CERN/PSCC/84-46
PSCC/P64 Add. 2
17.10.84

Addendum to the Proposal:

CERN/PSCC 82-86/P64; 84-18/P64 Add 1

Measurements of the ratio between the double- and single-ionization cross sections of helium by antiproton impact

Aarhus-CERN-Stockholm Collaboration

L.H.Andersen, J.Bak, P.Hvelplund, H.Knudsen,
S.P.Møller, and E.Uggerhøj **
Institute of Physics, University of Aarhus
DK-8000 Aarhus C, Denmark

A.H.Sørensen*
CERN, CH-1211 Geneva 23, Switzerland

G.Astner, I.Bergström, and L.Liljeby
Research Institute for Physics
S-104 05 Stockholm, Sweden

---

[*] Contact man

[**] Spokesman

Status

The physics aim of this proposal was already discussed by the Committee in February 1983 and recommended if technically feasible. A detailed technical solution was suggested in Add.1 but the equipment was not completely ready at that time and therefore no measurements with equivelocity protons in the setup could be presented.

In the present Addendum a short presentation of the physics program is given followed by a discussion of the experimental apparatus which is now completed. Finally the results are given of a test experiment with a 12-MeV proton beam incident into the actual setup.

A short Review of the Physics Program

1. Introduction

Although ionization processes during the penetration of charged particles through matter have been studied for more than fifty years, many questions remain unsolved - especially for multiple ionization processes. Here correlation effects between the target electrons strongly complicate the description. On the other hand, the understanding of these basic phenomena is considered one of the most fundamental problems in atomic physics today and an enormous amount of work is put into the field. The understanding of correlation effects in ion collisions with the most simple two-electron targets like H^- and He is far from being complete. Here we propose to use LEAR to study the ratio of double- to single-ionization in the interaction of antiprotons (and, elsewhere, protons) with helium. We have theoretical reasons to expect that this ratio will be sensitive to interference between even and odd terms in q, the charge of the impinging particle. Helium with only two electrons is clearly the simplest target seen from an experimental viewpoint, and furthermore, the theoretically most tractable system in which such an effect could be investigated. Moreover, helium represents a target where correlation effects play a major role. The use of the $p,\bar{p}$ pair of identical particles is essential because only this pair can (now!) be produced with the low velocities necessary. The experiment is thus a very fundamental one which, nevertheless, thanks to the large atomic cross sections, can be completed in one LEAR Operation Day at 200 MeV/c, which is our request of beam time.

Investigations of ionization using electron/positron beams in the proposed velocity region is of course also of big interest, but the low projectile mass means that such particles would lose at least 20% of their speed in a double ionization collision and that the straight path approximation is not justified. Electrons would be focussed onto the helium nucleus whereas positrons would be defocussed. Consequently kinematical and charge-difference effects are not separable for the e^+/e^- pair. Further on such low velocity electrons/positrons may give rise to exchange and annihilation problems. Therefore it is generally accepted in the atomic collision community that the proposed experiment is the most simple and "clean" investigation of correlation effects.

We point out that this problem is thematically related to the occurrence of q^3 terms in atomic stopping powers (first seen with pions: the Barkas effect), and that studies of this kind could be a logical next step. It is clearly important that the potential of LEAR for this research be demonstrated (or the opposite) before the ACOL shutdown.

2. Inelastic Collisions in Gases

As mentioned above, gas ionization due to penetration of particle beams has been the subject of numerous theoretical and experimental investigations. Despite this, however, many questions remain unanswered, often due to lack of the right beams. The theoretical treatment of inelastic collisions is usually concerned with one of the two regimes, i.e., (i) those collisions in which the projectile velocity V is high compared to a mean velocity of atomic electrons in the shell under consideration, and (ii) those where the velocity is low compared to that of the atomic electrons. For (i), Bohr$^{1)}$ early in this century published a theory, and more than fifty years ago, Bethe$^{2)}$ developed his quantum-mechanical perturbation theory based upon the Born approximation. For a recent review, see Ref.3. For single ionization by heavy, charged particles, the cross section σ^+ is well known both experimentally and theoretically. For singly charged projectiles with velocity V higher than $2v_o$, it is found that

$$\sigma^+ \propto \frac{q^2}{V^2} \ln V ,$$

where v_o and q is the Bohr velocity and the particle charge, respectively. here it is seen that σ^+ contains explicitly particle velocity rather than kinetic energy. Further, it should be noted that results from such perturbation treatments scale with q^2. This means that the single-ionization cross section for equivelocity electrons and protons is expected to be the same.

