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MIND OVER MATTER

THE INTELLECTUAL CONTENT OF EXPERIMENTAL PHYSICS

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MIND OVER MATTER:
THE INTELLECTUAL CONTENT OF EXPERIMENTAL PHYSICS

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According to my experience, the most brilliant physics students at any university want to become theoreticians, and this on both sides of the Atlantic ocean. It is rare that a person of the intellectual power of, say , a Gell-Mann or a Cabibbo decides to embark on a career in experimental physics. It is obvious that this fact entails a serious loss for physics, since physics is primarily a natural science. I have often asked myself about the reasons for this regrettable situation; once these are established, perhaps remedies could be suggested.

I have come up with two reasons. The first of these is the style in which physics is taught essentially everywhere. There are two models, A and B, both of which fail to convey to the students the <u>intellectual content</u> of important experiments. Following model A, the student is told that some great genius, identified by name, predicted a remarkable dependence y(x) of one observable upon another. That dependence was then subsequently brilliantly confirmed by experiment - by some unspecified person. In model B, one presents an observed dependence y(x) that constituted, at its time, a great puzzle. Again, a great genius (name given) came along and presented a theory which fitted the observations perfectly. In either model, the intellectual accomplishment of the experimentalist is generally not conveyed to the students. I shall illustrate this by two examples: (1) in Okun's masterful book "Leptons and Quarks", experiments are rarely described - although the authors are given - their results are merely quoted, as "one finds....". (2) I once gave a course "Great Experiments in Modern Physics" at MIT. It was attended by young students and ... senior theorists. Many of the latter learned for the first time <u>how</u> Willis Lamb had actually determined "his" shift, how many brilliant insights he had had to have to achieve his goals.

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Quite a few people concluded correctly that there was as much intellectual content in the Lamb experiment as in the QED explanation of it (This example is marred by the fact the Lamb was actually an accomplished theorist!).

A second, altogether different reason derives from what I might call the "theory of the father image ": In practice, all our physics courses are theoretical, whether the title of the course says so or not. The theorists teaching theory mostly know what they are talking about, and the experimentalist frequently do not. So the student (who though he may himself not understand the subject, still infallibly catches the lack of understanding of the lecturer!) says to himself: "I do not want to become like him (insert name of experimentalist) but like him (insert name of theorist)".

What can we do to remedy this situation? Two things: First, we must postpone the difference in training of future experimentalists and theorists as far as possible. The difference is one of technique and not one of intellectual competence. Second, we must teach courses in which brilliant experiments of great significance are analyzed in some detail.

I shall, in what follows, describe some experiments which fall into this category, of course more briefly that one would do so in a curricular lecture. I have avoided experiments which are (and should be) generally known, hoping to offer you some pleasant surprises. I shall discuss four experiments in chronological order.

1. Selényi's Experiment On Dipole Radiation

In 1911 a young Hungarian physicist, Paul Selényi, performed an experiment to demonstrate that wide-angle interference of light rays does take place [1]; what is meant is a wide angle at the emission, so to speak in the near zone of the source. It seems that at that time the possible occurrence of such an interference was the subject of considerable debate: I do no understand this, since interference is a relativistically invariant concept, and what is wide angle in one frame is narrow angle in another.

...2

Selényi's simple setup is schematically shown in Figure 1. Between a glass prism PR and thin mica sheet M there is a film of gelatin- fluorescein, the thickness of which is small as compared to the wave length of visible light. By a concentrated beam of light a small spot of the film is excited to fluorescence and fringes due to the interference of rays I and II are observed through a hand-spectroscope, not shown in the figure (this is necessary because the fluorescence light is not at all monochromatic). Selényi chose this arrangement because he realized that the light source required for producing wide-angle interference *must be essentially a two-dimensional light source,* lying exactly parallel to the mirror. This requires a gelatin layer say $\lambda/7$ thick.

Upon repeating the experiment in 1938 under more favorable conditions [2], Selényi obtained the following results: (a). The minima, as observed at an angle $\theta = 45°$, were never completely dark; (b) by inserting a polarization *filter* so oriented that only the electric light vector $\vec{E}$ perpendicular to the plane of incidence (i.e. of Fig. 1) was transmitted, the fringes became more brilliant and the minima became perfectly dark. Rotating the analyzer by 90° the fringes disappeared completely.

These observations prove, or are at least consistent with, the fact that the fluorescence light is emitted by *electric dipoles*. To see this, replace the randomly oriented dipoles by three mutually perpendicular, independent ones. The first of these, *not* shown, oscillates perpendicularly to the plane of Fig. 1. It emits equal amplitudes along the rays I and II, and hence produces interference fringes with perfect minima. The other two dipoles, 1 and 2 in Figure 1, produce no interference at all, since 1 does not emit along I, and 2 not along II.

