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ENERGY LOSS BY LOW ENERGY PROTONS IN GOLD

by

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A B S T R A C T

An experiment employing a new method of measuring stopping power at low energies is described and results given for protons on gold. dE/dx values for protons on gold have been obtained from measurements of the response of a silicon surface-barrier detector, covered with a surface layer of gold, to protons of energy below 50 keV. The response of the detector to H_2^+ and H_3^+ ions in the same energy range has been used to determine backscattering cross sections for protons on gold.

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CONTENTS

1. INTRODUCTION

Of the numerous experiments leading to a determination of dE/dx values for protons passing through gold, none appear to have been carried to lower proton energy, E, than 50 keV. Results to 1953 were discussed and summarised by Allison and Warshaw[1] and somewhat later values have been published by Bader et al.[2].

We present here estimates of dE/dx for protons on gold in the range below 50 keV, obtained from an examination of the response of a silicon surface barrier detector as a function of proton energy. The observed departure from linearity in the detector response to protons in this energy range is consistent with a variation in dE/dx with the energy of particles passing through the gold surface layer. In addition, pulse height distribution curves, obtained when the detector was exposed to H_2^+ and H_3^+ ions, showed secondary, lower energy peaks indicative of large angle Rutherford scattering of one atom from the ion-group. The magnitude of the secondary peaks enabled an estimate to be made of the cross section of elastic scattering by gold atoms.

2. EXPERIMENTAL PROCEDURE

Ions from a radio-frequency ion source were accelerated and focused through an Einsel lens system. Batteries provided the 1500 volt extractor potential and Brandenburg (model MR50/R) high voltage supplies were used for focusing and accelerating potentials. Two magnets and a series of apertures enabled a selected ion beam of desired intensity to be delivered to the 7 mm² Ortec surface barrier detector, placed at the double focus of the second magnet. Although a detector bias of 40 volts was used in order to obtain optimum signal to noise ratio, operation over the range 10-50 volts produced no change in pulse height output. The signal from the detector was fed via a charge sensitive pre-amplifier (Tennelec model 100 B), a low level amplifier and two high level amplifiers to a multichannel pulse height analyser (Laben model A51). The filament supply for the pre-amplifier was taken from an accumulator with a resulting improvement in signal to noise ratio. A comparison signal from a wave-form generator was available to the pre-amplifiers. Fig.1 shows the layout of the apparatus.

The initial energy E_0 of the ions was taken as equivalent to the measured acceleration potential above earth, plus the extraction potential. There were H_2^+ and H_3^+ ions present which did not achieve the additional energy of the fall through the extractor potential, presumably being formed by reactions between ions from the ion source and neutrals in the extractor channel. The acceleration potential was measured on the power supply-meter which was calibrated against a precision high-voltage meter. An assessment of the consistency of E_0 was obtained by using H.T. variation to select H_1^+, H_2^+ and H_3^+ beams and bring them to the detector while magnet currents were held constant. Under these conditions it was found that $E_0(H_1^+) = 2E_0(H_2^+) = 3E_0(H_3^+)$ to within ± 100 volts, except for the cases of low energy H_2^+ and H_3^+ ions mentioned above.

Pulse height distribution displays obtained on the multi-channel analyser were generally photographed, except when it was considered that the information sought required a "print-out". At intervals, between detector irradiations, voltage pulses of known amplitude, V, from the wave-form generator were presented, via a capacitor of measured value, to the pre-amplifier and a pulse-height distribution display taken. By this means the response of the detector to ions of energy E_0 could be expressed in terms of an equivalent comparison signal V, thus obviating the effects of long term drifts in the amplifier system.