For multiple ionization the understanding is far from complete. Even for the simplest two-electron atom He the situation is obscure. At very high projectile velocities ($V \gtrsim 20\ v_o$) the first Born approximation predicts that the cross section σ^{++} is proportional to the single-ionization cross section σ^+, and therefore it should be independent of the sign of the particle charge. The mechanism responsible for double ionization in this regime can be visualized in the following manner: First, one electron is removed due to the particle impact. Then the other electron relaxes onto the electronic states (including continuum states) of He^+. This is called the shake-off (SO) mechanism. The calculated ratio $R \equiv \sigma^{++}/\sigma^{+}$, however, depends critically on the amount of correlation between the two helium electrons that is incorporated both in the initial helium wave function used in the calculation as well as in the post-collision rearrangement process (Ref.4), and it is not known to better than a factor of ~ 3.

At somewhat lower particle velocities ($V \sim 10v_o$), it was recently found$^{5)}$ that quite surprisingly, the ratio between the double- and single-ionization cross sections R was not the same for equivelocity proton and electron impact, the latter giving R values a factor of two larger than the former (see Fig.1). This inspired McGuire$^{6)}$ to suggest that the observed effect was due to the influence of another mechanism for double ionization, the so-called "two-step" (TS) mechanism. Here double ionization is believed to take place due to two consecutive, close particle-electron collisions, and therefore:

$$\sigma_{TS}^{++} \propto (q/V)^4 .$$

However, the absolute magnitude of σ_{TS}^{++} could not be calculated.

To explain the electron and proton data, McGuire suggested that the amplitudes for the two mechanisms be added,

$$\sigma^{++} \propto |a|^2 = |-qa_{SO} + q^2 a_{TS}|^2 ,$$

this of course giving a difference between $q = 1$ and $q = -1$. In this model, the electron-proton difference is a charge-difference effect.

The addition of scattering amplitudes in the McGuire model has recently been questioned and it was suggested[7)] that the difference is due to kinematic differences between the electron and the proton - even at these large particle velocities.

The proposed investigation is therefore an ideal experiment, which could reveal whether McGuire's model is correct. Further on, we would obtain information on the basic mechanisms for double ionization at high impact velocities by comparing the measured ratio between double and single ionization of helium by 5 MeV antiprotons and the already existing proton- and electron-impact data[8)]. This experiment would also be the first very essential investigation of this type for which the results depend critically on electron-electron correlations.

3. Experimental Technique

The experimental apparatus, which was completed in the summer of 1984, is shown in Figs.2 and 3.

To obtain a suitable particle energy, the 200-MeV/c $\bar{p}$'s from LEAR are degraded in a plastic scintillator of thickness 4020 μm which, together with the 100-μm Al window of the LEAR vacuum system and a 1000-Å gold coating, will produce a beam of 5-MeV antiprotons of energy straggling 1.1 MeV and 7.4° angular width (FWHM). The gold coating of the down-stream side of the scintillator is raised to a voltage of +800 V to prevent electrons from exiting from the degrader into the target region.

In the target region, the antiprotons interact with a thin gas of pure helium and produce He^+ and He^{++} ions. These are extracted by a uniform transverse electric field (800 V/cm) between two condenser plates. The ions then pass through a flight tube, where they are focussed and accelerated onto a ceramic channeltron detector which counts the ions with an efficiency close to 100%. The antiprotons pass through a second plastic scintillator and are finally stopped in a beam dump about 1 m away.

The pulses created in the channeltron are used as start pulses in a time-of-flight electronic setup, and the pulses from the two scintillators (run in coincidence) supply the corresponding stop pulses after a delay of 600 ns. The flight times of the He^+ and He^{++} ions are $\sim$280 and $\sim$200 ns, respectively. The ion-optical system has been designed to give optimum time resolution (better than 10 ns) in spite of the broad $\bar{p}$ beam.

Using a helium-gas pressure of 3 mtorr and with 3×10^5 $\bar{p}$/s, we expect to detect 165 sec^{-1} He^+ ions and $\sim$0.4 sec^{-1} He^{++} ions (twice as much if the upper curve in Fig.1 is used to estimate the $\bar{p}$ cross section for double ionization). The signal/noise ratio of the He^{++} peak in the time-of-flight spectrum is expected to be in the order of one due to random coincidences stemming from the large count rate in the stop channel.

