transfer momentum and the reaction will thus resemble "recoilless" production. If the attractive pocket idea holds only for light nuclei like ^4He, the reaction $^6Li_3(\bar{p},d)^4He_{2,\bar{p}}$ could be studied.

f) Due to the short range of $\bar{p}$ in nuclear matter, excitation of nuclei by $\bar{p}$ is expected to be very selective. Comparison of excitation spectra with those obtained with other probes may provide interesting information about transition densities at the surface of nuclei.

III. EXPERIMENTAL SET UP

III.1. Elastic and inelastic scattering (fig. 4)

The $\bar{p}$ beam of LEAR will be focused on the target located in a vacuum chamber. It will be monitored by an in-beam thin scintillator located upstream of the target. In order to keep the beam spot as small as possible at the target, it is advisible that the scintillator be placed at an intermediate focus of the beam.

The scattered $\bar{p}$ will be detected in the magnetic spectrometer, SPES II, by a set of 3 multiwire proportionnal chambers and a hodoscope of scintillators. They will be discriminated against pions coming from annihilation by time of flight measurement between this hodoscope and the thin scintillator located in the beam line. The MWPC information together with the detailed knowledge of the spectrometer provide a momentum determination with an accuracy better than 10^{-3} and an angular resolution better than 5 mrad. The latter point allows to use the full acceptance of the spectrometer ($\Delta\theta = 6°$) while keeping a good resolution on the scattering angle. The full acceptance will be divided in 6 angular bins of 1°. The energy resolution will be of the order of 0.6 MeV (fwhm), assuming a beam energy spread of 10^{-3}. The momentum acceptance of SPES II is such that it will accept $\bar{p}$ inelastically scattered with excitation energies of the target nucleus up to 100 Mev. Angular distributions can be easily performed by rotating SPES II on its air pads.

III.2. Knocked out proton and quasi elastic scattering measurements

In order to detect the knocked-out protons in the same way as the $\bar{p}$ in elastic and inelastic scattering measurements, the magnetic field of SPES II will just be reversed. In addition, a simple $\bar{p}$ detector will be placed at the proper angular range to detect, in coincidence with the proton, the scattered $\bar{p}$ coming from quasi elastic scattering. It will be made of a stack of scintillators in which $\bar{p}$ annihilation will be characterized by a high amplitude signal.

III.3. Polarization measurements (fig. 5)

For the polarization measurements, a second target, of the same element as the one placed in the beam line, will be put in the focal plane of the spectrometer, just behind chamber 2, at the position of the elastic peak. A thin scintillator placed just in front of the second target will detect the $\bar{p}$ elastically scattered from the first target and discriminate them against pions coming from annihilation in the first target. A hodoscope of scintillators, located further down compared to the one used for single scattering experiments, will detect the twice scattered $\bar{p}$. Discrimination from pions will be achieved by time of flight measurement between the thin scintillator and the hodoscope. Chambers 1 and 2 will determine the angle $\theta 1$ at which the $\bar{p}$ has been scattered on the first target and, together with chamber 3, will also determine the angle θ_2 of the second scattering. There will be no energy selection for the $\bar{p}$ scattered from the second target, therefore the interpretation of the left-right asymmetry of the counting rates of the second target will only be simple in the forward region where the elastic scattering is dominant.

III.4 Total cross section measurements

Total cross-sections will be measured in a standard transmission experiment geometry when the spectrometer SPES II is set at scattering angles larger than 40° (fig. 4).

For such a measurement a set of circular concentric counters, subtending different solid angles, are positioned downstream of the target, at 0°. The smallest counter must have a size containing all the beam and the largest one must subtend a large scattering angle θ_{max}, for the Coulomb scattering cross-section to be negligible when compared to the nuclear cross-section. We estimated θ_{max} for the highest Z target we intend to use, ^{208}Pb, by calculating the coulomb scattering cross-sections, using a charge form factor for ^{208}Pb that corresponds to an exponential charge distribution. The comparison of these cross-sections with the nuclear ones calculated in Section IIa shows that the transmission counters must subtend about 15° for the measurements with Pb.

Taking into account the high counting rates at forward angles (see Table 1) the total cross-section measurements can be made with good statistical accuracy within less than an hour per target and incident energy.

IV. COUNTING RATES AND TIME REQUESTS

The solid angle of SPES II is 20 msr. Using a 1 g/cm^2 thick target, which provides an energy resolution better than 1 MeV, the counting rate, for a reaction with a cross-section $(\frac{d\sigma}{d\Omega})_{mb/sr}$ and a target of atomic mass A, will be :

$$n_{counts/sec} = \frac{6.10^{23}}{A} \, . \, 2 \; 10^{-2} . \; 10^{-27} \left(\frac{d\sigma}{d\Omega}\right)_{mb/sr} \qquad I_{beam} = \frac{12}{A} \left(\frac{d\sigma}{d\Omega}\right)_{mb/sr}$$

with $$I_{beam} = 10^6 \; \bar{p}/sec$$

which ranges from 1 count/sec with ^{12}C to 6.10^{-2} count/sec with ^{208}Pb for a 1 mb/sr cross section.

IV.1 Elastic scattering

Angular distributions will be performed by rotating SPES II by 5° steps, which allows a 1° overlap between two measurements. Four targets (^{12}C, ^{40}Ca, ^{90}Zr, ^{208}Pb) will be mounted on the same translatable frame and used successively for the same angular setting of the spectrometer.

Table 1 shows counting rates based on the theoretical estimates of section II.a. The time evaluation assumes a minimum of 100 counts for a 1° angular bin. The theoretical estimation is necessarily rough but it shows that the data taking time will not be too long even in the case of a low $\bar{p}$ beam intensity of 10^5 $\bar{p}$/s, and that valuable angular distributions can be obtained in one week.

