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A PROPOSED EXPERIMENT TO MEASURE THE ANGULAR CORRELATION OF ELECTRON RELATIVE TO HYPERON SPIN DIRECTION IN THE β DECAY OF THE Λ^0

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I. INTRODUCTION

Early in November 1962, a proposal entitled "Proposal for a Measurement of the Decay Mode $\Sigma^- \to \Lambda^0 + e^- + \nu$", was submitted for consideration by the EEC and NPRC. Subsequently, a test run was made at the PS during the period 18.1.63 to 3.2.63 to settle experimentally certain aspects of the proposal. A report presenting the detailed results of this test is in preparation and will be available soon.

Meanwhile, partly as a general result of the test run and partly as an outgrowth of additional thought on the possibilities of experiments relating to leptonic decays of hyperons, it has become clear that a new experimental approach to the β decay of the Λ^0 possesses a number of attractive features which make it of interest to reconsider such an experiment. The experimental arrangement to be discussed here has the following features:

1) It is designed to measure a specific correlation of the decay process $\Lambda^0 \to p + e^- + \nu$, namely the angular correlation of the decay electron relative to the spin direction of polarized Λ^0 particles, $\vec{\sigma}_\Lambda \cdot \hat{u}_e$, where $\vec{\sigma}_\Lambda$ is the spin of the Λ^0 and $\hat{u}_e$ is a unit vector in the direction of the emitted electron.

2) It should provide a counting rate of at least 0.5 event per hour of PS time, for an incident π^+ beam rate of 5×10^4 π^+/pulse. About 400 events are required to measure $\alpha_{\Lambda e}$, the correlation coefficient, to about 10 per cent if, as expected, no large source of background events is present.

3) The selection, recognition, and reconstruction of good events appears to be feasible without involving new technical problems or requiring that present techniques be used at the limit of their performance. Almost all experimental components have already been employed in the aforementioned test run.

4) The trigger rate is reasonably low; an upper limit of 50 pictures per hour may be set, yielding at least one good event per 100 pictures.

II. THEORY

It was, of course, study of the analogous correlation in the case of Co^{60} that provided the first evidence of the non-conservation of parity in weak interactions, and in the case of the neutron provides the relative amplitudes and signs of the Fermi and Gamow-Teller couplings. If one neglects nucleon recoil terms of order $\beta_{proton} = 0.1$ and also form factor effects due to finite momentum transfer (also small), then formulae for neutron decay are relevant to the Λ^0 decay. In Fig. 1 are shown the correlation coefficient $\alpha_{\Lambda e} = 2(G_F G_{GT} + G_{GT}^2) / (3 G_{GT}^2 + G_F^2)$, and also the coefficient of the electron-neutrino correlation, $\hat{u}_e \cdot \hat{u}_\nu$, for various mixtures of G_F and G_{GT}. The latter correlation appears to be the only one available to heavy liquid bubble chamber experiments, at least as long as no large homogeneous samples of β decays from polarized Λ^0 particles are collected. It is likely that both correlations may be needed if complicated interaction forms are present in the Λ^0 decay.

III. EXPERIMENT

1. Counting rate

The proposed experimental arrangement is shown schematically in Fig. 2. The production of a K^+ meson in association with a Λ^0 serves as a partial signature of the events we seek. Hence π^+ mesons of about 1.0 GeV/c are incident on a beryllium target 3 cm thick and produce 6×10^{-4} $\Lambda^0 K^+$ pairs per incident π^+. For this target and π^+ momentum, and looking at $90° \pm 55°$ in the centre of mass of the production system, Cool et al. have measured $\alpha_\Lambda \bar{P} = -0.55 \pm 0.1$, which yields (for $\alpha_\Lambda = -0.61 \pm 0.07$) $\bar{P} = +0.9 \pm 0.2$, so that we may expect the Λ^0 particles to form a highly polarized sample. We must, of course, measure $\alpha_\Lambda \bar{P}$ independently in this arrangement.

It is necessary for event recognition that the Λ^0 decay occurs at least 1 cm outside of the target. This probability is for a mean Λ^0 length of 3.9 cm about $1/2$, so that 3×10^{-4} $\Lambda^0 K^+ / \pi^+$ satisfy the experimental conditions.