The above simple argument is due to Selényi himself, who makes fun [3] of some theoreticians [4] who presented complicated mathematical arguments to explain an "experiment that can be performed in half a day at the utmost, and that can be clearly explained in a few lines and without any mathematical formulas."

...3

2. Michelson's Optical Demonstration Of The Earth's Rotation

When I was a graduate student at ETH, some 40 years ago, much of our theoretical knowledge was to be derived from G. Joos's one volume "Theoretische Physik". In that book a certain interference experiment carried out on a rotating platform (the Sagnac experiment) was discussed as the "optical analog of the Coriolis force". This affirmation puzzled me a great deal (as a potential contradiction with Mach's principle) for many years and I read a lot about the subject. Thus I came across Michelson's wonderful optical "Foucault pendulum".

Michelson considered [5] in 1904 a small (spherical) rectangle on the earth surface, bounded by two great circles and two latitudes $\phi \pm \delta\phi$. Two light rays from a single source and running in opposite directions along the perimeter were brought to interfere. Michelson predicted, no doubt by applying the then standard stationary ether theory, a fringe shift

$$\Delta = \frac{4 A \omega}{\lambda c} \sin \phi, \qquad \text{(no. of fringes)} \qquad (1)$$

where A = area of the light circuit, ω = angular frequency.

It is easy to see that this can be written in general as

$$\Delta = \frac{2}{\lambda} \int \vec{v} \cdot d\vec{s} \,/\, c, \qquad (2)$$

i.e. that one is dealing here with a v/c effect, so that applying relativity or not is irrelevant.

Sagnac, in 1913, performed the experiment with a rotating interferometer and confirmed the above formula [6]. He could, obviously, determine the shift Δ with reference to the interference on the stationary platform ($\omega = 0$).

Michelson, who performed in 1925 [7], in collaboration with Gale and Pearson, the experiment proposed by him in 1904, could obviously not stop the earth's rotation. How did he beat the devil?

First he built, out of evacuated pipes, a truly gigantic interferometer (Fig. 2), on a site near Chicago. The interferometer had long circuit ADEF, and a short circuit, ADCB. Since the shift Δ due to rotation is proportional to the area A enclosed by the light circuit, it was the interference pattern of the short circuit that served as reference (simulating $\omega = 0$).

There arises the question how a relative shift due to misalignment of the mirrors could be excluded. The argument goes as follows: Either circuit produces two images of the source, namely a direct and a reflected one (independently of interference or rotation). In the middle between these two images is the interference pattern, with the zero-order fringe in the center. The central fringes given by the short circuit and those of the long circuit would be halfway between the direct and reflected images if there were no difference due to the earth's rotation.

Ideally, the two sets of images should be superimposed. In practice, to correct for any lack of superposition, the observing telescope was focussed on the images of the source and the apparent relative displacement of the central fringes corrected by an amount equal to the difference in the mean positions of the two images of the two circuits.

The result, the mean of 13 series of observations, was

$$\Delta = 0.230 \pm 0.005$$

which is to be compared with the prediction ($\lambda = 5700$ Å, $\phi = 41°46'$)

$$\Delta = \frac{4A\omega}{\lambda c} \sin\phi = 0.236 \quad (2)$$

The Michelson-Sagnac effect is today no longer a mere scientific curiosity, but the basis of a practical instrument, the laser gyroscope, widely used for inertial guidance. The trick is to go from the λ-scale to the ν-scale, with a corresponding enormous increase in sensitivity. In a rotating ring-laser, given $(L = n\ \lambda)$ eigenmodes of two counterpropagating beams have frequencies differing by $\Delta\nu = v/\lambda$. By bringing them to interfere, one gets a beat at a frequency $2\ \upsilon\ v/c = 4\ \pi\ (R/\lambda)\nu_E$, where R = radius of (circular) ring laser, ν_E= rotation frequency of the earth $\approx 10^{-5}$ sec^{-1} . Hence for $R \sim 1$ cm one gets $\Omega \sim 1$ Hz, a well observable audio frequency. The device is a standard commercial item.

3. The Direct Measurement Of The Helicity Of The Electron Neutrino, ν_e, by Goldhaber, Grodzins and Sunyar [8]

When the lack of mirror symmetry (parity violation) in β-decay was discovered in January 1957, essentially all reliable experiments involved electrons (or positrons). It was established the $e^- = e_L$ (and $\bar{e} = e^+ = e^+_R$), but it was a burning open question whether one had $\nu = \nu_L$ (and $\bar{\nu}_R$) or $\nu = \nu_R$ (and $\bar{\nu} = \nu_L$). Here the indices L (left) and R (right) specify the handedness of the particle, i.e. the helicity defined as $h \equiv \langle \vec{\sigma} \cdot \hat{\upsilon}/c \rangle$. The choice (e_L, ν_L) corresponds, in technical parlance, to "V, A coupling" and the choice (e_L, ν_R) to "S, T coupling". This question was answered, about simultaneously, by a study of the correlations in the decay of polarized neutrons [7], and by a direct measurement of the helicity of the emitted neutrinos.