During the passage of the $\bar{p}$ beam through the 4020- μm plastic detector, we expect 6% of the $\bar{p}$'s to annihilate. This is based on the following estimated cross sections for annihilation of 150-MeV/c $\bar{p}$: in H: 480 mb; in C: 2500 mb.(In Add 1 , a geometric cross-section was erroneously used in this place). The resulting high-energy pions and other particles are not expected to increase significantly the background level in the time-of-flight spectrum as such radiation is detected by the channeltron detector with very low efficiency.

Assuming the count rates and signal-to-noise ratio mentioned above, we expect sufficient statistics on the measured value of R in around six hours for one gas pressure. In the whole context we find it necessary to measure for two different pressures. The additional beam time is used for "setting up".

4. Test Experiments

The apparatus has been thoroughly tested and used to measure R for 12-MeV p extracted from the Aarhus Tandem accelerator and degraded in a 1290-μm plastic scintillator to 5 MeV. Figure 4 shows one of the time-of-flight spectra obtained (note that increasing flight time corresponds to decreasing channel number). We observe the peaks stemming from He^+ and He^{++} ions. Furthermore, a peak (marked H^+) stems from dissociation of water vapour in the rest gas. There is a 'tail' on the He^+ peak stemming from the process

$$He^+ + He \rightarrow He + He^+ ,$$

which takes place in the helium gas. The intensity of this tail is proportional to the target pressure squared. If the tail is included in the integration of the He^+ peak, we obtain measured values of R which do not depend on the target-gas pressure as can be seen in Fig.5. The value of R obtained from Fig.5 is 2.4×10^{-3}, which is in excellent agreement with our earlier results obtained with a rather different experimental apparatus[8)].

In Fig.6 we have shown a calculation of the energy of protons and antiprotons as a function of scintillator thickness and an impact energy of 21.08 MeV. The curves are based on the stopping-power tables of Andersen and Ziegler[9] together with 'higher-order Z effects' found in Ref.10. It should be noted that a 5% error in the stopping power will lead to a more than 1-MeV shift in the outgoing particle energy of 5 MeV. Hence, it is important to check experimentally whether we have chosen the right degrader thickness. To this end, we have obtained beam time at the AVF-MC30 cyclotron at the Institute of Physics, Oslo, where 21.08-MeV p's are available at the 5×10^5 sec^{-1} level. Such a measurement will also enhance the importance of the CERN $\bar{p}$ measurement as we shall then have measured R(p) and R($\bar{p}$) using exactly the same experimental conditions.

5. Beam Requirements at LEAR

Beam time	1 day of LEAR operation
Intensity	$\sim 3 \times 10^5$ $\bar{p}$/sec
Beam diameter	~ 2 mm (FWHM)
Beam divergence	$\sim 2^{\circ}$ (FWHM)
Beam energy	21.08 MeV (= 200 MeV/c)

6. References

1) N.Bohr, Phil.Mag.30 (1915) 581

2) H.Bethe, Ann.Phys.5 (1930) 326

3) M.Inokuti, Rev.Mod.Phys.43 (1971) 297

4) F.W.Byron and C.J.Jochain, Phys.Rev.Lett.16 (1966) 1139

5) H.K.Haugen, L.H.Andersen, P.Hvelplund, and H.Knudsen, Phys. Rev.A 26 (1982) 1962

6) J.H.McGuire, Phys.Rev.Lett.49 (1982) 1153

7) J.Reading, private communication (1984)

8) H.Knudsen, L.H.Andersen, P.Hvelplund, G.Astner, H.Cederquist, H.Danared, L.Liljeby, and K.-G.Rensfelt,H.J.Phys.B 17 (1984) 3545

9) H.H.Andersen and J.F.Ziegler, vol.3 of The Stopping and Ranges of Ions in Matter, Pergamon (1977)