From the production kinematics and the K^+ detector shown in Fig. 2, it can be calculated that we can safely expect to subtend a relative solid angle of 0.25 with the K^+ detector. Experience has taught us that about 0.6 of all K^+ stopping in the K^+ detector decay with a lifetime sufficiently long to distinguish them from prompt events, and that 0.8 of the latter events give secondaries that produce a delayed count in the K^+ detector. Hence we anticipate $3\times 10^{-4}\times 0.25\times 0.6\times 0.8 = 0.36\times 10^{-4}$ Λ^0K^+/π^+ events in which the K^+ is detected and the Λ^0 decays outside of the production region.

Again from the kinematics of the Λ decay, we calculate (see Fig. 3) that the fraction of decay electrons between 70° and 120° in the laboratory is 0.4, of which we see only half because we include only half of the azimuthal angle. Assuming an efficiency of 0.75 for the electron detector (see Fig. 2), we find $0.36\times 10^{-4}\times 0.4\times \frac{1}{2}\times 0.75 = 5.4\times 10^{-6}$ Λ^0K^+/π^+ events in which the K^+ is detected, the Λ^0 decays outside the target and the electron from the Λ^0 is also detected.

Finally, part of the K^+ detector is required to "see" also the proton produced in the Λ^0 decay as the last triggering requirement, but this is expected to introduce only a factor of 0.9 into the rate. Thus the rate of Λ^0-β decays to be observed is then $5.4\times 10^{-6}\times 0.9\times 10^{-3} = 4.9\times 10^{-9}$ per incident π^+ meson, where 10^{-3} is the known branching ratio. If we assume an incident flux of 5×10^4 π^+/pulse, we obtain 2.5×10^{-4} Λ-β decays/pulse yielding, for 1.6×10^3 pulses/hr, 0.4 Λ-β decays /hr.

It should be emphasized that several of the values given above represent somewhat conservative estimates. In particular, we might anticipate that a K^+ detector with a properly designed absorber wedge (see Fig. 2) to aid in stopping the faster K^+ mesons will give a solid angle of 0.4; that the efficiency of the electron detector can be raised to 0.9; and that the incident beam rate can be raised to 7.7×10^4 π^+/pulse. Under these conditions, we should expect

$$0.4\times\frac{0.4}{0.25}\times\frac{0.90}{0.75}\times\frac{7.5}{5.0} = 1.15\ \Lambda\text{-}\beta\ \text{decays/hr.}$$

On this basis, we feel it reasonable to look forward to 0.5 useful events per hour or about 10 events per day of PS time.

2. Event discrimination and reconstruction

The main difference of the present experimental approach relative to earlier ones lies in the fact that here electrons emitted in the vicinity of 90° in the laboratory system are observed, rather than those emitted in the more forward direction. It is shown in Fig. 4 that $\alpha_{\Lambda e}/\alpha_{\Lambda e\,\max}$ is a slowly varying function of the laboratory angle of emission of the electron, so that very little physical information is lost in observing electrons at large emission angles. The selection of 90^{+30}_{-20} degree electrons has the advantage that such electrons, with an energy spectrum largely determined by the phase space (Fig. 5), have a mean kinetic energy of about 80 MeV. On the other hand, the charged pions from the usual decay $\Lambda^0 \to p + \pi^-$ are very weakly energetic at such large laboratory angles. This is shown in Fig. 6 where the kinetic energy of the pions from Λ^0 decay is plotted against the laboratory emission angle of the pions for several values of Λ^0 momentum. It is clear that for $p_\Lambda \geq 450$ MeV/c, which is the minimum value produced at any angle in the production process on hydrogen, the maximum pion kinetic energy in the angular region 70° to 120° (lab.) is 31 MeV, and the mean kinetic energy of such pions is appreciably less than that value. Even if the Fermi momentum in the Be target gives rise to Λ^0 particles with much less momentum, the maximum kinetic energy of the emitted pions in this angular region remains small, as is illustrated by the curve in Fig. 6 for $p_\Lambda = 0.200$ GeV/c, although the mean energy approaches the maximum energy more closely. Hence it appears feasible to base the discrimination of Λ-β decay events from ordinary Λ decays -- which is, apart from rate, the primary experimental problem -- on the discrimination of electrons with a mean kinetic energy of about 80 MeV from pions of maximum kinetic energy about 35 MeV. The electron detector shown in Fig. 2 embodies a thin-plate spark chamber for accurate reconstruction of the event, a dE/dx scintillation counter, a water Čerenkov counter, and a thick-plate spark chamber for shower production and observation. A 35 MeV pion has a range of 5.2 gm/cm^2 of water and should ionize two times minimum. The pions should, therefore, produce a large pulse in the dE/dx counter, no pulse in the water Čerenkov counter (not even δ rays) and, for our thickness of water, fail to enter the thick-plate spark chamber. The ratio $(\Lambda \to p + \pi^-)/(\Lambda \to p\,e\,\nu) = 660$, but since electrons are faster than the pions and tend therefore to come off at larger angles, one is required to discriminate against 300 pions per electron for $\Theta_{lab} \geq 70°$. This discrimination factor should be obtained in the electron detector described above, since only secondary effects will produce a spurious count in the electron detector. The most important of these are:

