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SUMMARY

In this paper the methods and apparatus are described with which the intensity of the 591-MeV external proton beam of the CERN synchro-cyclotron can be measured to a relative accuracy of 1% and an absolute accuracy of 3% at any value of the beam flux.

Using this intensity calibration, the absolute cross-section of the reaction C^{12} (p, pn) C^{11} was determined and a value of $29.9 \pm 1.6$ mb was obtained for an incident proton energy of 591 MeV.
I. Introduction

The external proton beam of the CERN 600-MeV synchro-cyclotron, extracted by the regenerative method, has an energy of 591 MeV and a maximum intensity of $10^{11}$ protons per second over an area of a few centimeters square. In this report a description is given of the apparatus with which the intensity of this beam can be continuously measured to a relative accuracy of 1% and an absolute accuracy of 3% at any value of the proton flux. The knowledge of the absolute intensity has been used to obtain a value for the cross section of the reaction $\text{C}^{12}(p, pn)\text{C}^{11}$ at 591-MeV incident proton energy.

For monitoring the proton beam up to an intensity of $10^8$ protons per second an ionization chamber is the ideal instrument, combining strictly linear characteristics with a high stability over long periods of time. The maximum flux of the external proton beam is however too high to be monitored with an ionization chamber, as for very high ionization density recombination is not negligible at reasonable pressures of the chamber filling gas. This causes an undesirable dependence of the multiplication factor of the chamber on the intensity of the beam and on the area of the beam cross-section.

Among the several instruments that are reputed to give an output strictly linear with the beam current even at high intensities, the secondary emission chamber, developed at Stanford University\(^1\), has the most attractive properties for general beam monitoring, as it is inherently stable and presents very little material to the beam so that it can be used in any position without causing undue scattering. In this respect it is to be preferred to a Faraday cage in which the whole beam is caught. The only advantage of the Faraday cage, viz. that it is in principle an absolute instrument, is largely lost at these high energies, because it is unpracticable to make the stopping block sufficiently big to prevent an appreciable escape of charged particles. A secondary emission chamber is therefore used to monitor the proton beam if the beam flux exceeds $10^8$ protons per second. When it is necessary to know the absolute sensitivity
of this chamber, it is calibrated relative to an ionization chamber which
is considered as the absolute standard instrument for all beam intensity
measurements. The multiplication factor of this ionization chamber for
591-MeV protons has been determined once and for all by comparing its
output with the number of protons passing through at a beam flux of
$10^2 - 10^3$ protons per second. At this very low intensity the protons in
the beam could be directly counted with a counter telescope.

II. Technical details of the apparatus

The ionization chamber

The constructional details of the ionization chamber are shown
in Fig. 1. The electrode system of the chamber consists of seven Mylar
foils of 0.29 mg cm$^{-2}$ each, covered on both sides with Aquadag. The
effective length of the chamber is 13.15 cm and it is filled with 638 mm
Hg of argon and 10 mm Hg of CO$_2$ at 20°C. Assuming a mean energy loss per
ion pair of 26.3 eV for the filling gas, the calculated multiplication
factor is 1320 for 591-MeV protons. The constancy of this chamber has
been checked regularly by placing a 50 millicurie Co$^{60}$ source on it in a
well-determined position, and measuring the output current with the current
integrator described below. The result of these checks over a period of
more than one year is shown in Fig. 2. After an initial period, when the
chamber had just been filled, the sensitivity has been constant to within
0.5%.

The secondary emission chamber

The secondary emission chamber is essentially constructed like
an evacuated ionization chamber (Fig. 3). The twenty plates are aluminium
foils, 0.02 mm thick, alternately connected to the positive high voltage
and to the collector terminal. The charge collected, which is propor-
tional to the number of secondary electrons ejected from the foils when
protons pass through the chamber, is again measured with a current
integrator.
The multiplication factor $N_{SEC}$ of the secondary emission chamber cannot be calculated accurately as several factors, especially the surface condition of the foils, are not well enough known. A derivation given in ref. 1, based on the scattering of atomic electrons by protons according to the Rutherford formula, is incorrect, as this treatment fails to explain the very low average energy of the secondary electrons which is found experimentally. An estimate can however be made in the following way. When an incident proton passes through one of the foils in the chamber in a direction normal to the foil-surface, this proton induces mainly two processes in which secondary electrons are produced:

1) In a number of atoms along the path of the proton, electrons are excited into higher energy levels, and in many cases the atom is ionized. This process is analogous to the ionization of gas atoms along the path of a high energy charged particle. Electrons, that have been liberated by the ionization process, can escape from the foil if their energy is sufficiently high to overcome the surface potential barrier, and if they are produced near enough to the foil surface. There is a large amount of experimental and theoretical evidence to show that the maximum depth below the surface from where secondary electrons can escape is of the order of $10^{-6}$ cm and that the most probable energy of the escaping electrons is about 20 eV. These statements are true, independent of the energy of the incident particle, if the velocity of this particle is much higher than that of the atomic electrons. Subject to this condition, the secondary emission coefficient $\delta$, which is the number of secondary electrons produced at one foil surface per incident particle, can be written as:

$$\delta = - K \frac{dE_i}{dx}$$

(1)

where $\frac{dE_i}{dx}$ is the energy loss per gr cm$^{-2}$ of the incident particle in the foil material and $K$ is a constant. No direct measurements exist on the production of secondary electrons by protons of very high energy, but the relation (1) can be used to calculate $\delta$ for 591-MeV protons from measure-
ments at lower energies\(^2\). In this way one finds:

\[ 8 \times (591\text{-MeV protons}) = 0.012 \]

The collector foils present 19 surfaces to the protons, so that the contribution to \(M_{SEC}\), due to direct secondary electron emission by the protons, is:

\[ (M_{SEC})_1 = 0.23 \]

This number is independent of the foil thickness \(\xi\) if \(\xi > 10^{-5}\text{cm}\).

ii) A proton passing through a foil produces scattered electrons due to Rutherford scattering. The most probable energy of these electrons when they leave the foil, depends slightly on the foil thickness and is of the order of 20 KeV for a foil of 0.006 gr cm\(^{-2}\) aluminium. The voltage of 1 KeV, applied to the electrode system of the chamber, is too low to influence the motion of these electrons appreciably. Therefore, the charge of the electrons ejected from a collector foil will be almost completely compensated by electrons, originating in neighbouring foils, that are stopped in this foil. The total number of scattered electrons ejected from the 10 collector foils can be calculated and is 0.14 per proton. Certainly more than 80% of this number is compensated for by electron capture, so that the direct contribution of the scattered electrons to \(M_{SEC}\) is less than 0.03. This contribution can be neglected.

The scattered electrons, however, produce in their turn secondary electrons when they pass a surface of a collector foil. The number of secondary electrons produced per proton in this process depends on

a) the number of electrons scattered per proton.

b) the number of collector-foil surfaces which the scattered electron traverses.

c) the energy of the scattered electron when it passes a foil surface.

A calculation, which will not be given here, leads to an estimated contribution to \(M_{SEC}\) of

\[ (M_{SEC})_2 = 0.07 \]
This value depends slightly on the foil thickness $\xi$, but increases more slowly than $\xi^{\frac{3}{2}}$.

The total calculated value of the multiplication factor of the secondary emission chamber is thus:

$$M_{SC} = 0.30$$

This value may be subject to comparatively large variations, as the secondary electron emission process is strongly influenced by the surface condition of the foils.

The current integrator

The current integrator was developed from a circuit due to Lewis and Collinge\(^3\). This circuit has an intrinsic stability of better than 0.5\% over very long periods of time. For the details of the way this is achieved the reader is referred to their original paper. The integrator measures the charge in the form of a number of counts and is provided with three ranges of sensitivity:

Range 1: One count corresponds to $5 \times 10^{-7}$ coulomb
Range 2: One count corresponds to $5 \times 10^{-9}$ coulomb
Range 3: One count corresponds to $5 \times 10^{-11}$ coulomb

The complete circuit diagram is given in Fig. 4. Each time the circuit triggers, a standard output pulse is produced at terminal A. This pulse may be used to operate start-stop and timing equipment. To prevent damage to the electrometer valve an overcurrent protection is incorporated.

The absolute sensitivity of the integrator was adjusted to the values given above to better than 1\% on all three ranges in the following way. Range 1 was calibrated by feeding an accurately known current of 0.5 $\mu$A into the integrator. This current is obtained by connecting a voltage of 300V, measured with a Leeds-Northrup potentiometer, to a high stability (Victoreen) resistor of $10^9$ ohm. The value of this resistor was measured in a bridge circuit, in which the current integrator itself was used as a null indicator. The other elements in the bridge were accurately measured wire-wound resistors of lower value. The circuitry for
the calibration measurements is shown in Fig. 5. As the value of the 10^9-ohm resistor depends upon the applied voltage, the arrangement was made such that the voltage applied to this resistor in the bridge was the same as that used in the integrator calibration. The results of the measurements are shown in Fig. 6. The ratio of the sensitivities of the three ranges was hereafter accurately adjusted by measuring the same current from an ionization chamber plus radioactive source successively on range 1 and range 2. This procedure was repeated at a lower input current to adjust the ratio of range 2 and range 3.