10) H.H.Andersen, J.F.Bak, H.Knudsen, and B.R.Nielsen, Phys.Rev.A 16 (1977) 1929

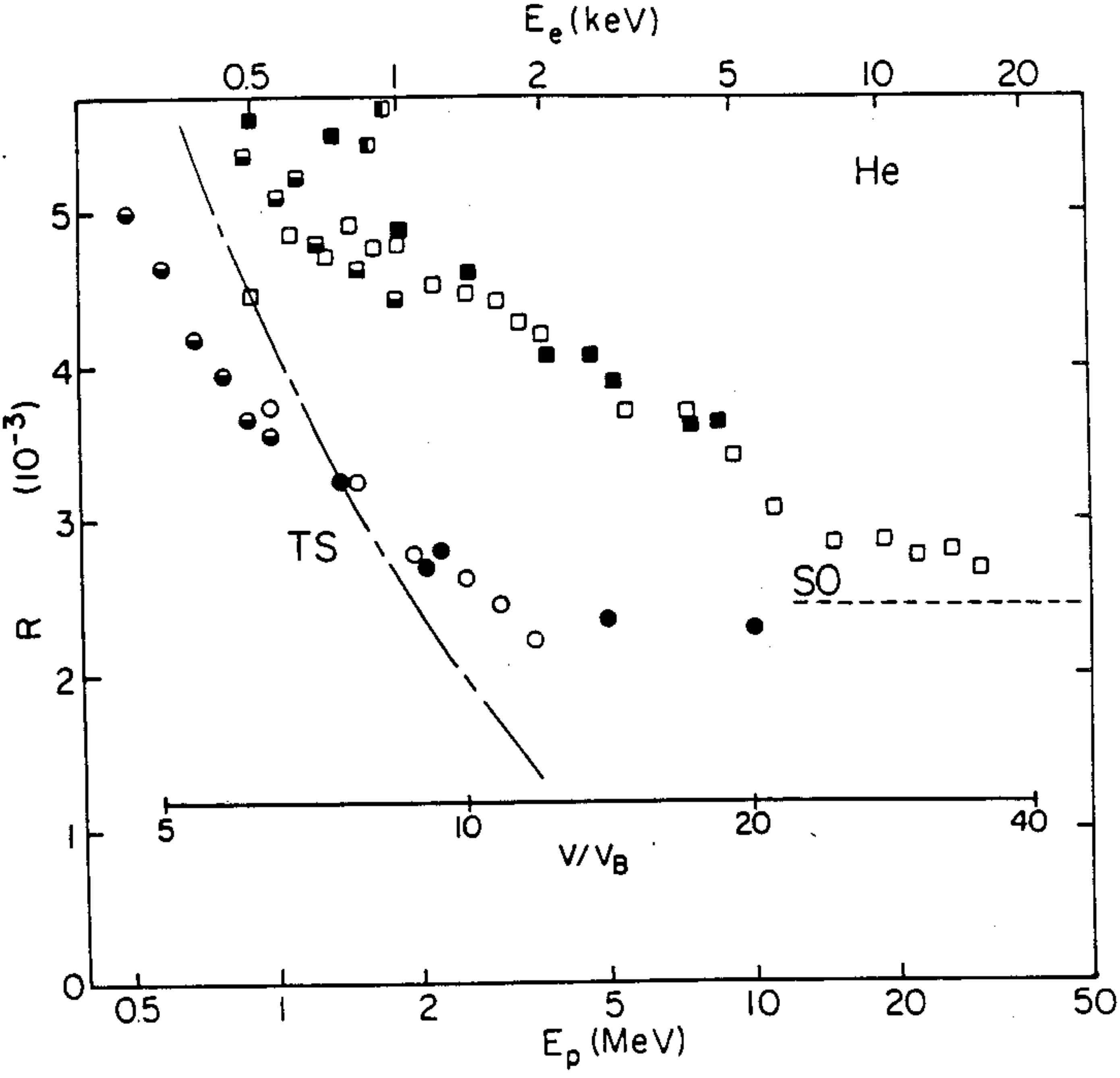


Figure 1

R as function of particle velocity. Squares: electron data; circles: proton data. From Ref. 6.