1) A pion may decay in flight into a muon for which the probability here is approximately 0.02. A pion of 35 MeV may emit a muon with as much as 55 MeV kinetic energy, which is exactly at the threshold of the water Čerenkov counter, $\beta_+ = 0.75$. However, only a small fraction ($\lesssim 0.04$) of the pions will have kinetic energy greater than 30 MeV, and only a small fraction ($\lesssim 0.10$) of the muons from the decay in flight of those pions will attain a kinetic energy larger than 50 MeV. Hence, at most, $0.02 \times 0.04 \times 0.10 = 8 \times 10^{-5}$ of pions from ordinary Λ^0 decay emitted in the direction of the electron counter will produce a count in the water Čerenkov counter by decaying in flight. Further, such events will also fail to produce a shower in the heavy-plate spark chamber.

The same process from pions emitted at smaller angles and therefore with larger energy allows for the possibility that the pion decay will occur very close to the Λ^0-decay point so that no change in the track direction is apparent. Fortunately the muon energy falls off with increasing π-μ decay angle more rapidly than the pion energy increases with decreasing angle of emission, and hence the considerations above also provide a conservative upper limit for this type of background.

Muon decay at rest or in flight and the decay mode $\pi \to e + \nu$ contribute negligibly.

2) A charged pion may interact in flight or at rest to give a π^0. No π^0 production for π^- at rest may take place in oxygen or carbon because the binding energy of the daughter nucleus is larger than the available energy. Thus the hydrogen in the water Čerenkov counter is the main source of π^0. All properly directed pions from Λ^0 decay will stop in the water, but at most 10 per cent of them will fail to produce a veto signal in the dE/dx counter. The probability of π^0 production by stopping π^- in the water counter can be estimated as $\sim 1/_{500}$, in agreement with measurements by the $\pi^+\pi^0$ group. Finally, less than 20% of the π^0 gamma rays will be converted in the water. Hence neutral pions should contribute a background at most 0.01 of the desired events.

3) A charged pion may stop in the water producing a star containing γ rays and heavy prongs. In general, the heavy prongs will involve very few ($< 1/_{1000}$) charged particles of kinetic energy greater than 30 MeV. It is more difficult to make reliable estimate of the γ-ray production and interaction. It is expected that the resulting γ-ray energy will not exceed about 10 MeV, which would make this a negligible contribution.

The processes 2) and 3) are subject to direct and convenient measurement at the SC, which should also make clear the presence of other background processes, if any. A completed electron detector will necessarily have to be tested for this purpose before any run at the PS.

3. Trigger rate

As indicated earlier, the trigger system selects events containing three emerging particles. The forward emitted particles must satisfy dE/dx criteria and fail to give Čerenkov light in water. The particle at large angles must be minimum ionizing and produce Čerenkov light in water. The data of our test run, in which the only trigger requirement was on the K^+ particle, show that one out of thirty pictures contains three emerging particles. Using this value and adjusting only for different cross-section and target thickness, we find about 50 triggers per hour. It should be emphasized that this value is a conservative upper limit since it does not include any discrimination on the electron or proton from the Λ^0 decay.

4. Event reconstruction

The distinguishing features of a Λ^0-β decay event have already been outlined as:

1) observation of a Λ^0-K^+ pair for which the lifetime of the K^+ is measured and the vertex of the Λ^0 is seen directly;
2) observation of the fast particle from the Λ^0 decay in the electron detector, including production of a shower by that particle.