III. The proton beam calibration measurements

The proton beam

The energy of the external proton beam is 591 ± 3 MeV, a value calculated from the Hp value of the cyclotron magnetic field at the extraction radius. The total energy spread is smaller than ± 3 MeV. The beam leaves the cyclotron with an angular spread of ± 1/2°, passes first through a pair of quadrupole lenses and is then bent by a bending magnet over 26° into a channel through the 6-meter thick heavy-concrete shielding wall which separates the cyclotron hall from the experimental room. The beam passes through vacuum pipes all the way until it emerges into the air through a Mylar window of 0.1 mm thickness just before the calibration equipment in the experimental room. A large plate of plastic scintillator, 2.5 cm thick, was placed in the beam at this point and the beam spot was observed with closed circuit television. The area of the beam cross-section could now easily be minimized by adjusting the currents in the quadrupole lenses. The intensity distribution in the beam spot was studied by irradiating aluminium foils of 10 mg cm^{-2} thickness. After irradiation the foils were cut into squares of 2 × 2 cm² and the activity of each of the squares was counted separately. From these measurements (Fig. 7) it was inferred that the number of protons outside an area of 5 × 5 cm² is less than 2% of the total, which proves that a negligibly
small number of protons passes outside the sensitive area of any of the instruments used in the calibration. Actually 70% of the total intensity falls within an area of 2 × 4 cm². The intensity of the proton beam could be reduced down to 10⁷ protons per second by means of a "beam chopper", a copper wire which can be moved upwards into the internal cyclotron beam at a radius of 50 cm. For very low beam intensities, down to 10² protons per second, the ion source and the hydrogen gas flow were turned off.

The measurement of the multiplication factor of the ionization chamber

For this measurement the ionization chamber was put in the proton beam and a telescope of three scintillation counters was placed before or behind it. Coincidences in the three counters were measured with two triple coincidence circuits in parallel with a resolving time of 5.5 nsec. The outputs of the coincidence circuits were fed to Hewlett-Packard fast scalers with a dead-time of 0.1 μsec. Even at the low beam intensities used, between 10² and 10³ protons per second, counting losses were however not negligible as the duty cycle of the external proton beam is under these conditions only 0.001. The number of coincidences counted per 10⁻⁶ C of charge collected in the ionization chamber was therefore measured for a number of different proton beam fluxes and the results were extrapolated to zero beam intensity by means of the counting loss formula

\[ X(0) = \frac{X(N)}{1 - cN} \]

in which \( X(N) \) is the number of coincidences counted per 10⁻⁶ C of collected charge if the average counting rate during the measurement is \( N \) per second. The constant \( c \) depends on the duty cycle and on the dead-time of the counting equipment. The result of one series of measurements is shown in Fig. 8.
Actually three series of measurements were made. In two of these the charge collected in the ionization chamber was measured with the current integrator. In the third series however, as an alternative method, the charge was fed to a vibrating reed electrometer, the input of which was connected to one terminal of a low leakage capacitor of accurately known value (Fig. 9). The charge collected was compensated during each run by changing the voltage on the other terminal of the capacitor, which was connected to a potentiometer, in such a way that the indication of the electrometer remained zero. The total change of the potentiometer voltage during the measurement is then a measure for the charge collected. The two integrating methods were checked against each other by measuring in both ways the same current of $10^{-13} \text{A}$ from a battery plus resistor. It should be mentioned that the background current from the ionization chamber was rather large, of the same order of magnitude as the current to be measured, because the chamber was slightly radioactive. This background was however very constant and could be subtracted.

The results of the three series of measurements agree within the errors after applying a correction of $0.5\%$ for nuclear absorption loss of the proton beam in each of the scintillation counters. The final result is, that $(4.84 \pm 0.10) \times 10^6$ protons correspond to a collected charge of $10^{-9} \text{C}$, so that the multiplication factor of the ionization chamber is

$$M_{IC} = 1290 \pm 25$$

This is slightly lower than the value 1320 for the multiplication factor which was calculated on the basis of an average loss per ion pair of 26.3 eV. In this connection it is interesting to remark that the measured values for the multiplication factor of the Liverpool air-filled chamber$^4$ and the present argon-filled chamber agree within 1%. The comparison is made directly on the basis of the ratio of the ion pair production efficiencies in air and argon, which was measured by Bakker and Segré$^5$.  