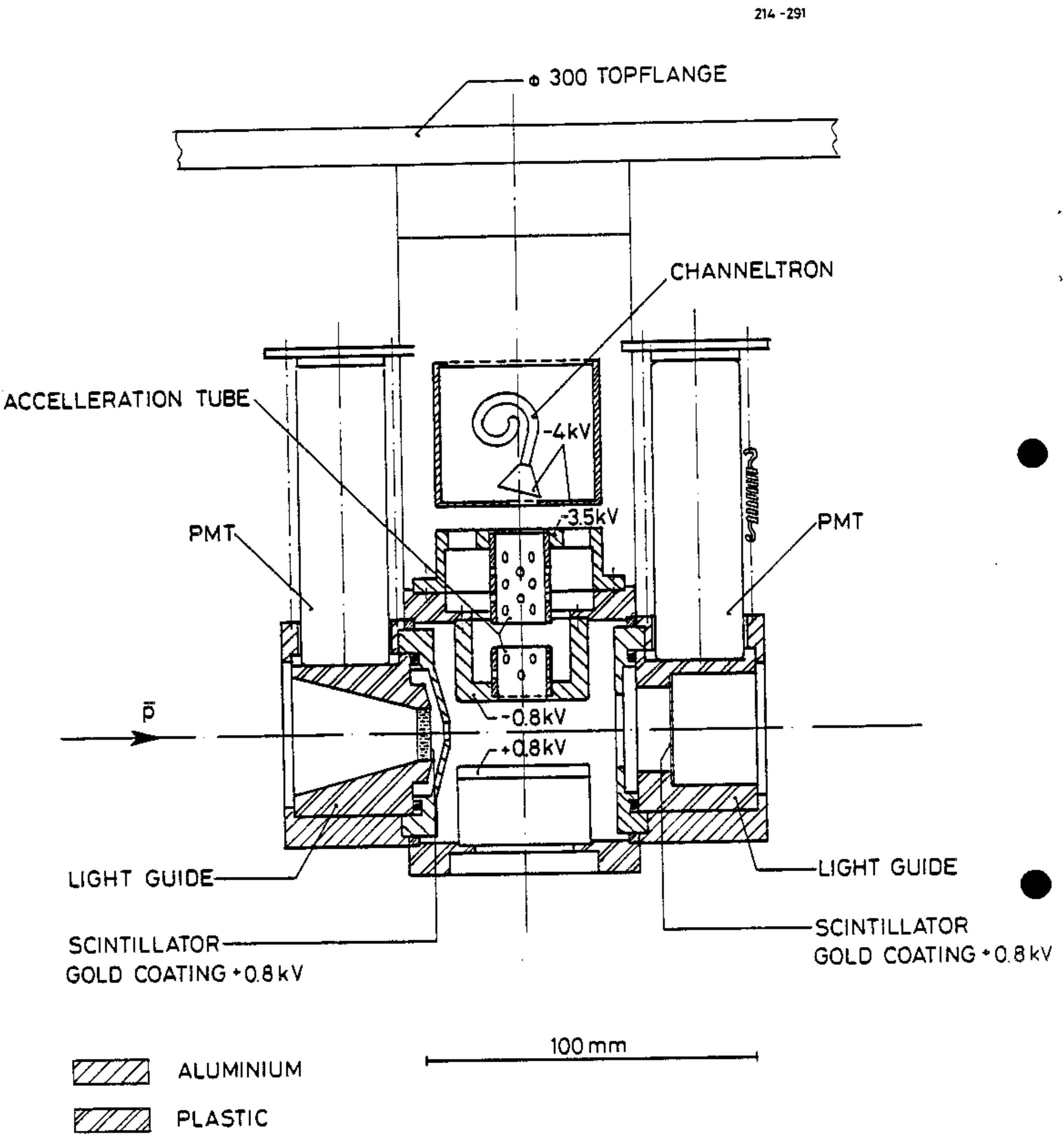


Figure 2

Experimental apparatus.