These requirements should ensure, first, that only Λ^0 decays are accepted and, second, that only Λ^0-β decays are accepted. The latter condition is, fo course, harder to enforce since some contamination from pathological cases of normal Λ^0 decay cannot be ruled out a priori. Any such events should, however, be apparent to us in preliminary testing of the electron counter and, providing that our expectation of a negligibly small contamination is borne out in those tests, remeasurement of the known branching ratio, $\Lambda^0 \rightarrow p + e^- + \nu$ will provide additional evidence that the bulk of events is of leptonic nature. Finally, at least for some small subset of good events, failure to satisfy coplanarity will be evident. It is apparent, however, that the latter two conditions are only mildly restrictive, indicating clearly that the proposed experimental arrangment is primarily dependent on counter discrimination for event recognition. The function of the spark chambers is two-fold: they eliminate obviously unqualified events and also certain events of questionable nature, e.g., those in which one of the decay products is scattered through more than a few degrees, and they provide with good accuracy the raw data of the correlation to be measured.

* * *

Figure captions

Fig. 1 : The coefficients of the correlations $\vec{\sigma}_\Lambda \cdot \hat{u}_e$ and $\hat{u}_e \cdot \hat{u}_\nu$ as functions of the coupling mixture.

Fig. 2 : Schematic outline of the proposed experimental arrangement.

Fig. 3 : Relative solid angle of electrons from $\Lambda^0 \rightarrow p + e^- + \nu$ as function of laboratory angle of emission of the electron.

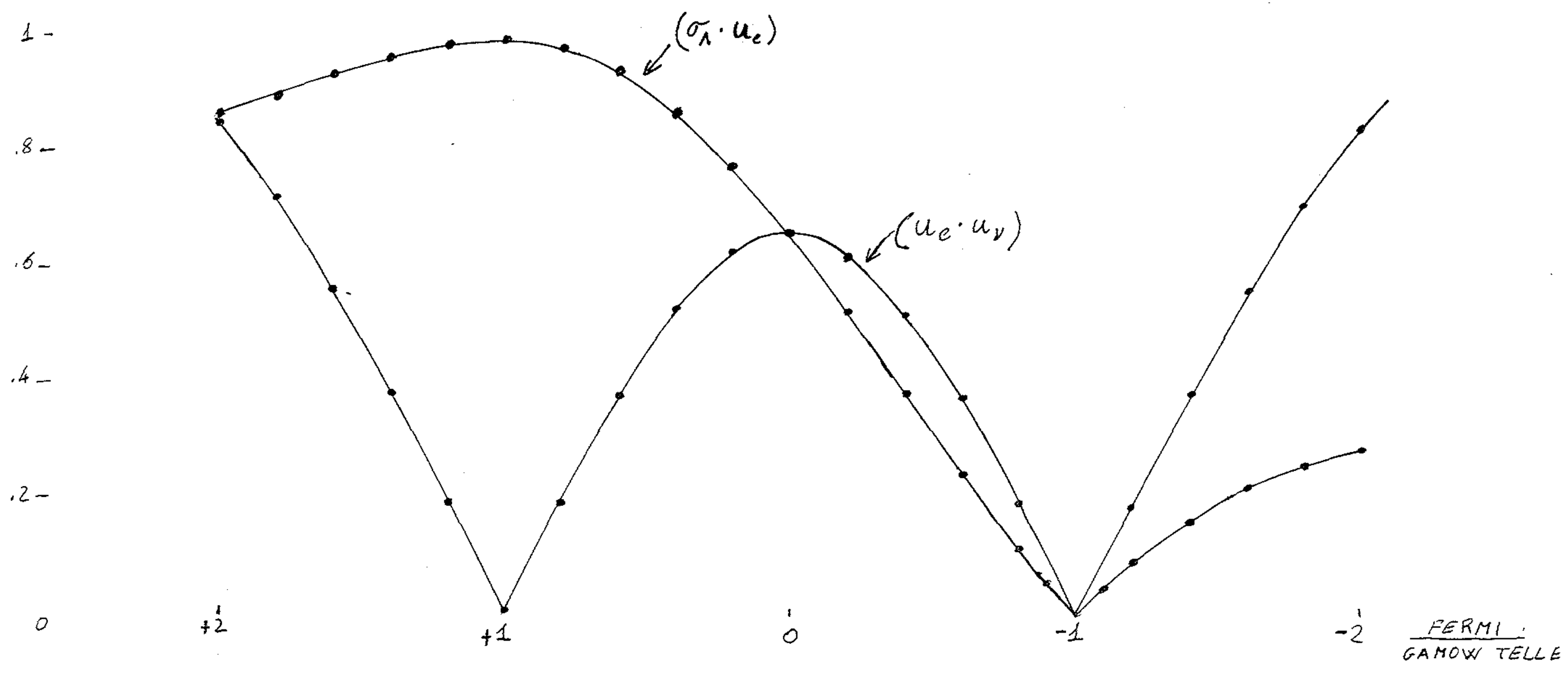
Fig. 4 : $\alpha_{\Lambda e}/d_{\Lambda e\,\max}$ versus laboratory angle of emission of electron.