It is impossible to measure the helicity of neutrinos by methods analogous to those used for electrons, e.g. by scattering them from polarized electrons, since neutrinos interact only weakly. Hence a radically new idea was needed.

Following M. Goldhaber, consider a decay chain leading from a parent nucleus A (spin $J_A = 0$) via an excited state B* ($J_B{}^* = 1$) to a final daughter nucleus B ($J_B = 0$).

...6

One thus has the sequence:

$A + e^-$ (e-capture) ⟶ B^* (deexcitation) ⟶ B (ground state) + γ. Let us represent the conservation of angular momentum and momentum graphically, assuming $\nu = \nu_L$ (Fig. 3)

Thus a photon emitted along the direction of flight of the excited nucleus B^* will be left-handed ($\gamma = \gamma_L$) - i.e. its helicity will be the same as that of the emitted neutrino. Obviously, this helicity transfer would also occur if one had $\nu = \nu_R$. (Note that the drawing assumes equal energy releases in both steps). Thus experimentally one must (a) measure the circular polarization of the emitted γ-ray, (b) establish that it went along $\vec{P}_{B^*}$. Step (a) is comparatively easy, magnetized iron serving as an analyzer. Step (b) is more subtle - one must use "resonant fluorescence" to accomplish it.

Assume we had the nucleus B^*, with excitation energy E_o, at rest in the laboratory and we wanted to scatter the photon it emits from a nucleus B. Because of recoil the photon energy $E_\gamma = cp_\gamma$ would be less than E_o, approximately as $E_\gamma = E_o - E_o^2/2Mc^2$. In the act of absorbtion, the nucleus recoils again, so that the energy available for excitation is $E_\gamma{}' = E_o - E_o^2/Mc^2$. Thus the resonance condition is missed by E_o^2/Mc^2. When B^* decays forward in flight, as shown in Fig. 3, the resonance condition is restored (assuming $p_\nu \sim p_\gamma$).

A little thought reveals that an exceptional set of conditions had to be met simultaneously to make this experiment possible in practice, viz.

(a) The spin sequence 0 - 1 - 0;

(b) The spin-parity sequence 0^- - 1^- - 0^+. For B^* to decay rapidly, i.e. in flight, its γ-decay must be E 1 (the ground state B has almost unavoidably spin-parity 0^+). Thus 1^- for B^*; for the e-capture to be an allowed one, A must be 0^-.

(c) The energies cp_ν and E_0 must be essentially the same.

(d) These energies must be large (few hundred keV) to avoid the Mößbauer effect and to make the polarisation analysis possible.

(e) The stable nucleus B must be an abundant isotope so as to serve in practice as a scattering target.

All these conditions were met by $A = Eu^{152m}$, $B = Sm^{152}$. Note that at that time this decay scheme was known only to Goldhaber and his collaborators.

Napoleon once said that "the Lord is always on the side of the stronger armies", and I say that the Lord is always on the side of the ingenous experimentalist.

Fig. 4 shows the experimental setup used by Goldhaber and his collaborators. Their result was $h_{\nu_e} = -1 \pm 0.3$, i.e. the e-neutrino is lefthanded.

4. The Determination of the Helicity of the Muonic Neutrino
by Grenács et al. [9] al.

Muon capture proceeds, as was first realized by B. Pontecorvo, in full analogy with e-capture. Thus one is immediately tempted to measure the helicity of the ν_μ in analogy with the GGS experiment I just described. The analogy, however, breaks down because the energy release (p_ν) in μ-capture is much larger than any nuclear excitation energy E_0. Thus an entirely different way must be found to determine the longitudinal polarization of B*, even assuming the same spin sequence. Consider the decay chain

$$A\ (0^+) + \mu^- \longrightarrow B\ (1^+) + \nu_\mu$$

$$B\ (1^+) \longrightarrow C\ (0^+) + e^- + \bar{\nu}_e;\ C = A$$

The longitudinal polarization $\vec{P}$ of B is directly measured via the known (maximal) up-down asymmetry in its decay to A; the only - highly non-trivial - condition is that B be sufficiently short-lived for it not to be depolarized in matter before its decay.