IV.2 Inelastic scattering

Data for inelastic scattering will be recorded in the same time as the elastic scattering angular distributions are performed. In order to estimate the countings for inelastic scattering, a calculation has been made for the 3^- collective state at 3.73 MeV excitation energy of ^{40}Ca. The results given in Table 2 show that for strongly excited states angular distributions can be extracted while for weakly excited states the angular bin should be adjusted in order to get reasonable statistics.

IV.3 $(\bar{p},p)$ knock out reaction

From previous $\bar{p}$-d experiments we expect a proton background produced by $\bar{p}$ annihilation in the target, with a cross section of a few hundred μb/sr. It will therefore take one day to see a state with three standard deviations over the background, assuming a 10 μb/sr cross-section. One week of running time is necessary to investigate four targets at eventually several angles.

IV.4 Polarization measurements

Counting rates and asymmetries have been estimated using the calculations of G. Alberi et al.[10] which are presented in fig. 5 together with the figure of merit $P^2\ d\sigma/d\Omega$. The angular distribution of this latter quantity shows that, from a purely statistical point of view, the forward region (around 6°) is about a factor of 10 better than the region around the second maximum at 18°. Nevertheless we intend to set SPES II at 18° because it is difficult to measure very small asymmetries. The expected asymmetries measured in the second scattering are then about 3 % in the foward region and 10 % in the region around the second maximum. The corresponding counting rates will be 1.5 c/sec and $1.5\ .\ 10^{-2}$ c/sec in 6° angular bins, using 4 g/cm^2 and 5 g/cm^2 targets for the first and second scattering respectively. The statistical uncertainties on those asymmetries will be 0.2 % and 2 % respectively. The experiment will actually provide a continuous angular distribution for the second scattering.

IV.5 Summary of time request

Elastic and inelastic scattering cross sections should be measured before polarization measurements. Therefore we ask for two periods of data acquisition, separated by enough time (at least 3 months) in order to complete the analysis of the first period data and use them to prepare the second set of experiments.

These two periods are subdivided as follows :

First period :

- Beam tuning + setting-up + test : 1 week
- Elastic and inelastic scattering measurements : 1 week
- Knock out reaction and preliminary tests for polarization experiments : 1 week.

Second period :

- Polarization measurements and complementary elastic and inelastic studies : 2 weeks.

V. REQUIREMENTS

- The magnetic spectrometer SPES II belongs to the Laboratoire National Saturne. Its utilization for this experiment will be submitted to approval from the LNS authorities.

- The target vacuum chamber, the complete detection system of SPES II and the corresponding electronics have already been used ; they are provided by the DPh-N/ME.

- A SAR computer ("Systeme d'Acquisition Rapide"), built at Saclay, will be provided by the DPh-N/ME.

- The apparatus for total cross-section measurements will be provided by CRN Strasbourg.

- The $\bar{p}$ detector used for quasi-elastic scattering detection will be provided by the DPh-N/ME.

Requirements from CERN

- The space available for the experiment should be large enough to allow the rotation of SPES II up to 25° counterclockwise (necessary for polarization measurements) and 50° clockwise. The fulfilment of this latter requirement, necessary for large angle elastic scattering measurements, will also provide enough room to park SPES II beside the experimental area which will become available for medium size experiments (see fig. 7). We want to point out that this operation is very easy and very fast (not more than a couple of days) and has already been performed on the experimental area S163.

- We will need a connection of the SAR to CERNET

- Data checking and software development will require 20 h of CPU time on the CERN IBM computer. Data analysis will be performed at CERN with SAR as well as at Saclay and Strasbourg.

TABLE I

Counting rates estimation for elastic scattering by 1 g/cm^2 targets.

a) Minimum counting rate for a 1° angular bin assuming a 10^6 $\bar{p}$/sec beam.

b) Corresponding counting time to get at least 100 events in 1° angular bin.

c) Same as b) with a 10^5 $\bar{p}$/sec beam.

B) Total time necessary for the four targets, including the rotation of SPES II, assuming a 10^6 $\bar{p}$/sec beam.

C) Same as B) with à 10^5 $\bar{p}$/sec beam.

Counting times in b) and c) are assumed a minimum value of 15 min for practical reasons.

SPES II angle		θ_{min} / θ_{max}	5 / 10	10 / 15	15 / 20	20 / 25	25 / 30	30 / 35	35 / 40	40 / 45
^{12}C	a)	$n^{min}_{c/s}$	170	25	0.5	0.5	1	0.12	0.02	0.05
	b)	$t(10^6)$	15 min	15 min	15 min	15 min	15 min	15 min	1h30	45 min
	c)	$t(10^5)$	15 min	15 min	30 min	30 min	15 min	2h15	14h	5h30
^{40}Ca	a)	$n^{min}_{c/s}$	33	2.5	2.3	0.2	0.25	0.02	0.02	.003
	b)	$t(10^6)$	15 min	15 min	15 min	15 min	15 min	1h30	1h30	9h15
	c)	$t(10^5)$	15 min	15 min	15 min	1h30	1h15	14h	14h	(4 days)
^{90}Zr	a)	$n^{min}_{c/s}$	8	6	1	0.2	0.13	0.02	0.013	0.003
	b)	$t(10^6)$	15 min	15 min	15 min	15 min	15 min	1h30	2h15	9h15
	c)	$t(10^5)$	15 min	15 min	15 min	1h30	2h15	14h	(1 day)	(4days)
^{208}Pb	a)	$n^{min}_{c/s}$	24	2.6	0.6	0.4	0.13	.04	.01	
	b)	$t(10^6)$	15 min	15 min	15 min	15 min	15 min	45 min	3h	
	c)	$t(10^5)$	15 min	15 min	30 min	45 min	2h15	7h	(1 day)	
TOTAL	B)	$T(10^6)$	1h15	1h15	1h15	1h15	1h15	4h15	8h30	19h30
	C)	$T(10^5)$	1h15	1h15	1h45	4h30	6h15	38h	28h	5h45

TABLE 2

Counting estimates for the first 3^- state in ^{40}Ca recorded during the elastic scattering experiment.

a) Differentiel cross section averaged over the angular acceptance of the spectrometer.

b) Maximum cross section in the same angular range.

c) Counting time as determined in Table 1, assuming a 10^6 $\bar{p}$/sec beam.

d) Counting expected for the full acceptance of SPES II.

e) Counting expected in a 1° angular bin where the cross section is maximum.