Average beam intensities were found by injecting pulses from the wave-form generator during detector irradiations and comparing the rate of development of the two "energy peaks" obtained on the kicksorter. For signals of sufficient amplitude to be well clear of the background the beam intensity was kept in the range 10^3-10^4 particles sec^{-1}. Pile-up pulses became noticeable when the beam intensity exceeded 5×10^4 sec^{-1}, but no variation was observed in the channel number of the peak of the pulse-height distribution until the arrival rate of particles exceeded about $10^5 sec^{-1}$, when there was a depression of the channel number corresponding to the peak. For particle energies below those for which the pulse-height peaks were separated from the background (12 keV for protons), the Laben background subtraction facility was employed.

In determining the kicksorter channel number of the peak of the pulse-height distribution curve, from photographed displays, estimates were made individually by three people and the mean value of the three readings taken. No systematic error depending on the individual reader was apparent.

3. RESULTS

The detector output response to protons, expressed in terms of an equivalent injected signal V, as a function of initial energy, E_0, is shown in Fig.2. The solid line is a least-squares fit to the data. The experimental values, shown as open circles, are average values of V for each value of E_0. The probable errors of these values, on the assumption that the errors are random, would fall within the open circles. Where insufficient readings were taken to obtain a meaningful probable error the experimental values are shown as dots. The straight line OA through the origin of Fig.2 shows the relationship between V and E_0 which would be expected if the total energy, E_0, of the particles was converted to electron-hole pairs in the detector at the rate of 3.6 eV[3] per pair.

As was found by Ewing[4] the pulse-height obtained when the detector was exposed to H_2^+ and H_3^+ ions was less than twice and three times, respectively, the pulse height given by protons at the same velocity. The resolution obtained with the three ion species was similar to that of Ewing. In our case, however, both the variation in pulse-height and variation in resolution with particle were consistent with the presence of H_2^+ and H_3^+ ions formed in the extractor channel of the ion source.

In Fig.3 are shown photographed displays of the pulse-height distributions for the three ion species, with E_0 = 45 keV, and for an injected signal of 1.70 mV.

4. DISCUSSION AND RESULTS

An extrapolation of the response curve in Fig.2 intercepts the abscissa at about 1 keV. This suggests a loss in the detector other than for the production of electron-hole pairs. It has been estimated by Schweinler (see Dearnaley and Northrop[(3)]) that the threshold energy for protons in silicon, below which the average proton energy loss (3.6 eV) in producing an electron-hole pair ceases to be constant, is 125-340 eV, depending on crystal orientation. This would mean that the response curve should cut the abscissa at some point below the threshold energy. However, in the absence of other experimental evidence we have accepted a value of 1 keV as the energy lost by a proton in collisions with silicon atoms, assuming that this non-ionizing loss occurs only at the end of the proton range in silicon. Under these circumstances the line OA of Fig.2 is replaced by PB.

The difference between PB and the experimental response curve, for each value of E_o, is a measure of the enery lost by the protons in passing through the layer of gold on the face of the detector.

dE/dx for Protons on Gold

In order to obtain $\frac{dE}{dx}(E)$ from $\Delta E = E_o - V$ it is necessary to know the thickness, t, of the gold layer. Assuming $\frac{dE}{dx} = -\alpha E^{\beta}$, where β is taken as a constant over the range of all the experimental measurements, and α is regarded as an average value in the range $E = E_o$ to $E = E_t$, E_t being the energy of the particle as it leaves the gold layer, we have

$$\frac{1}{1-\beta}\left(E_o^{1-\beta} - E_t^{1-\beta}\right) = \alpha t$$

There is a value of $E^{\beta} = E_m^{\beta}$ in the range E_o to E_t, given by

$$E_m^{\beta} = (E_o^{\beta+1} - E_t^{\beta+1})/(\beta + 1)\,(E_o - E_t)$$

for which α has its correct value. Using these relations with experimental values of E_o and $E_t = V$ (least-squares-fit values of V were taken) corresponding values of α_t and E_m were obtained. This procedure was similar to that used by Bader et al[2], except that in our case t was unknown, beyond the supplier's figure of 50-100 μg cm^{-2}, and we took $\beta = +\frac{1}{2}$ instead of $-\frac{1}{2}$, to conform with the lower energy range covered in our experiment. Our value of α_t, found for $E_m = 50$ keV, was matched with that of Bader et al to evaluate t. The fitting of our curve to that of Bader et al, at the 50 keV point, gave a much smoother transition between the results of the two experiments than was obtained when we matched with the 50 keV point of Allison and Warshaw. Having determined t, $\frac{dE}{dx}(E)$, for our experimental range of E, was obtained (Fig.4).