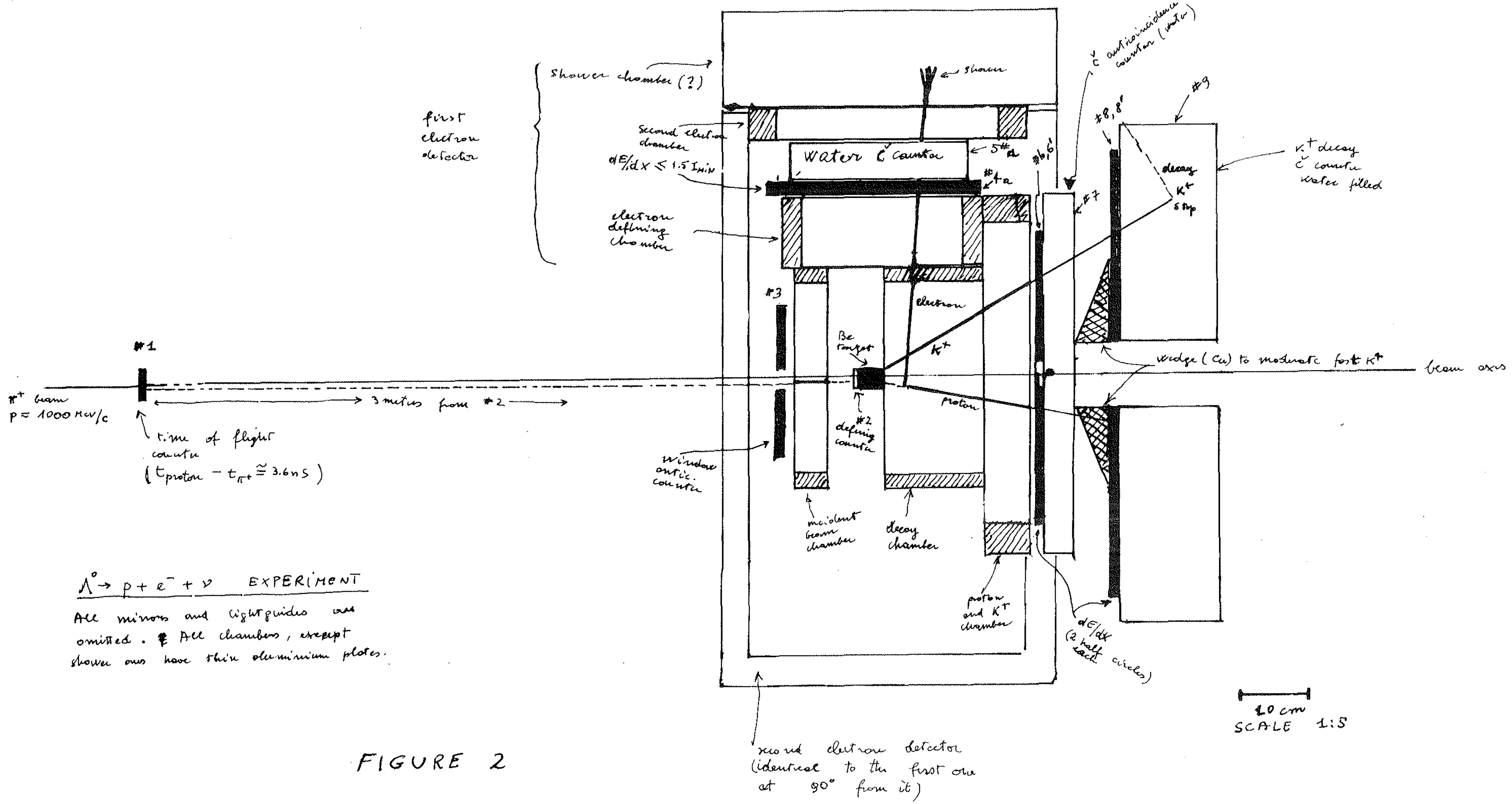
Fig. 5 : Laboratory energy spectrum of electrons from $\Lambda^0 \rightarrow p + e^- + \nu$.