SPES II angle		θ_{min}	5	10	15	20	25	30	35	40
		θ_{max}	10	15	20	25	30	35	40	45
^{40}Ca	a)	$(\frac{d\sigma}{d\Omega})^{min}$ mb/sr	17	29	10	3	2.4	0.45	0.4	0.085
	b)	$(\frac{d\sigma}{d\Omega})^{max}$ mb/sr	27	33	23	4.4	4.4	0.6	0.6	0.18
	c)	$t(10^6)$	15 min	15 min	15 min	15 min	15 min	1h30	1h30	9h15
3^-	d)	$n^{peak}(10^6)$	4500	7800	2700	540	650	730	650	850
	e)	$n^{peak}(10^6)$	1200	1500	1000	200	200	160	160	300

REFERENCES

1) B. Cork et al., Phys. Rev. 107 (1957) 248 ;
L.E. Agnew et al., Phys. Rev. 108 (1957) 1545.

2) J. Rafelski, Phys. Lett. 91B (1980) 281 ;
J. Rafelski et al., 5 th European Symposium on Nucleon antinucleon interactions Bressanone (1980), CLEUP, p. 357.

3) R.F. Frosch et al., Phys. Rev. 174 (1968) 1380.

4) A. Chaumeaux et al., Annals of Phys. 11b (1978) 247 and ref. herein.

5) Proceedings of the Kaon Factory Workshop, 8th ICOHEPANS Vancouver (1979) ;
R.A. Eisenstein, ibid... p. 75.

6) C.L. Morris, Proceedings of the Workshop on Nuclear Structure with Intermediate Energy Probes. Los Alamos (1980) 57.

7) C.B. Dover, Proceedings of the 5th European Symposium on Nucleon Antinucleon interaction, Bressanone (1980) 626.

8) W. Grein, Nucl. Phys. 131 (1977) 255.

9) V. Flaminio et al., CERN - HERA 79-03 (1979).

10) G. Alberi et al., Proceedings of the 5th European Symposium on Nucleon-antinucleon interaction, Bressanone (1980) 51.

11) V. Flaminio et al., CERN-HERA 79-02 (1979).

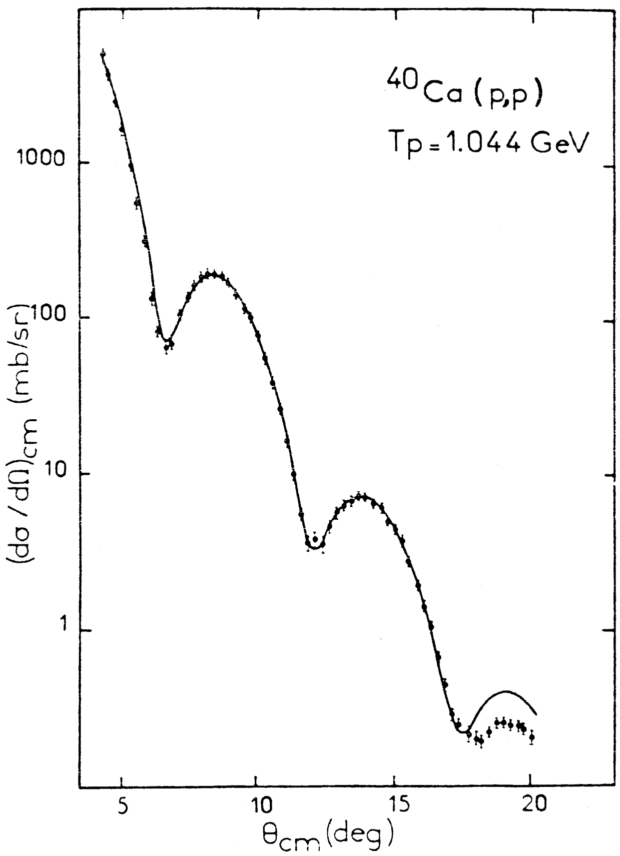
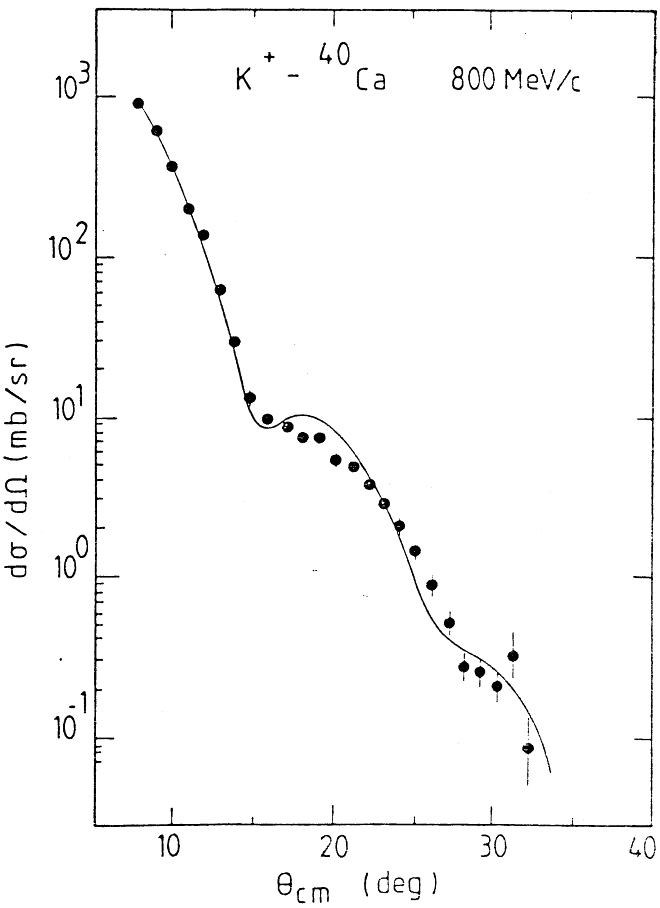