Again Nature is kind and provides a decay chain with the proper spin-parity sequence, viz.

$$C^{12}\ (\text{g.s.},\ 0^{+}) + \mu^{-} \longrightarrow B^{12}\ (\text{g.s.},\ 1^{+}) + \nu_{\mu}$$

$$B^{12}\ (\text{g.s.},\ 1^{+}) \longrightarrow C^{12}\ (\text{g.s.},\ 0^{+}) + e^{-} + \bar{\nu}_{e},$$

the old "Godfrey-Tiomno" cycle. B^{12} is short-lived (28 msec), and furthermore its polarization can indeed be preserved in certain materials. These facts are, however, only necessary but not sufficient for an actual experiment. How does one tell which way the recoil, i.e. the neutrino ν_{μ}, went? The trick is illustrated in Fig. 5 : A very thin carbon layer C, in which the μ-capture occurs, is sandwiched between a polarization-retaining layer P and a depolarizing layer D. Boron recoils going into the D hemisphere decay isotropically, while those stopping in P decay with the characteristic "up-down" asymmetry. Note that P, in the absence of a holding field $\vec{B}$, becomes also depolarizing, which is useful for systematics checks. As indicated in Fig. 5 (a), the sandwich can be flipped by 180° leading to a change of the counting rate in either telescope (per fixed number of muon stops). In actual practice (see Fig. 5 b) the target consisted of a stack of 1000 P/C/D sandwiches, as specified in the figure caption. The whole stack contained only 60 mg/cm² of carbon (!), so that extraneous carbon in the apparatus had to be carefully avoided. For that reason, proportional chambers rather than scintillators were used in the telescopes. The data shown in Fig. 6 are averages of the two telescopes. Correcting the raw longitudinal polarization $\bar{P}^{i}$, Grenàcs et al. obtained the final result

$$h_{\nu_{\mu}} = -1.06\ (11),$$

i.e. the muon neutrino is lefthanded, like ν_{e}.

Added remark: The τ-neutrino helicity [11]

Recently, the quantity h_{ν_τ} has been experimentally determined by the ARGUS collaboration [12].

They assume the decay chain (or its charge conjugate)

$$\tau^- \to a_1^- + \nu_\tau$$

$$a_1^- \to \rho^\circ + \pi_1^-, \quad \rho^\circ \to \pi^+ + \pi_2^-$$

The a_1 meson, of spin parity 1^{++}, plays here the role of the B^* nucleus, ρ° that of the photon, and π_1^- that of B. The polarization of the a_1 is detected through the asymmetry of the normal to the 3 π decay plane with respect to the boost direction.

I dedicate this essay to Torleif Ericson, in the occasion of his sixtieth birthday. My first opportunity to express publicly the views presented here as an introduction was at a Varenna Summer School organized by Torleif many years ago. May Torleif and his "better half", Magda, enjoy many more years of creativity and intellectual vigor. My better half, Lia, joins me in this good wish.

...10

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...11

FIGURE CAPTIONS

Figure 1 Schematic of Selényi's experiment. M = mica sheet, PR = glass prism. Between the two is the thin gelatin-fluorescein layer.

Figure 2 Ground plan, showing mirror arrangement, of Michelson's "Foucault' experiment. AD = FE = 67 m, AF = DE = 37 m.

Figure 3 Angular momentum conservation in the GGS helicity experiment.

Figure 4 Apparatus used in the GGS helicity experiment.

Figure 5 Apparatus used in the helicity experiment of Grenàcs et al. (a) Principle of the experiment: C = carbon layer, D = depolarizing, and P = polarization preserving layer; T_1 , T_2 = telescopes. b) Actual setup: S = stack target, Ab = absorber, HC = Helmholtz coils, S_1 S_2 = beam monitor, 1, 2, 3, = multiwire proportional chambers, and B = longitudinal holding field. S consists of one thousand sandwiches Al (1.5 μm) / C (60 μg/cm²) / Ag (1200 μg/cm²).

Figure 6 (a) Schematic relationships of the polarizations in the two stack orientations (boundary of polarization retaining layer P is shaded). (b) Results of raw polarization measurements with the stack target in its two orientations. The data represent averages of the two telescopes; the various points plotted horizontally represent independent runs.

$\bar{P}^{i} \equiv [1 - N^{i}(B) / N^{i}(o)]$, i = specifies orientation, i.e. F or B; N β-rates with and without field B.