Our value of t (99 μg cm^{-2}) was the indicated average path length through the gold for 50 keV protons, the true foil thickness being somewhat less, as our experiment did not discriminate against plurally scattered ions, as did that of Bader et al. An estimate of the effect of plural scattering was made on the assumption of a quasi Thomas-Fermi potential for the gold atom scattering centres. Individual deflections of the protons were taken as due to an effective atomic charge of $Ze\exp(-b/a)$, with a cut-off at a minimum angle θ_m, given by $\theta_m = Zze^2/Mv^2a$[5], where Ze and ze are the nuclear charges of the gold atom and proton respectively, M the proton mass, v its velocity and $a = a_o Z^{-1/3}$, a_o being the radius of the first Bohr orbit of the hydrogen atom. b is the distance of closest approach for a head-on collision, given by

$$\frac{Ze}{b}\exp(-b/a) = \tfrac{1}{2}Mv^2.$$

The individual small angle deflections were summed and the average increase in the path length of protons through the gold obtained. This was about 9-10%, indicating 90 μg cm^{-2} for the actual foil thickness.

Variation of average path length through the gold, with particle energy, should not be significant as the effects of variation in small angle scattering cross section and the variation in θ_m compensate. The product of the minimum scattering angle, θ_m, and the differential scattering cross section with respect to $\theta^{(6)}$, at θ_m, i.e. $\theta_m\, d\sigma_{sc}/d\theta$, is given by

$$\theta_m \frac{d\sigma_{sc}}{d\theta} = \theta_m \frac{\pi b^2}{4} \cot \frac{\theta_m}{2} \cdot \operatorname{cosec}^2 \frac{\theta_m}{2} .$$

with θ_m small, as it is for plural scattering the product reduces to $8\pi a^2$ which is independent of particle energy.

Backscattering

From detector irradiations by H_2^+ and H_3^+ ions at 45 keV (Fig.3) the ratios of 22.5 keV (mean ~ 20.25 keV) and 15 keV (mean ~ 13.42 keV) peaks, respectively to the main peaks were measured. Neglecting beam attenuation within the gold layer the ratio of the secondary peak to the main peak for H_2^+ is $\frac{2\, n\, \sigma_B}{1 - n\sigma_B}$, and for H_3^+ is $\frac{3\, n\, \sigma_B}{1 - n\sigma_B}$ where n is the number of gold atoms per cm^2 and σ_B is the cross section for scattering angles greater than $\pi/2$. $n\,\sigma_B$ is the probability that a proton will not pass through the gold to the silicon. Taking $n = 3 \times 10^{17}$ (100 $\mu g\ cm^{-2}$) we obtain

$$\sigma_B \text{ (13.42 keV)} = 1.89 \pm 0.27 \times 10^{-19}\ cm^2$$

and

$$\sigma_B \text{ (20.25 keV)} = 1.31 \pm 0.30 \times 10^{-19}\ cm^2 ,$$

compared with values, deduced from the quasi Thomas-Fermi potential with $\sigma_B = \frac{\pi b^2(6)}{4}$, of $2.33 \times 10^{-19}\ cm^2$ and $1.28 \times 10^{-19}\ cm^2$ respectively.

Although protons scattered, soon after entering the gold, at angles somewhat less than $\pi/2$ would not contribute to the main peak of the pulse height distribution, their number would only amount to a small fraction of those scattered at $\theta > \pi/2$. Their effect on the experimentally determined value of σ_B would be within the limits of experimental error.

Although σ_B is not a true backscattering cross section the number of particles scattered at angles below 90^o and still not contributing to the main peak of the pulse-height distribution will be only a small fraction of the integrated cross section for 90^o to 180^o.