Fig 1a - K.M.T. calculation for ^{40}Ca (ref. 4). The N-N amplitude is determined directly from N-N scattering results. The proton density is taken from ref. 3. The neutron density is obtained by least-scare fit on Saclay data.

Fig 1b - K.M.T. calculation and Brookhaven data[5]. The K^+-N amplitude is directly determined from K^+-N scattering results[11]. Proton and neutron densities are taken from ref. 4.



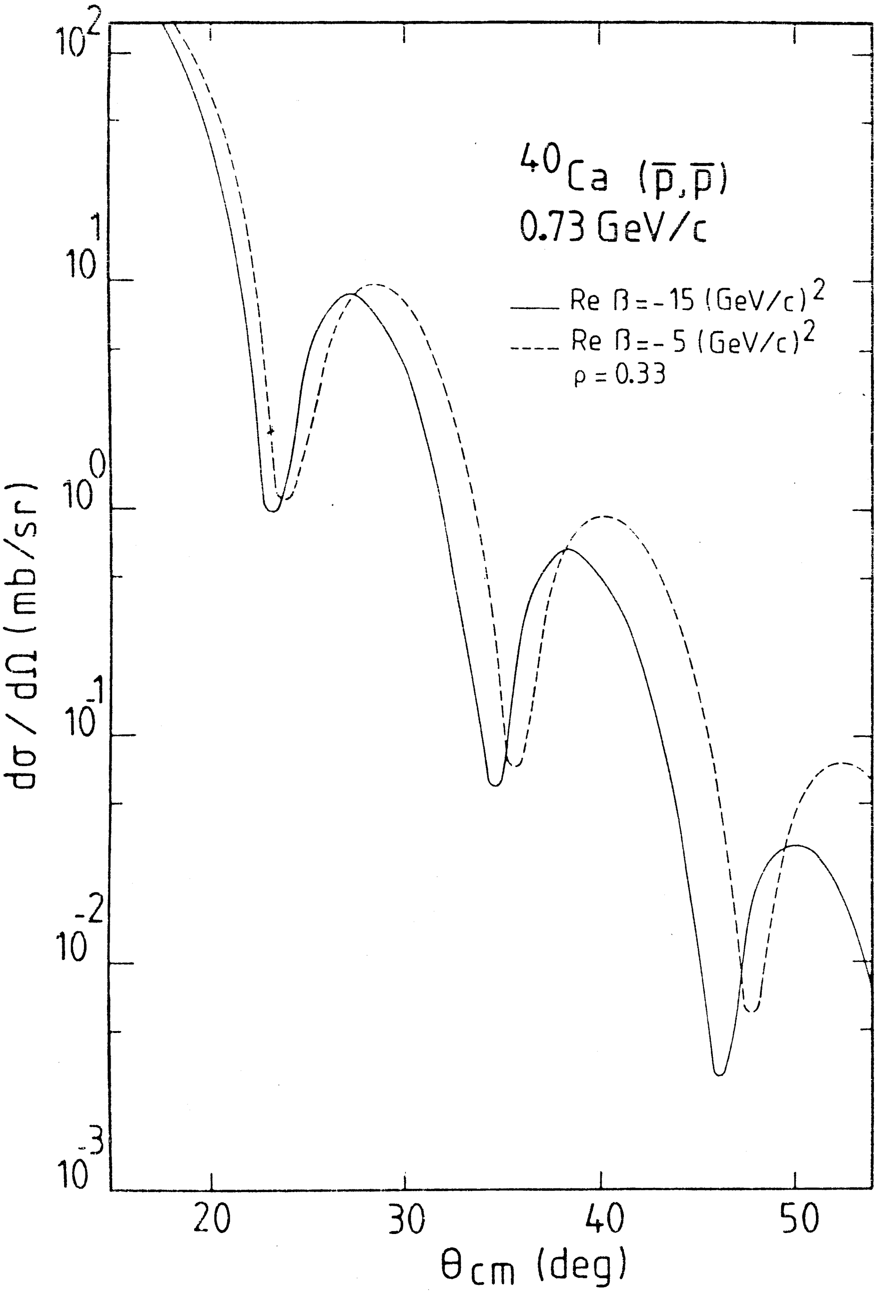


Fig 2a. - Dependence of the elastic $\bar{p}$ - ^{40}Ca differential cross-section on the $\bar{p}$ - N amplitude slope parameter. In this calculation the ratio of the real to the imaginary part of the $\bar{p}$ - N amplitude is given Grein[redacted]'s value.