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The calibration of the secondary emission chamber

The sensitivity of the secondary emission chamber was measured by direct comparison with the known ionization chamber sensitivity. The chambers were placed behind each other in the same proton beam of $10^8$ protons per second and the charges collected in the two chambers during the same period were compared with two current integrators. This procedure leads to the right value for the absolute sensitivity of the secondary emission chamber at high beam intensities if the following two assumptions can be made:

i) The ionization chamber is still linear at a proton beam flux of $10^8$ protons per second.

ii) The secondary emission chamber is linear for beam fluxes between $10^8$ and $10^{14}$ protons per second.

Assumption ii) was proved to be justified by $C'^2(p, pn)C'$ activation measurements. At four different beam intensities, ranging from $1.7 \times 10^9$ to $10^{14}$ protons per second, polythene plates of 0.3 cm thickness were irradiated, while the beam was monitored with the secondary emission chamber. There should be a constant ratio between the charge collected in the chamber during the irradiation and the activity of the plates, measured afterwards with a gamma-ray spectrometer which will be described below. The linearity of the chamber over this range of beam intensities was established to within 2%, which is the accuracy of the method used. Assumption i) was then checked by repeating the comparison of ionization chamber and secondary emission chamber at different beam intensities. Only for intensities above $10^9$ protons per second does the ratio of the output currents of the chambers start to drop appreciably (Fig.10), from which it may be inferred that at an intensity of $10^8$ protons per second the ionization chamber is still linear with beam intensity.

Although the sensitivity of the secondary emission chamber has always been found to be constant to within ±1% as long as the vacuum is maintained, there have sometimes been appreciable changes in the sensitivity from one running period to another, when air had been admitted in the meantime. The calibration is therefore repeated every time that an
accurate knowledge of the sensitivity is essential. A typical value for the multiplication factor of the secondary emission chamber is

\[ M_{SEC} = \frac{M_{IC}}{2400} = 0.54 \]

in which 2400 is the measured ratio of the sensitivities of the two chambers.

IV. Measurement of the cross-section of the reaction \( ^{12}C (p, \alpha n) ^{11}C \) at a proton energy of 591 MeV.

**Experimental method**

In the previous chapter a description was given of a check on the linearity of the secondary emission chamber by polythene irradiation measurements. As the activity of the irradiated polythene plates was measured in absolute value, it is possible, making use of the knowledge of the absolute sensitivity of the secondary emission chamber, to calculate from these measurements a value for the cross-section of the reaction \( ^{12}C (p, \alpha n) ^{11}C \) at a proton energy of 591 MeV. A similar measurement by Goebel et al. on the reaction \( ^{27}Al (p, 3\alpha n) ^{24}Na \) is reported separately.²

Four polythene plates of 18 x 12 x 0.3 cm³ were irradiated in the proton beam while the secondary emission chamber was monitoring the number of protons passing through the plate. After the irradiation the 0.51 MeV annihilation gamma rays from the decay positrons of the \(^{11}C\) nuclei produced in the polythene were counted with a conventional single-channel pulse height analyser, adjusted so that the total energy peak of the 0.51 MeV annihilation radiation was covered by the window. After each measurement the polythene plate was replaced by a calibrated \(^{22}Na\) source, which is also a positron emitter. From the comparison of the activities of the irradiated polythene and the calibrated \(^{22}Na\) source, the number of \(^{11}C\) nuclei produced during the irradiation can be calculated. As the number of protons that caused this activity is known the cross-section of the reaction \( ^{12}C (p, \alpha n) ^{11}C \) can be computed.
The measurement of the C¹⁴ activity in the polythene plate

If the duration of the irradiation is $T$ minutes and if the carbon activity at $t$ minutes after the end of the irradiation is $A_C(t)$, the saturation activity $A_\infty$ can be derived from $A_C(t)$ by the formula

$$A_\infty = \frac{A_C(t)}{e^{-\lambda T} (1 - e^{-\lambda T})}$$

(1)

in which $\lambda$, the decay constant, is equal to $\lambda = 3.38 \times 10^{-2}$ min⁻¹.

This value corresponds to a half life of 20.5 min. The cross-section $\sigma$ is then given by:

$$\sigma = \frac{A_\infty M}{N_p N \xi}$$

(2)

where, $N_p$ is the number of protons per second, $N$ is Avogadro's number, $\xi$ is the thickness of the polythene plate in g cm⁻², $M$ is the molecular weight of CH₂.