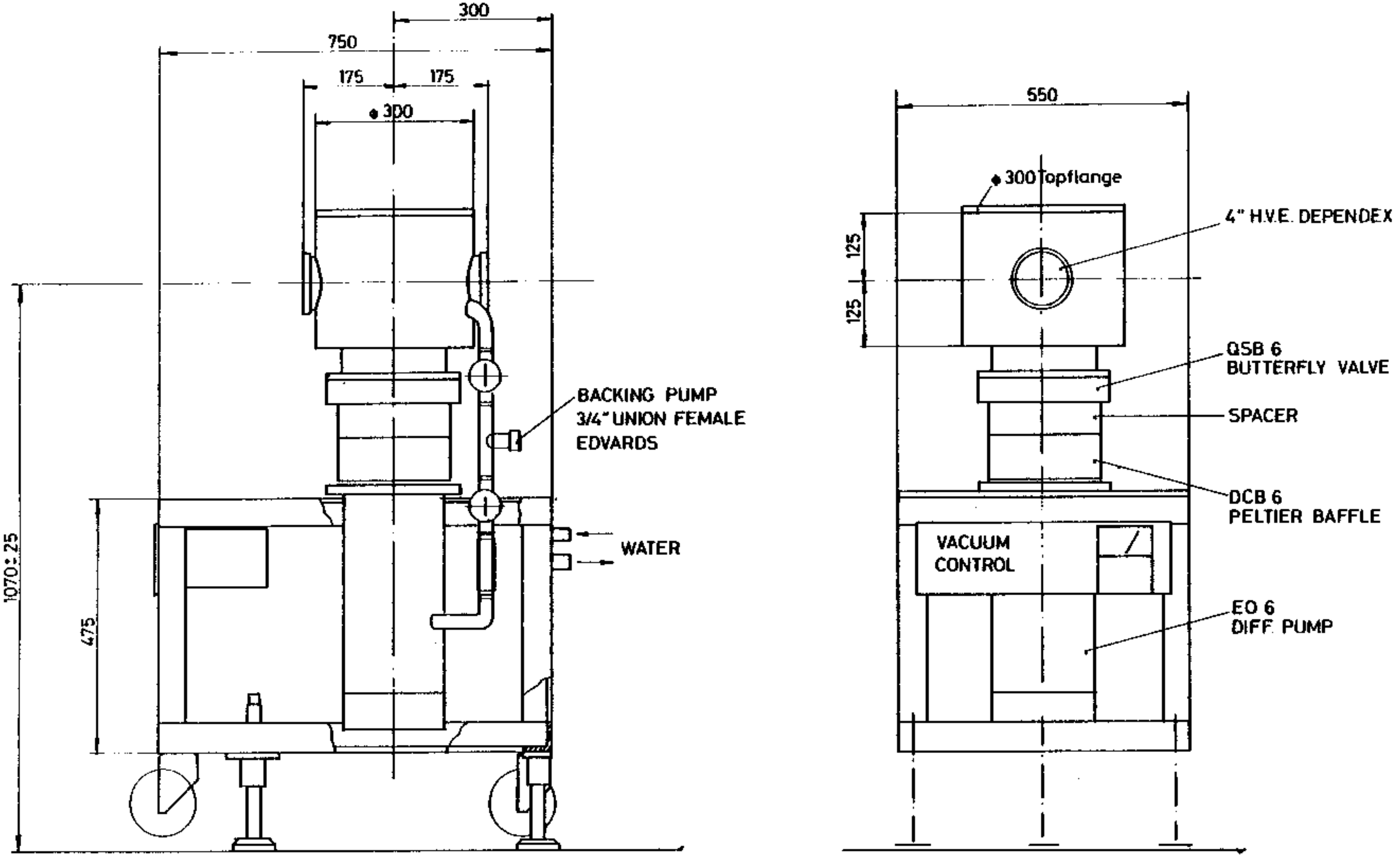


Figure 3

Vacuum system and support.