...12

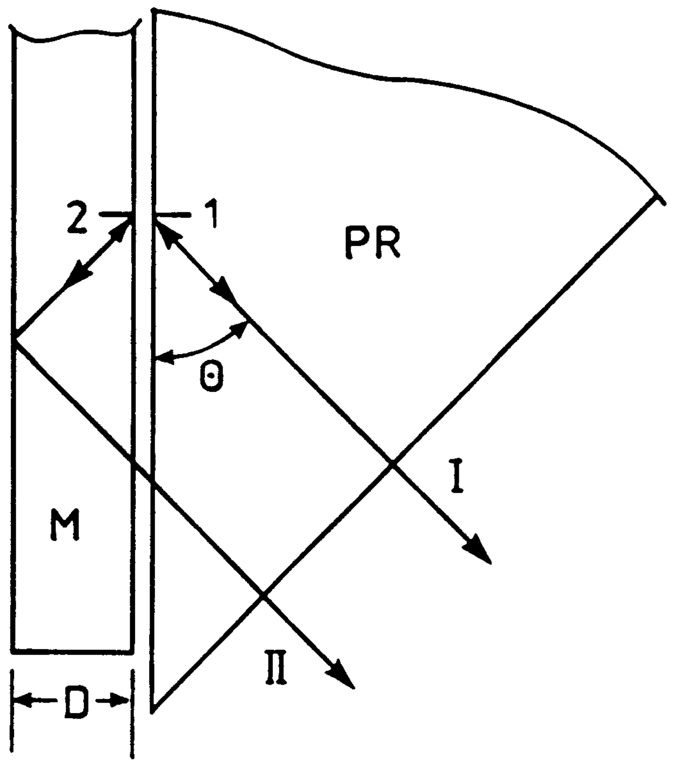


FIGURE 1

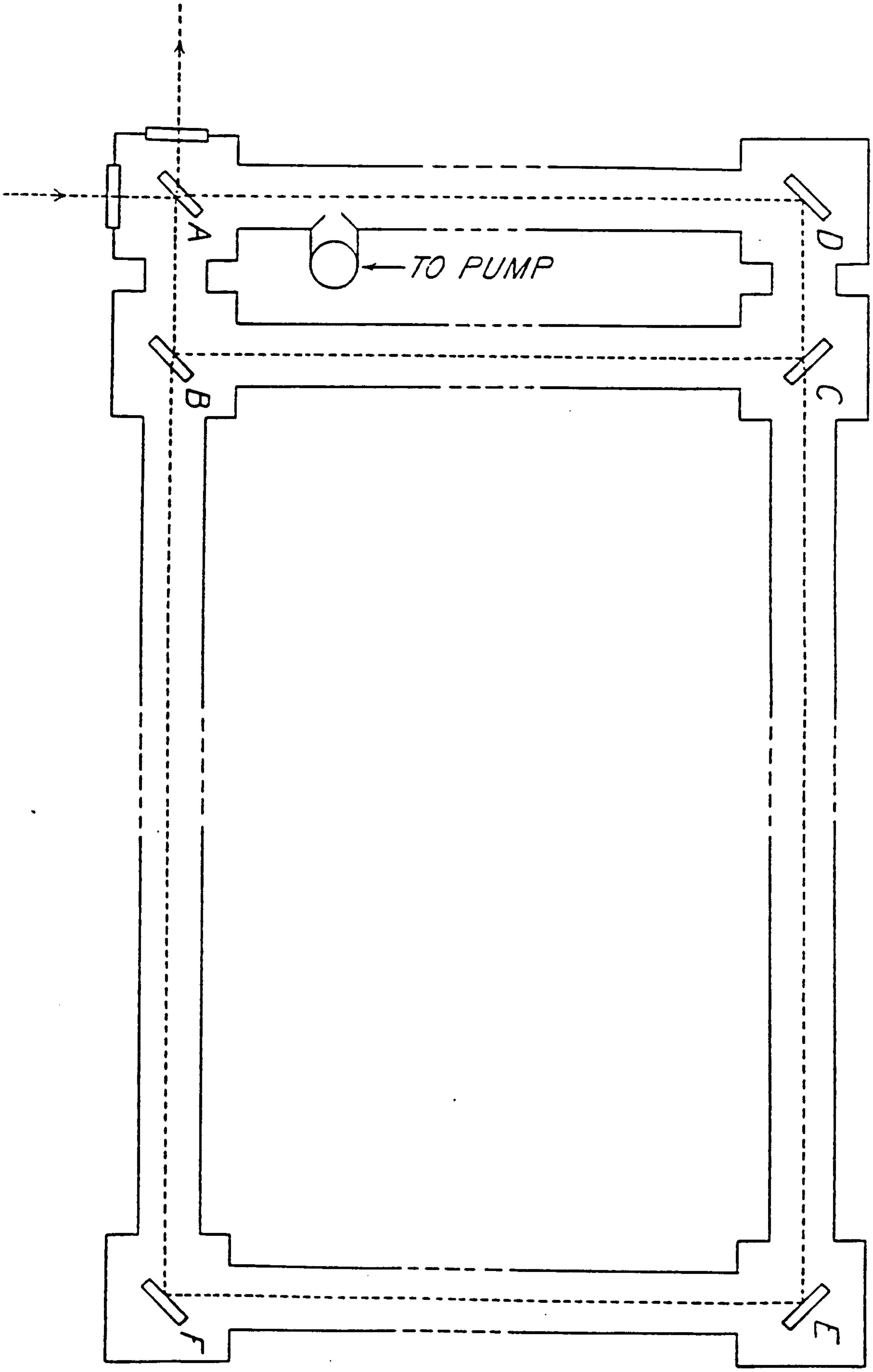


FIGURE 2

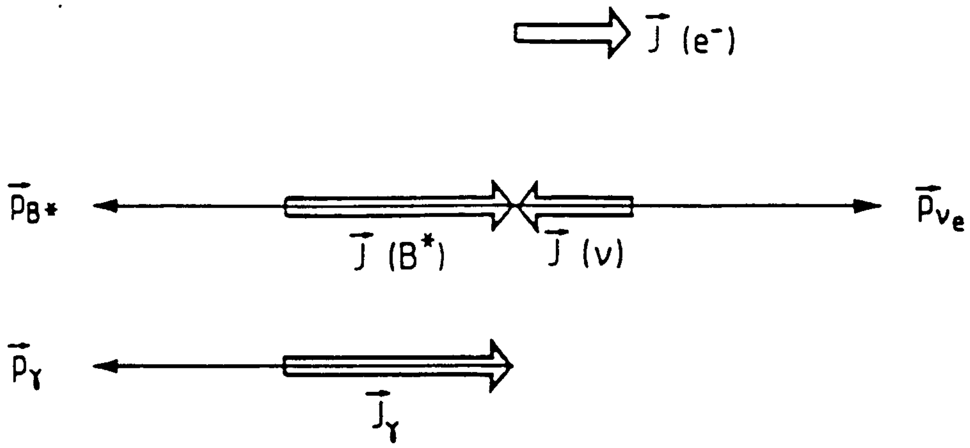


FIGURE 3