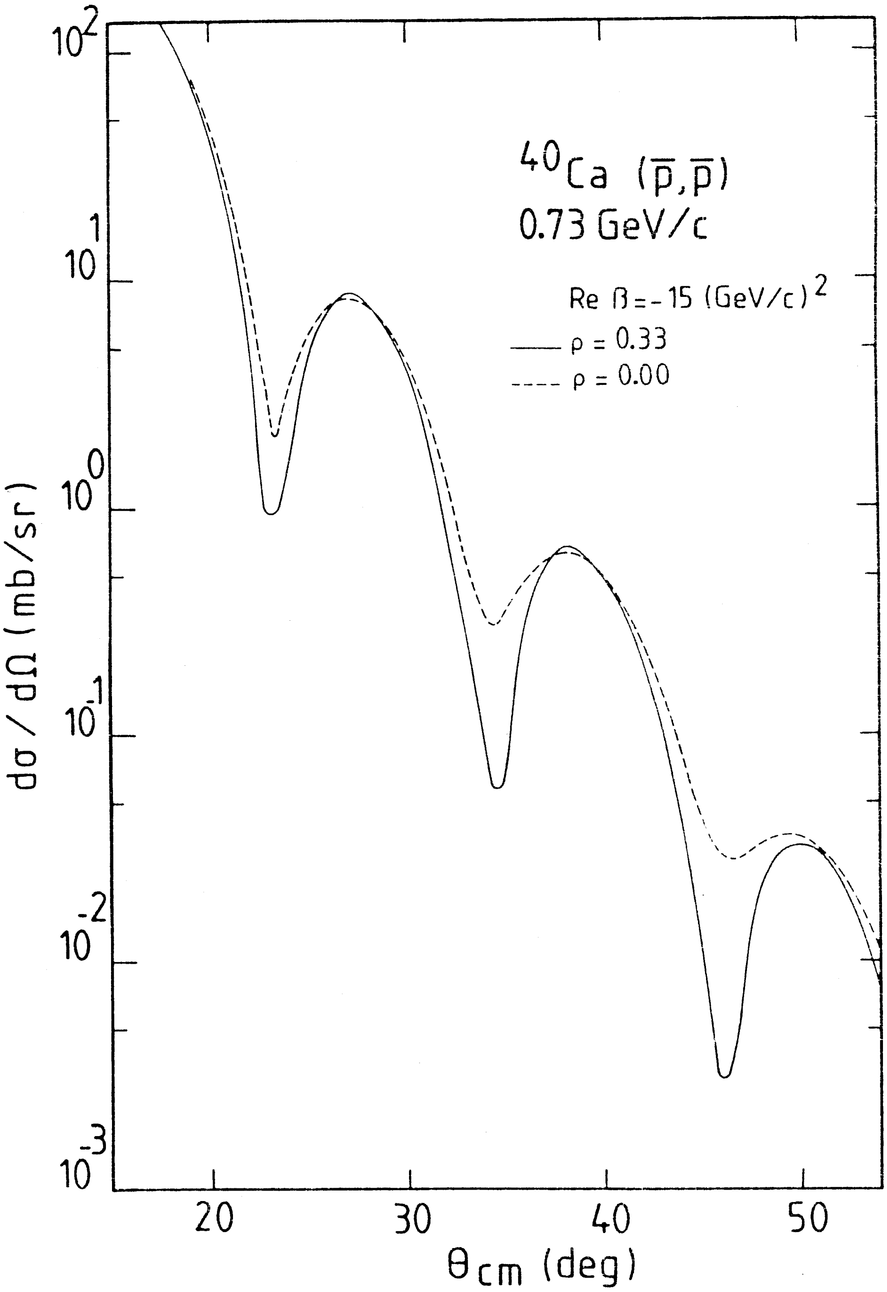


Fig 2b. - Dependence of the elastic $\bar{p}$ - ^{40}Ca differential cross-section on the ratio of the real to the imaginary part of the $\bar{p}$ - N amplitude. The slope parameter is given Grein's value.