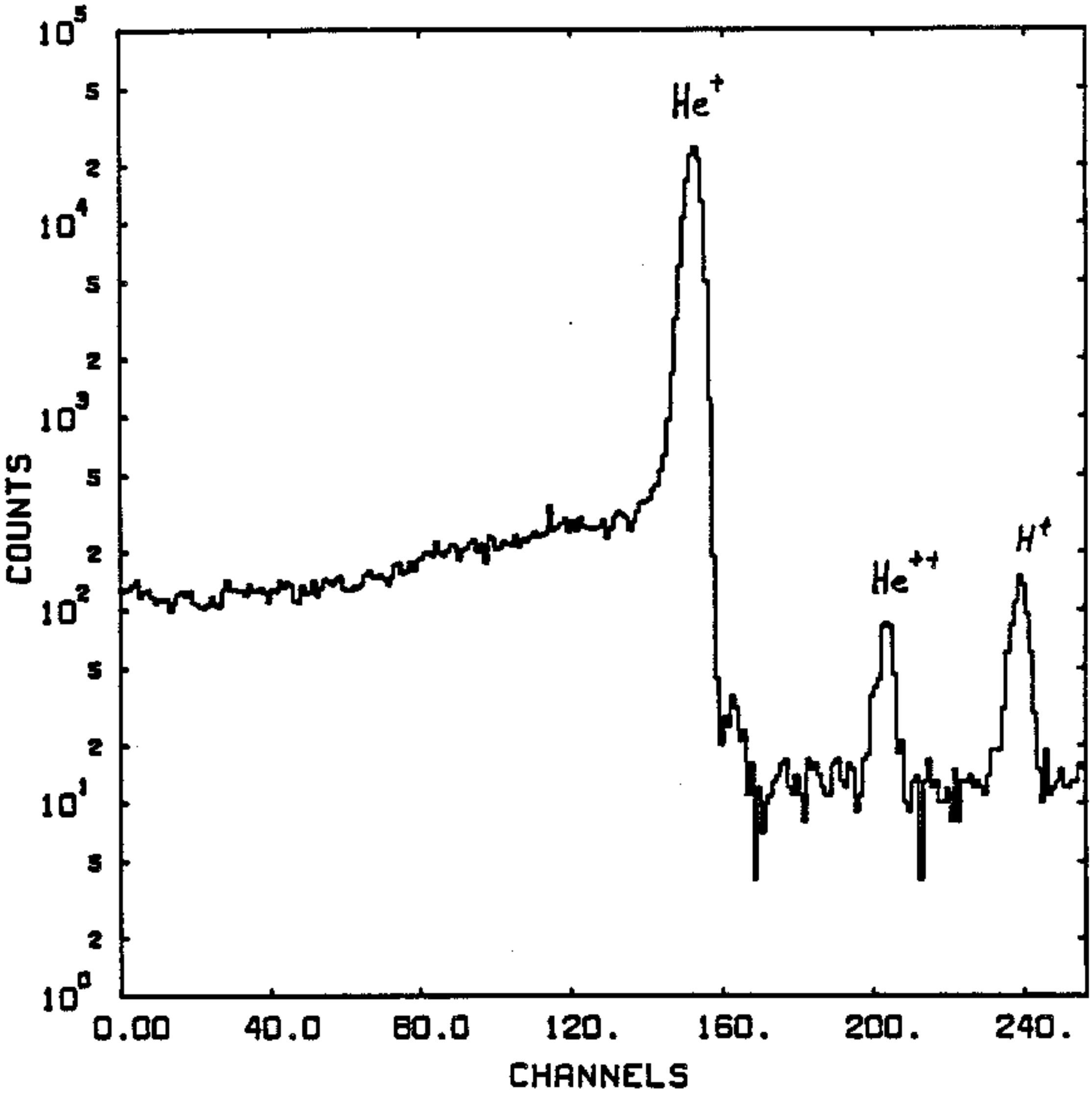
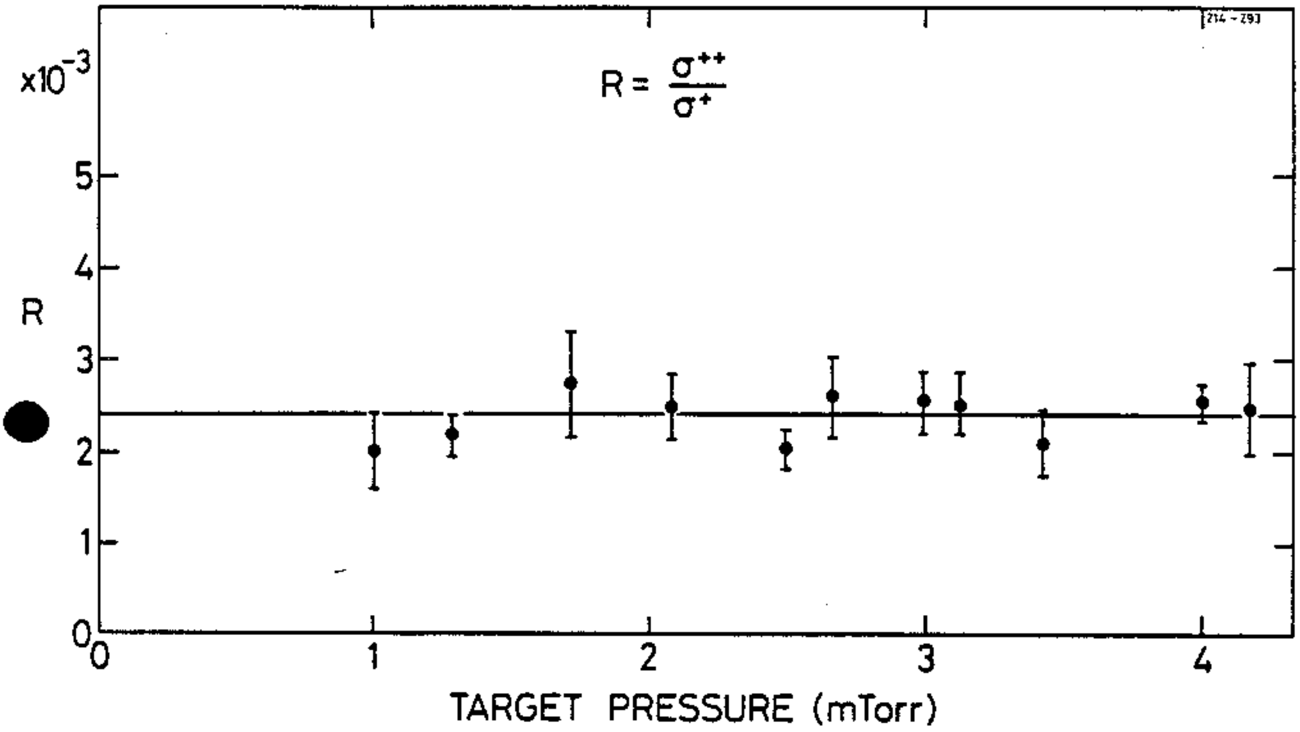