5. CONCLUSIONS

Measurements of energy loss by protons in passing through the gold layer on the face of a silicon surface barrier detector, based on an assumption that the total number of electron-hole pairs produced in the silicon varies linearly with the particle energy, for energies above a keV or so, have enabled an extension of the $\frac{dE}{dx}$ (E) curve for protons on gold to be made down to less than 10 keV proton energy. Although the method suffers from bad geometry in that particles scattered through relatively large angles are included in the measurements it is not believed that the effect of these is significant.

Our stopping power determination depends on the widely accepted value of 3.6 eV for the average energy expended by a proton in producing an electron-hole pair. A recent accurate measurement of the average loss rate for α particles in silicon, by Emery and Rabson[7], gives a value of 3.61 ± 0.1 eV/pair. Even allowing for a possible variation in loss rate with particles species (Emery and Rabson obtained 3.74 eV/pair for electrons) the value of 3.6 eV which we have used would be well within the accuracy of our experimental results.

6. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig.1 (a) Schematic and (b) Block diagrams of apparatus

Fig.2 Energy response of detector to protons

Fig.3 Displays of pulse heigh distributions

(a) H_1^+ at 45 keV (b) H_2^+ at 45 keV

(c) H_3^+ at 45 keV (d) injected signal of 1.70 mV

The pulse heights, abscissae, are expressed as equivalent incident particle energies.

Fig.4 $\frac{dE}{dx}$ curve for protons on gold as a function of proton energy.

The error bars at proton energies of 10, 30 and 50 keV show the calculated probable errors, including ± 6% in estimation of gold layer thickness.