Fig. 6 : T_π(lab) versus Θ_π(lab) for the decay mode $\Lambda^0 \rightarrow p + \pi^-$.

FIGURE 1

Λ β-DECAY
EFFECTS OF THE
INTERACTION FORM





$\Lambda^0 \rightarrow p + e^- + \nu$ EXPERIMENT

All mirrors and lightguides are omitted. All chambers, except shower ones have thin aluminium plates.

FIGURE 2

FIGURE 3

$\Lambda \to e + p + \nu$

$p_\Lambda = .6$ GeV/c

PHASE SPACE

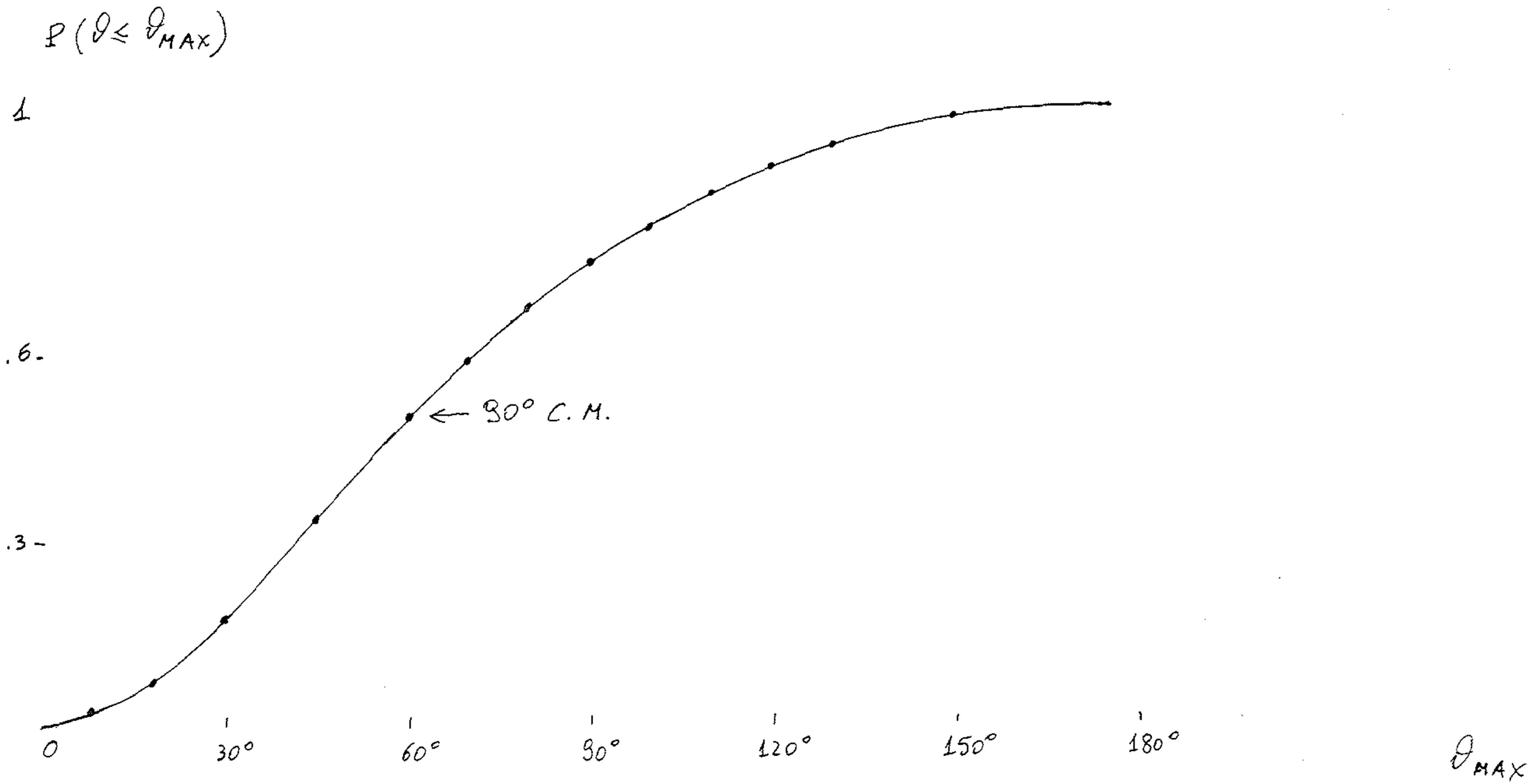


FIGURE 4

$\Lambda \rightarrow e + p + \gamma$

ELECTRON ASYMMETRY AS A FUNCTION OF THE LABORATORY ANGLE ϑ_{LAB}

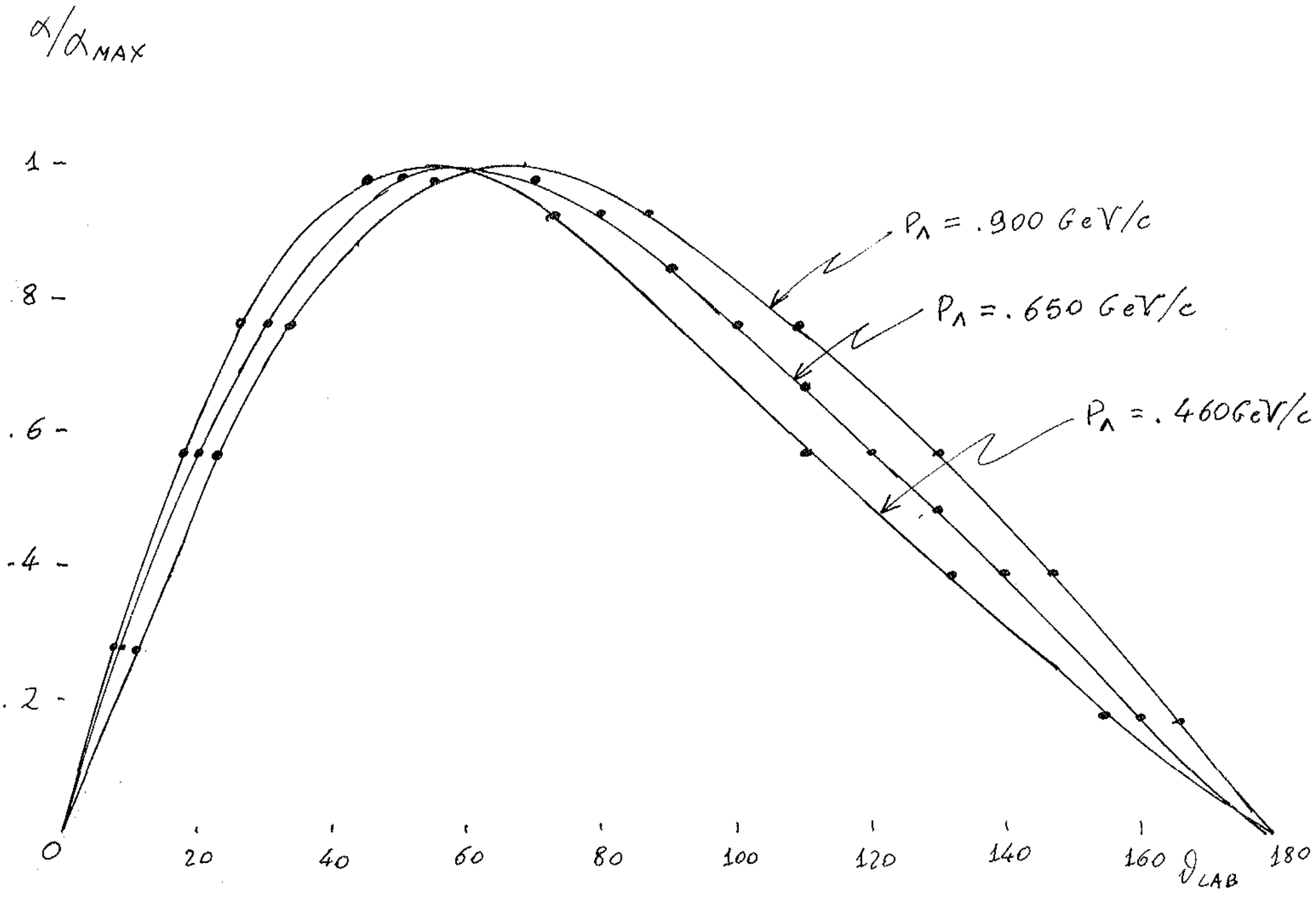


FIGURE 5