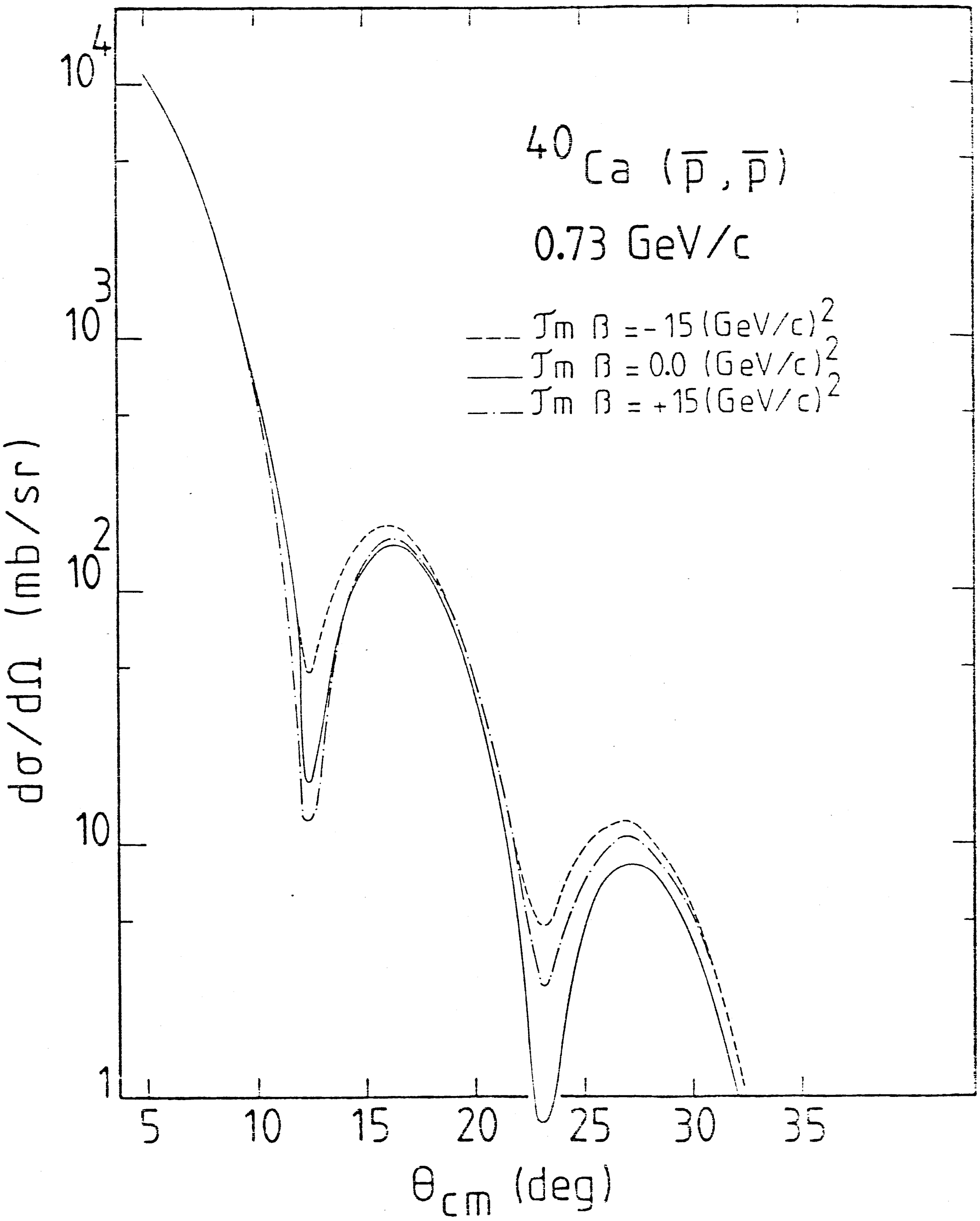


Fig 3. - Change of the elastic differential cross-section when the $\bar{p}$ - N amplitude is multiplied by a phase factor exp (i Im βq^2).

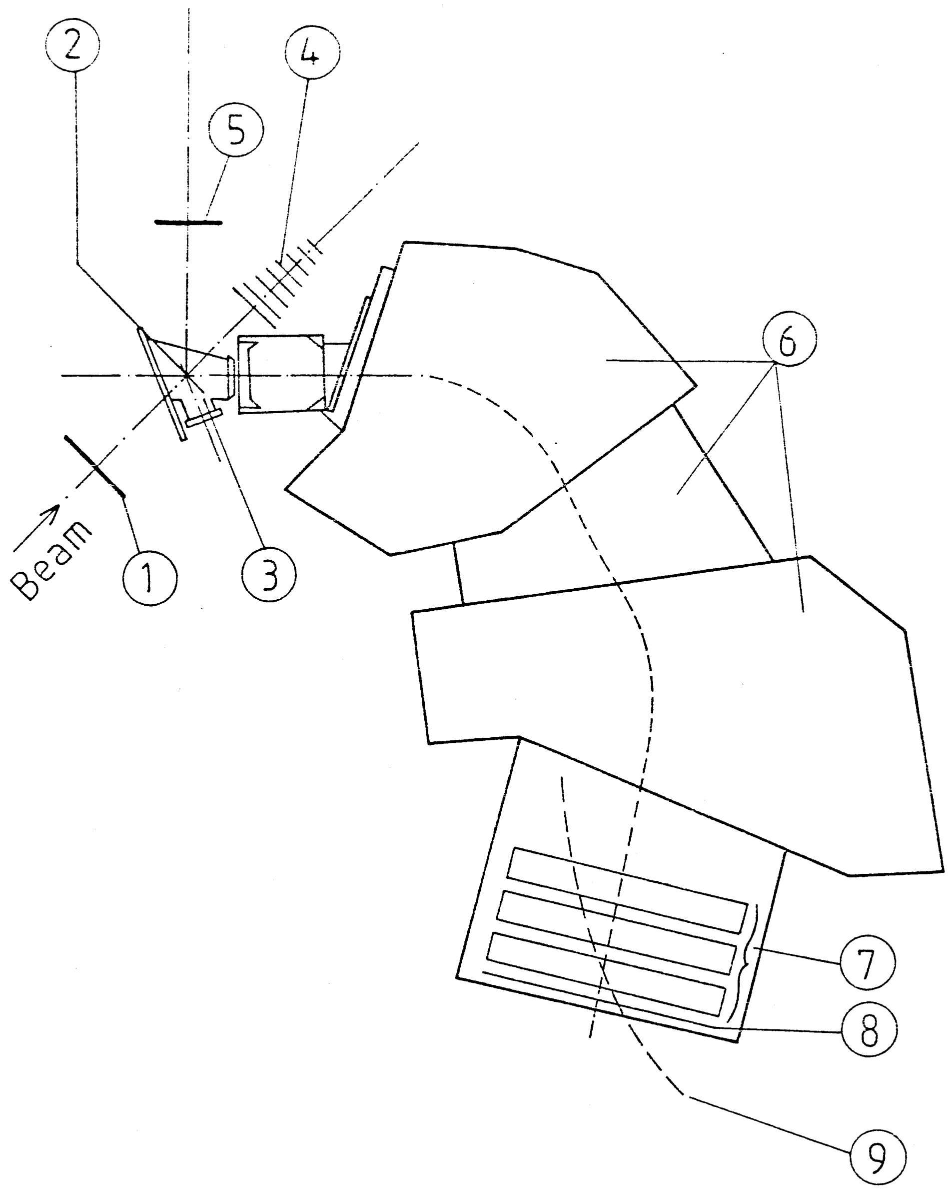


Fig 4. - General lay-out of the experimental set up.