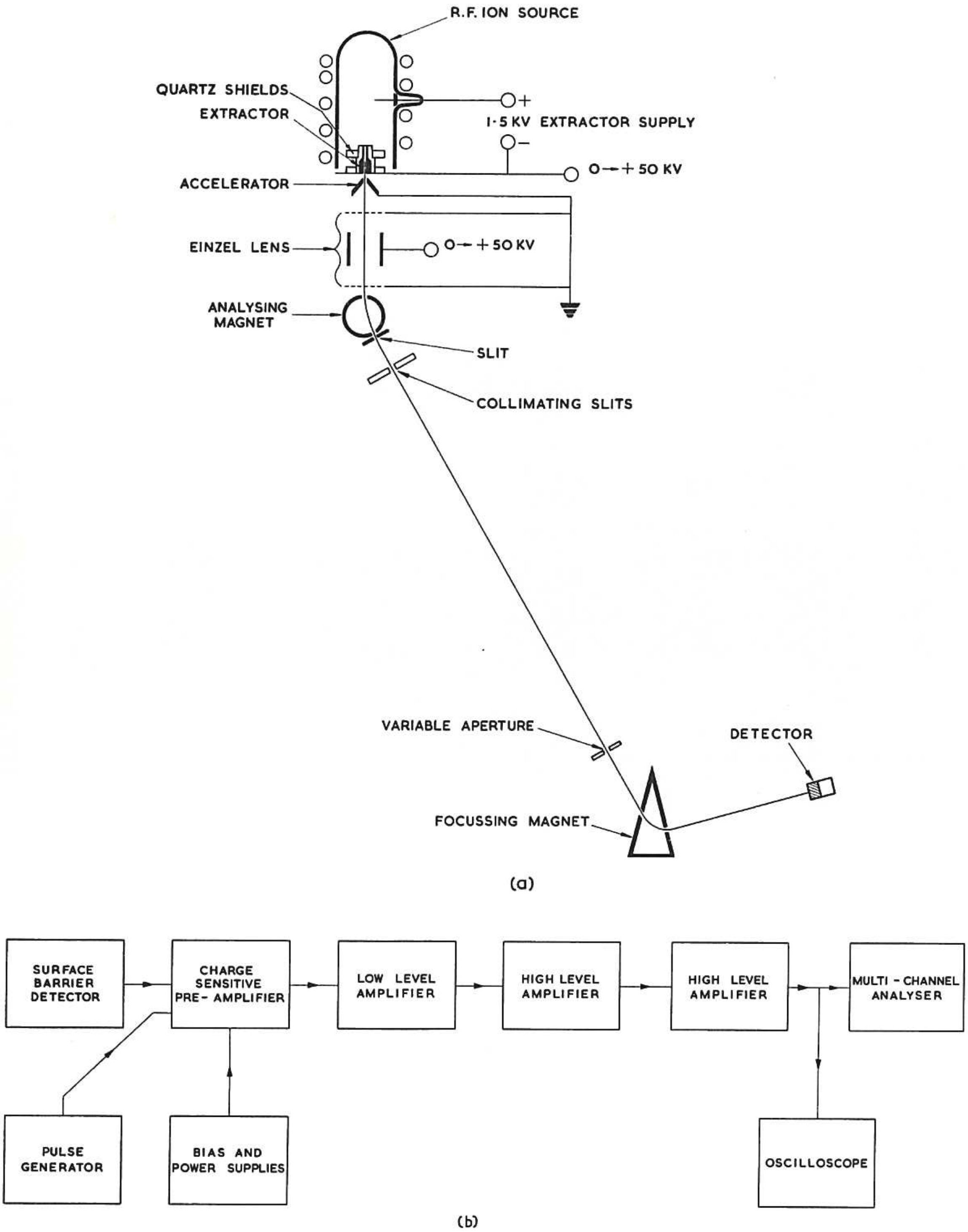

FIG. 1. a) SCHEMATIC AND b) BLOCK DIAGRAMS OF APPARATUS.

Fig. 1 (a) Schematic and (b) Block diagrams of apparatus (CLM-P 107)