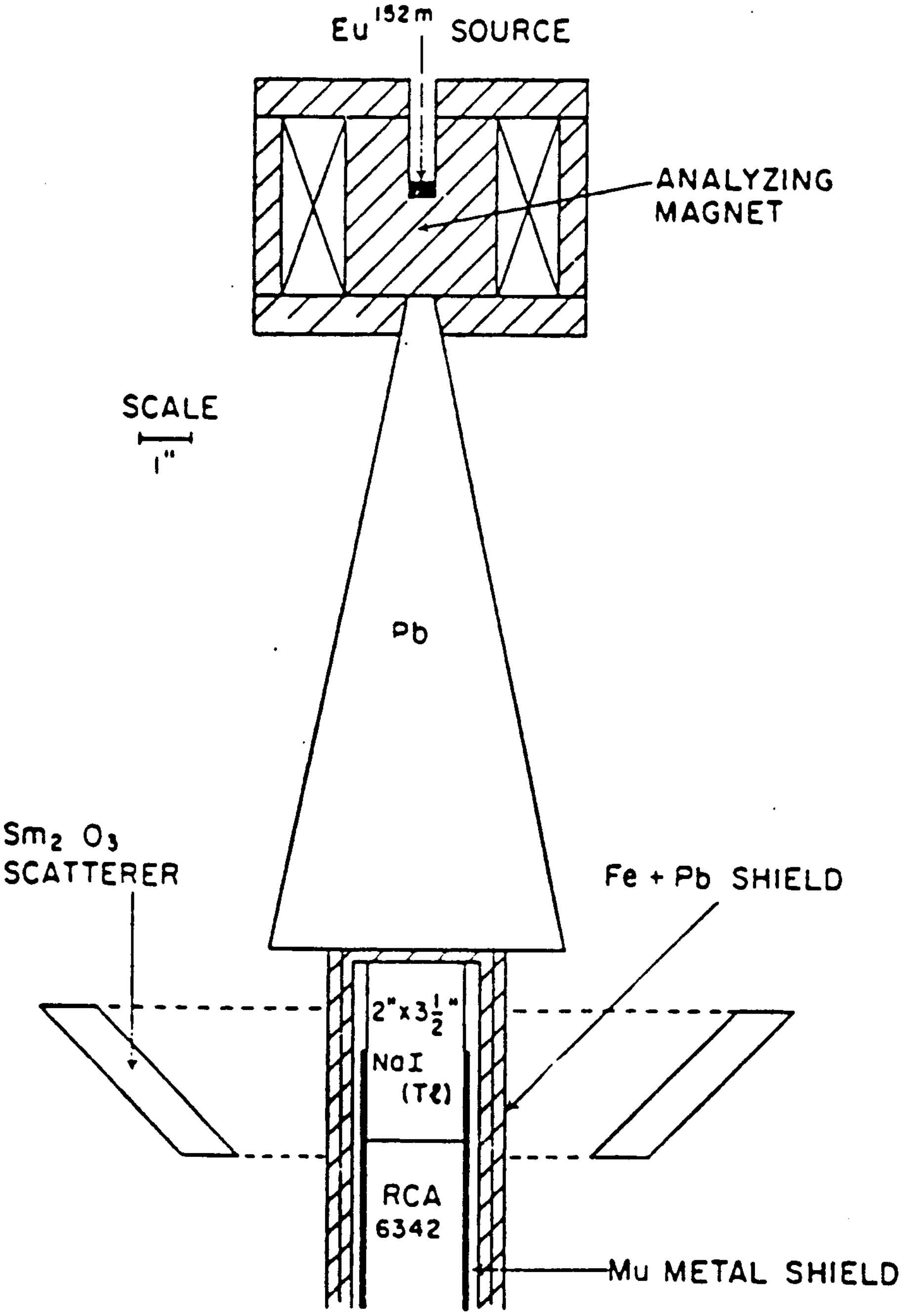

Eu^{152m} SOURCE
ANALYZING MAGNET
SCALE
1"
Pb
Sm$_2$ O$_3$ SCATTERER
Fe + Pb SHIELD
2"x3$\frac{1}{2}$"
NaI (Tl)
RCA 6342
Mu METAL SHIELD