Figure 4

Time-of-flight spectrum of extracted ions from 12-MeV p degraded to 5 MeV colliding with He.



<u>Figure 5</u>

Measured values of R as function of target pressure. Test run with 12-MeV p degraded to 5 MeV. Running time per point is around 15 min.

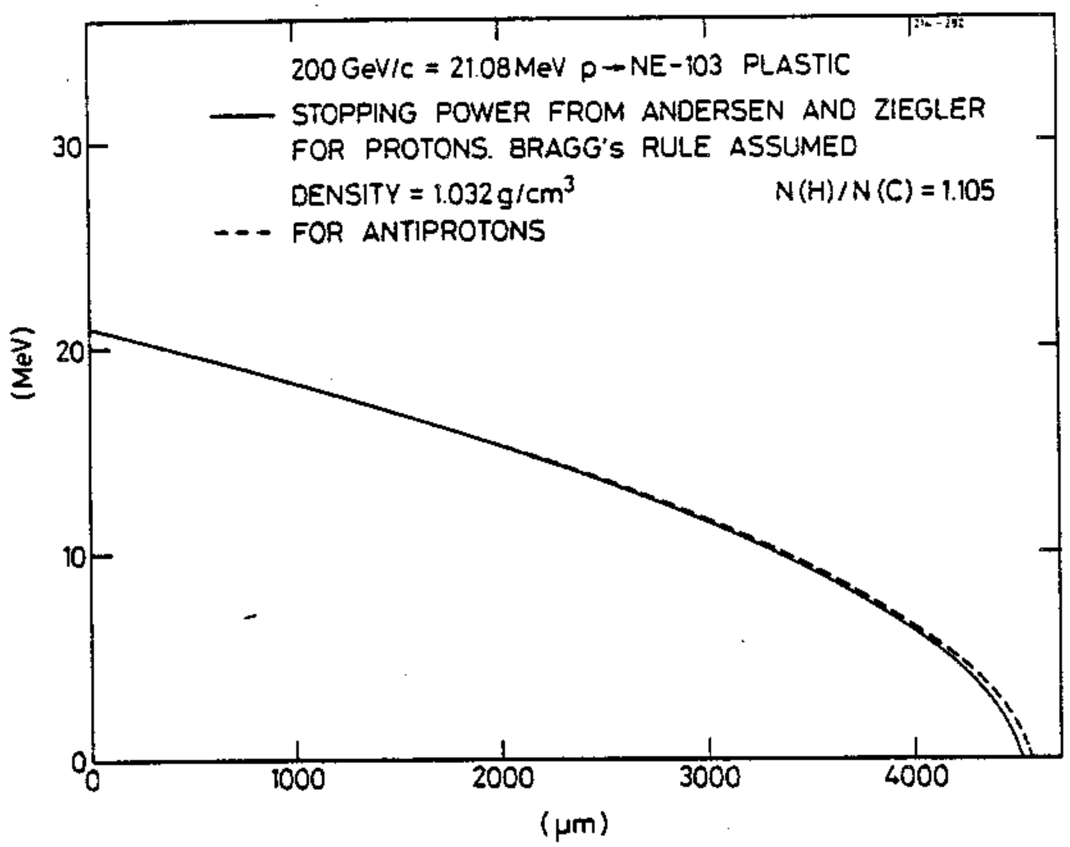


Figure 6
Calculated particle energy as function of scintillator thickness for 21.08-MeV impinging p and $\bar{p}$.