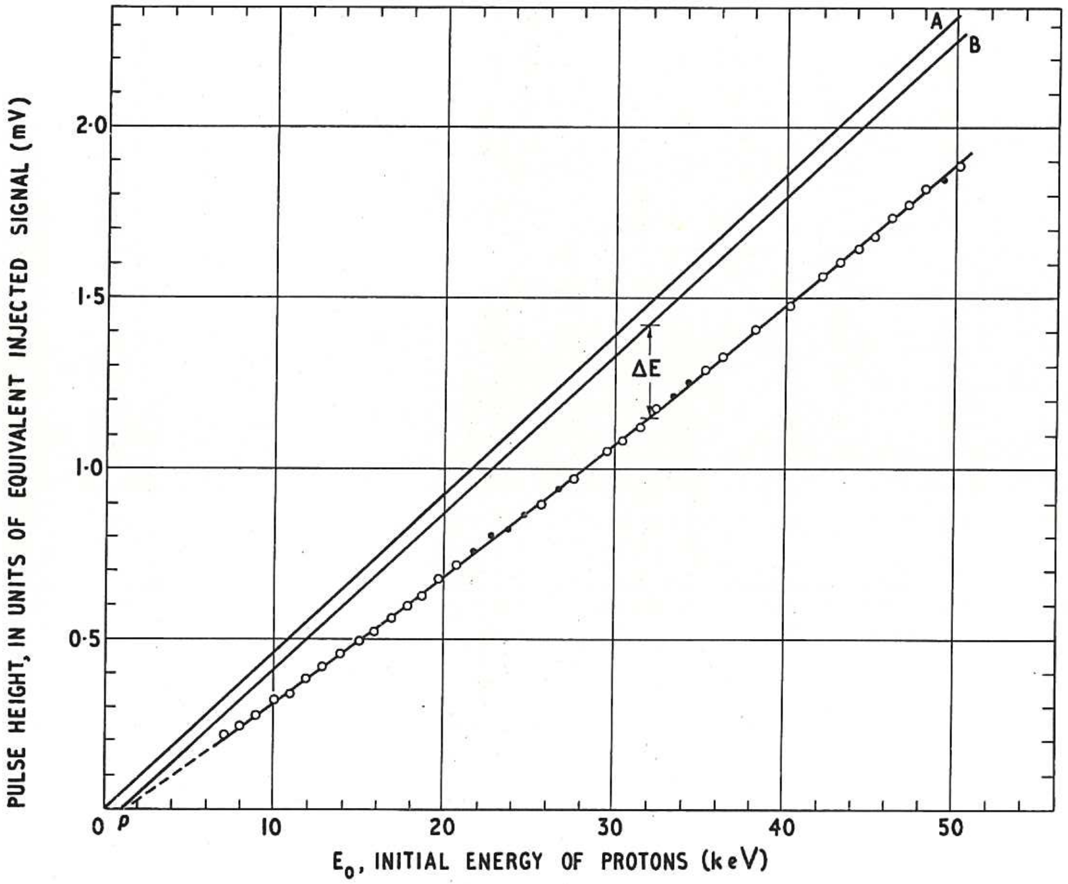

Fig. 2 Energy response of detector to protons (CLM-P 107)