If the intensity of the proton beam was not constant during the irradiation the irradiation period can be sub-divided into $n$ equal time intervals, in each of which the intensity was reasonably constant. $N_p$ must then be replaced by

$$N_p = \frac{n}{\sum_{i=1}^{n} N_{pi} \left(1 - e^{-\lambda T/n}\right) e^{-\lambda(n-i)/n}} \left(\frac{n}{T}\right)$$

(3)

where $N_{pi}$ is the number of protons recorded by the secondary emission chamber in interval number $i$.

To compute $A_C(t)$ from the ratio of the counting rates of the Na²² source and the polythene plate, the following effects have to be kept in mind.
A few other effects which might influence the results are briefly mentioned here although they do not contribute to the error in the present measurements. In the first place, the loss of C^{11} atoms from the polythene due to recoil is very small for a 0.3 cm thick target. On the other hand, the target is not thick enough to get an appreciable effect from secondary particles, produced in the plate by the proton beam, for which the C^{12}(p, pn) C^{11} cross-section may be larger than that for 591-MeV protons. Finally, difficulties might be expected from neutron contamination of the proton beam. The relative number of neutrons in the beam is however already negligibly small before the proton bending magnet, and this magnet again reduces the contamination by a large factor.

### Results

The complete results of the measurements are:

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Calculated cross-section $\sigma$ ($10^{-27}$ cm$^2$)</th>
<th>Average proton beam intensity during irradiation ($\times 10^{10}$ protons per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>30.1</td>
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<tr>
<td>3</td>
<td>29.6 $\pm$ 1.6</td>
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</tr>
<tr>
<td>4</td>
<td>29.9</td>
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</tr>
<tr>
<td>6</td>
<td>31.4</td>
<td>3</td>
</tr>
</tbody>
</table>

The cross-section $\sigma$ of the reaction C^{12}(p, pn) C^{11} for 591-MeV protons, found as the mean value of these figures, is:

$$\sigma = (29.9 \pm 1.6) \times 10^{-27} \text{ cm}^2$$

The error assigned to the mean value of $\sigma$ is not smaller than that of the separate measurements, because it is almost exclusively due to uncertainties in the calculation of $\sigma$ from the measured numbers. This final value of $\sigma$ is shown in Fig.11, together with a number of earlier measurements in this energy range.
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FIG. 1 Schematic diagram of ionization chamber. Each set of plates is mounted on three brass rod, of which only one is shown.
Fig. 2 Output current $\dot{i}$ of the ionization chamber, with a Co$^{60}$ source in a fixed position, as a function of the time of the measurement. The curve gives the expected current-time relation if $t_{1/2} = 5.25$ years for Co$^{60}$.
FIG. 3 Schematic diagram of secondary emission chamber.
FIG. 5 Circuit diagram for integrator calibration. For the measurement of $R_X$ the switches are all changed to their other position.

![Circuit Diagram]

FIG. 6 Voltage dependence of the resistance of the $10^9 \Omega$ resistor
**FIG. 7** The intensity distribution in the proton beam spot at the place of the calibration apparatus. The figures give the fraction of the beam observed in each area in percentages. Less than 0.5% of the beam is observed outside the diagram.

Number of protons counted per $10^{-9}$ C collected charged.

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<tbody>
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<tr>
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**FIG. 8** A measurement of the absolute sensitivity of the ionisation chamber for 591-MeV protons. The straight line given by the counting loss formula is the best fit to the points.
Proton beam

Ionization chamber

HT (+150V)

253 ± 2 pF

Vibrating reed electrometer
1 volt full scale

-2 V

0.1% Voltmeter

VRE input shorting switch

**Fig. 9** Circuit diagram for ionization chamber calibration measurements with vibrating reed electrometer.

![Graph showing the ratio of $M_{IC}/M_{SEC}$ vs. proton beam intensity. The graph indicates a linear decrease in the ratio with increasing beam intensity.](image)

**Fig. 10** Ratio of the multiplication factors of ionization chamber ($M_{IC}$) and secondary emission chamber ($M_{SEC}$) as a function of the proton beam intensity. The linear dependence is expected if the change in $R$ is due to recombination in the ionization chamber.
FIG. 11 Measurements of the $^{12}\text{C} \ (p, pn) ^{11}\text{C}$ cross section for incident proton energies between 300 MeV and 1000 MeV.