FIGURE 4

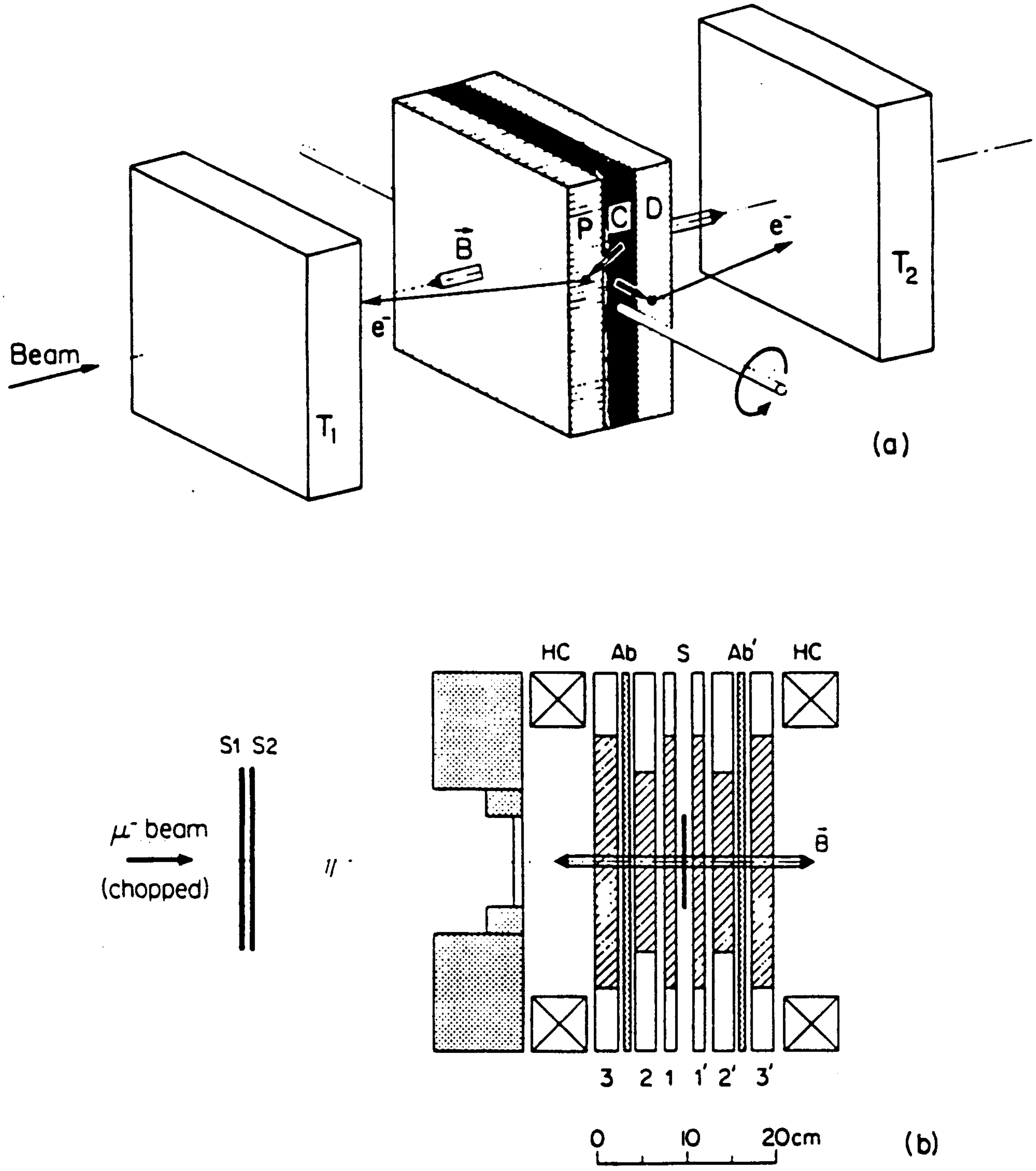
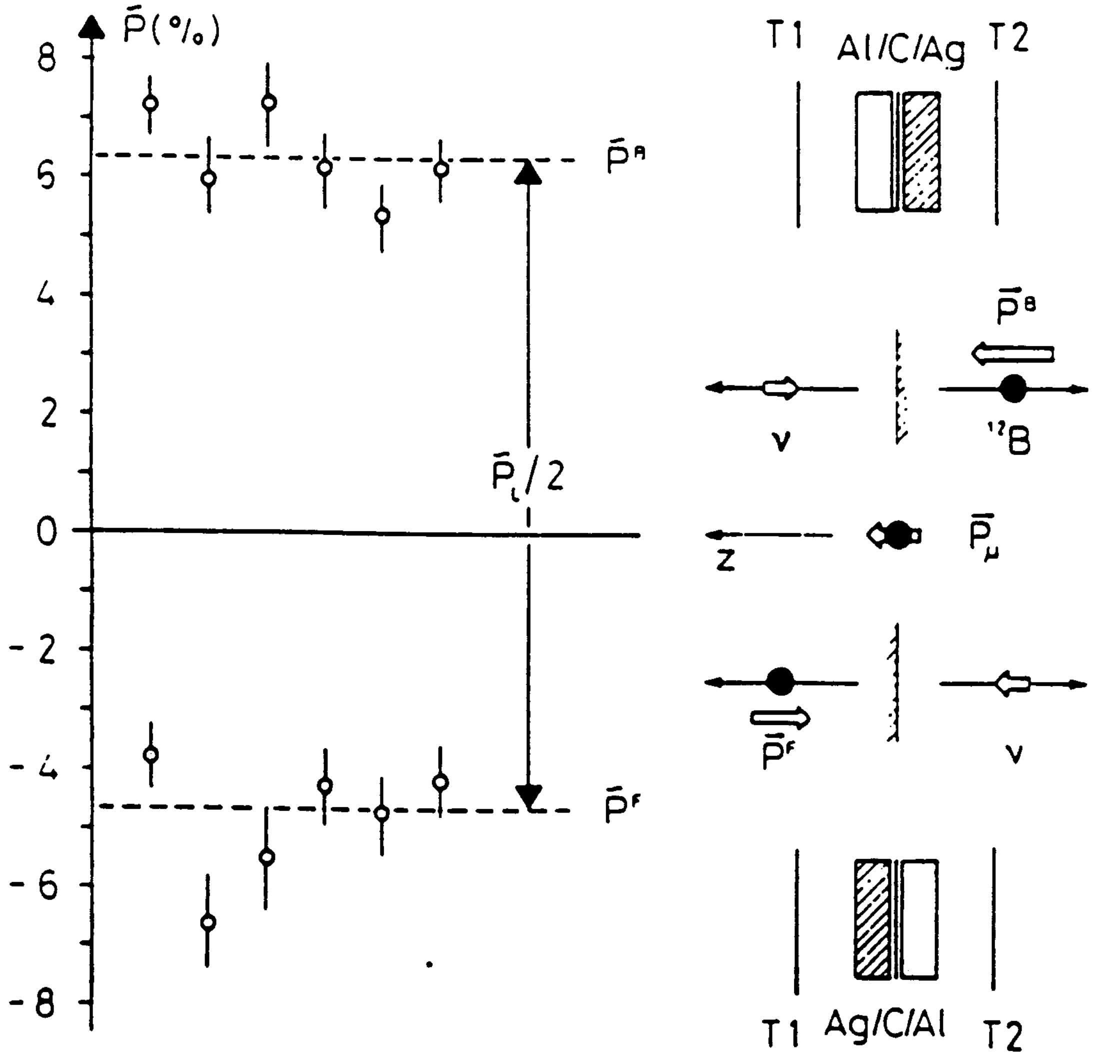

Beam
T1
e⁻
B
P
C
D
e⁻
T2
(a)
μ⁻ beam
(chopped)
S1 S2
HC
Ab
S
Ab'
HC
B
3
2
1
1'
2'
3'
0
10
20cm
(b)

FIGURE 5



(b) (a)

FIGURE 6

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