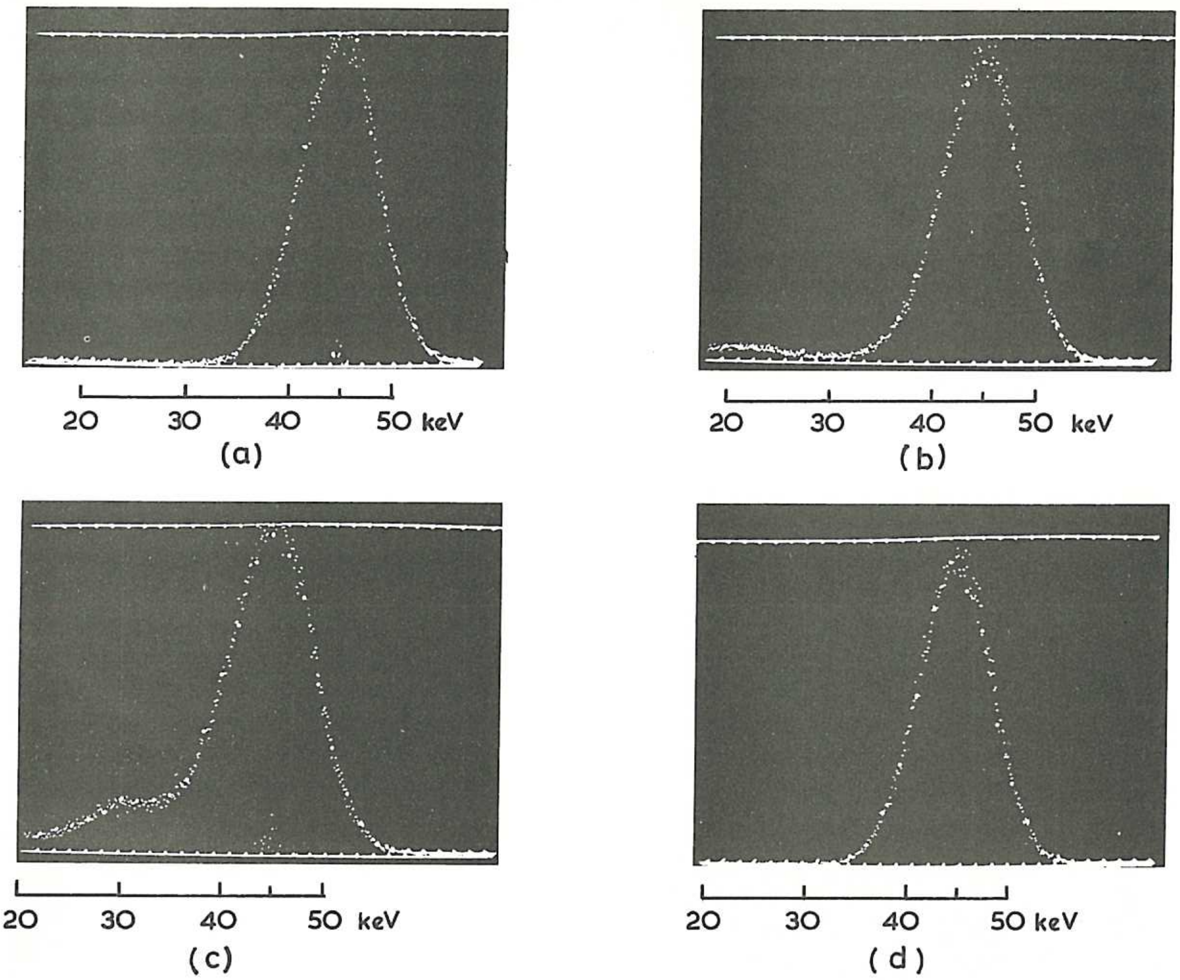

Fig. 3 (CLM-P 107)

Displays of pulse height distributions: (a) H_1^+ at 45 keV; (b) H_2^+ at 45 keV; (c) H_3^+ at 45 keV; (d) injected signal of 1.70 mV. The pulse heights, abscissae, are expressed as equivalent incident particle energies

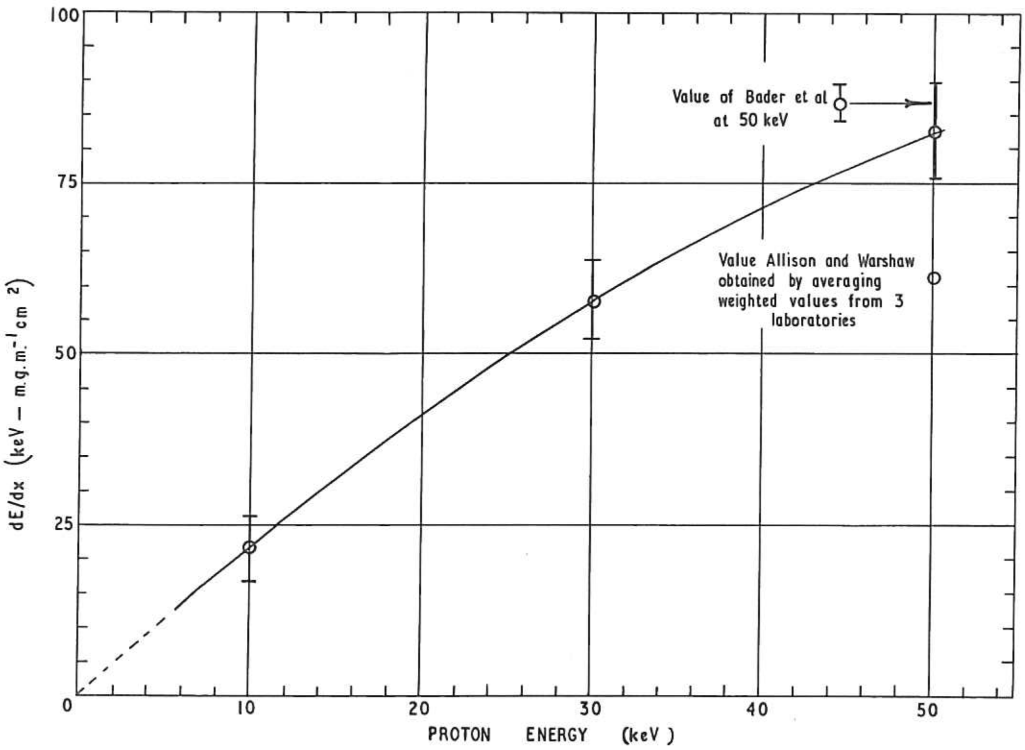

Fig. 4 (CLM-P 107)

dE/dx curve for protons on gold as a function of proton energy. The error bars at proton energies of 10, 30 and 50 keV show the calculated probable errors, including ± 6% in estimation of gold layer thickness