1. In beam monitor and TOF start thin scintillator.
2. Target
3. Target vacuum chamber
4. Total cross-section measurement counter.
5. Coincidence counter
6. SPES II Spectrometer
7. Multiwire chambers
8. Scintillator hodoscope
9. Horizontal focal surface

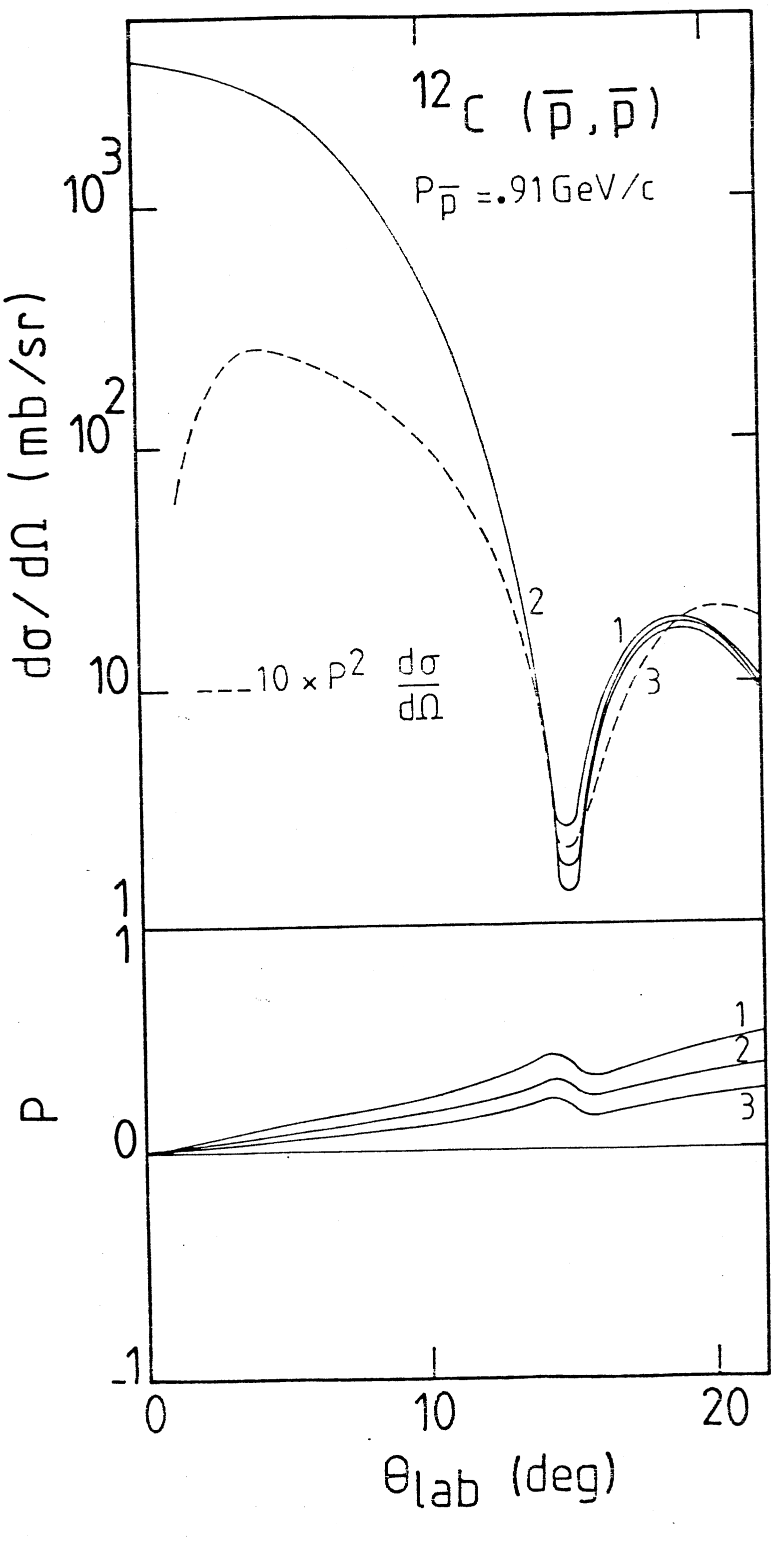


Fig 5. - Differential cross-sections and polarisations as calculated by Alberi et al[10] (full curves) for 0.91 GeV/c $\bar{p}$ elastic scattering by ^{12}C (see ref. 10 for details). Also plotted is the merit function p^2 dσ/dΩ (dashed line) calculated from the theoritical set ≠ 2.