$\Lambda \to e + p + \nu$

Lab energy / CM energy as a function of ϑ_{LAB} of the decay electron

$E_{MAX}(C.M.) = 176$ MeV

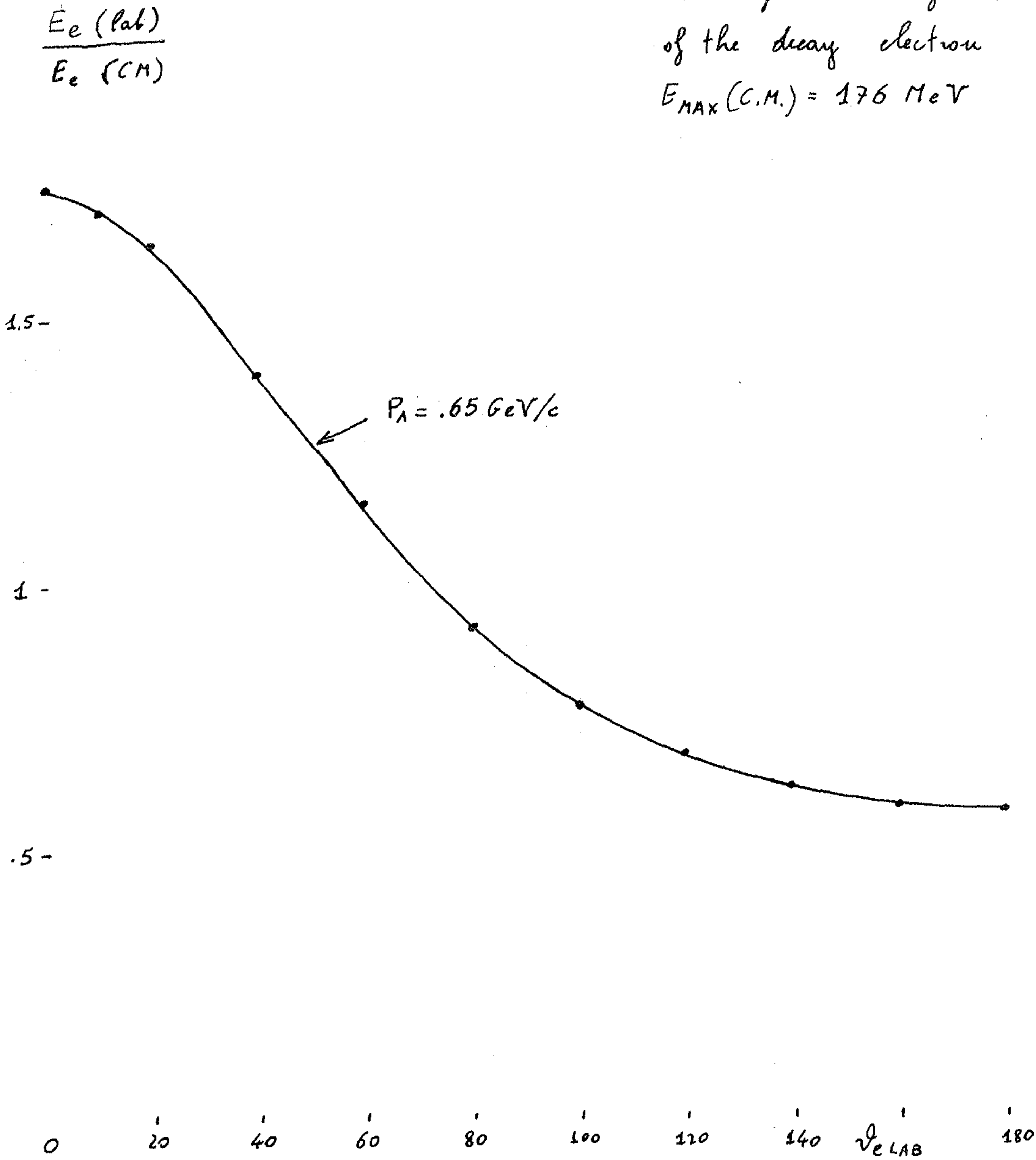


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FIGURE 5

DECAY MODE

$\Lambda \rightarrow \pi^- + p$

π^- KINEMATICS