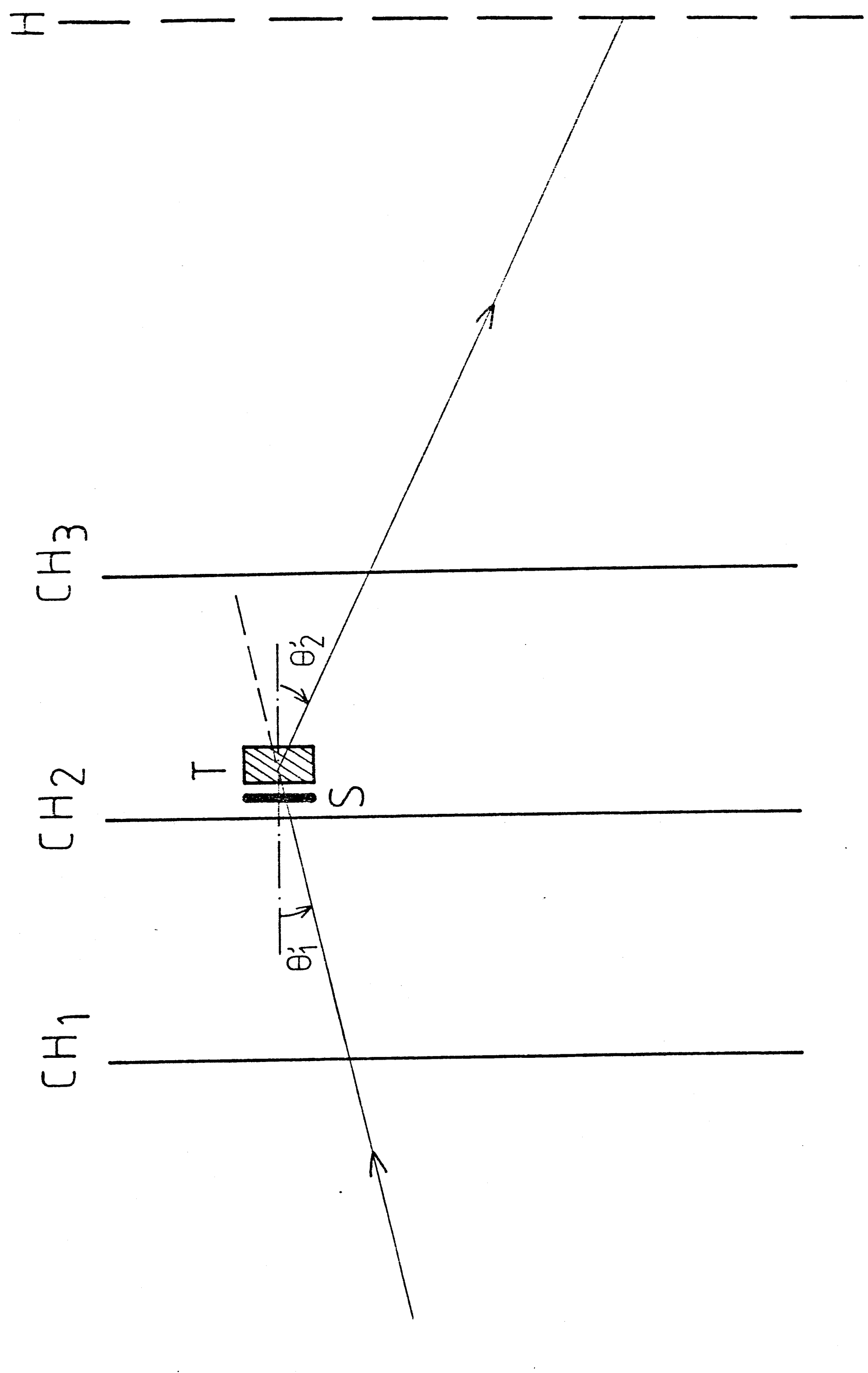


Fig 6. - Special set-up for polarization measurements. A thin scintillator S and a second target T are located at the elastic peak area on the focal plane behind the second multiwire chamber CH2. H represents the back hodoscope. The first scattering angle is defined as $\theta_1 = \theta_{SPES} + \theta'_1/S_{22}$ where S_{22} is the angular magnification of SPES II and the second scattering angle as $\theta_2 = \theta'_2 - \theta'_1$.

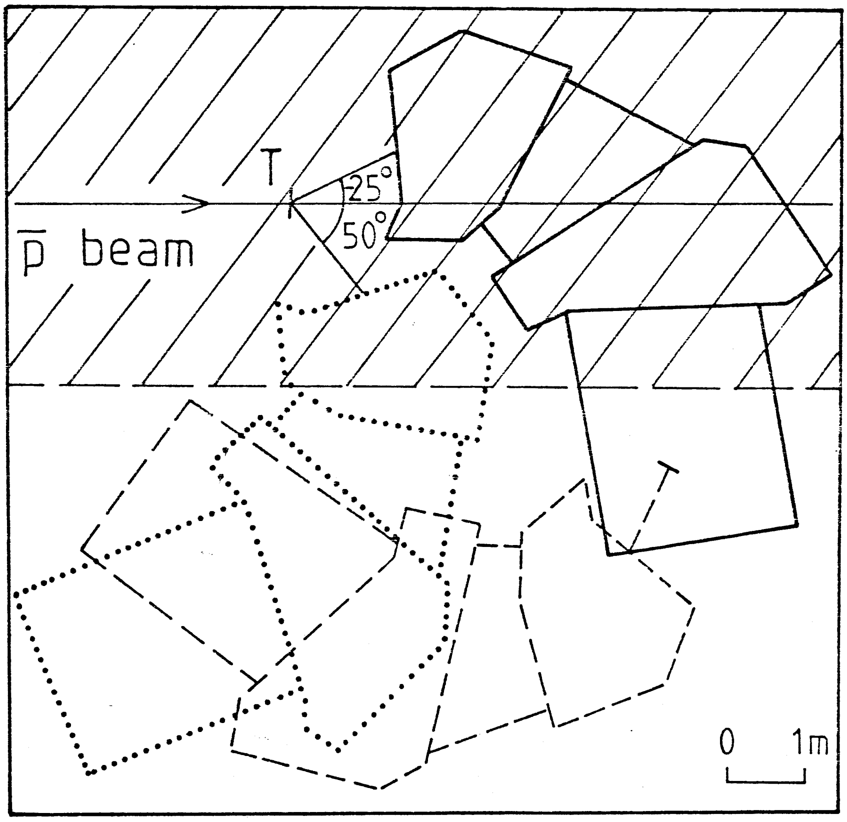


Fig 7. - Minimum area requested for SPES II moving - 25° (solid line) to 50° (dotted line) around the target T. When the spectrometer is not used it can be moved (dashed line) in such a way that the hachured region is free for smaller size zxperiments. The detection system is drawn in its extended configuration needed for polarization measurements.