Title
SUMMARY OF THE RESEARCH PROGRESS MEETING OF JULY 20, 1950

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October 23, 1950

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Stopping Power of Various Materials for 300 Mev Protons. C. J. Bakker.

By means of the apparatus shown schematically in Fig. 1, the stopping power of various materials relative to copper was measured. The 335 Mev deflected proton beam from the 184-inch cyclotron was brought outside the cave, passed through an argon filled ionization chamber, then through a thickness of material which was, according to W. Aron's range-energy calculations equivalent to about 30 gm/cm^2 of copper, then through 60 gm/cm^2 of copper, thence through a remotely operated wheel equipped with 12 windows of copper foil ranging in thickness from 0 to 11.7 gm/cm^2, and finally through a second argon filled ionization chamber.

If one plots the ratio of ionization produced in the second chamber to the ionization produced by the raw beam when the absorber consists of 30 gm/cm^2 of copper versus thickness of copper corresponding to foils of different thicknesses one obtains a curve that appears somewhat like that of Fig. 2. If one now replaces the copper absorber by an equivalent thickness of another material, the curve is essentially displaced somewhat along the axis of abscissas. Since the displacement is not strictly uniform along the entire curve a reference point was chosen on each curve and the lateral displacement of the reference point was then regarded as being representative of the relative displacement of the curves. Although the choice of reference point was not critical, the point of half-ionization on the straggling end of the curve was picked. Since in passing through 30 gm/cm^2 copper equivalent of material the mean beam energy is reduced to 300 Mev, the measurements yielded the number of gm/cm^2 which are equivalent in stopping power for 300 Mev protons to 1 gm/cm^2 of copper. These numbers are set down in column 1 of Table 1. Corresponding numbers calculated with respect to aluminum are shown in the second column of the table. The stopping powers relative to aluminum which are obtained from the numbers of column 2 by multiplying the inverses by $(A/Z)_X/(A/Z)_{Al}$ are given in column 4. Column 5 contains the corresponding values for 95 Mev protons as determined by C. Tobias from the values in column 3 as measured by Thornton and Stephan with 190 Mev deuterons.

The stopping power is given by the following formula:

$$-\frac{\partial E}{\partial x} = \frac{4\pi e^4}{mV^2} NZ \left\{ \log \frac{2mV^2}{I} - \log (1-\beta^2) - \beta^2 \right\},$$

e being the electron charge, m the mass of the electron, V the speed of the protons, N the number of atoms of substance in unit volume, Z the atomic number, I the mean ionization potential and $\beta = V/c$. This formula gives a relativistic account of the rate of energy loss due to ionization. It neglects energy loss due to nuclear processes. By means of this formula one can express the relative stopping power per electron q, that is, the number for each element contained in column 4 and finds, letting K=stopping power/electron for aluminum, and using Bloch's hypothesis that $I = B'Z$, that

$$Kq = -\log B' - \log Z + \left[\log 2mV^2 - \log (1-\beta^2) - \beta^2\right]$$

By plotting log Z versus the experimentally obtained values of q one obtains a curve that, for elements of Z greater than that of Al, indeed approaches a line very closely. The value of Bloch's constant B' that is read from this curve is B'=5.9 ev. From the following table, the variation with energy of Bloch's number is apparent:

Investigator	Energy of protons (Mev)	B' (ev)
R. R. Wilson (1941)	4	11.5
R. R. Wilson	Po α	11.6
Teasdale	12	9 ± 1.5
Stephan and Thornton	95	8
Bakker, Segrè et al.	300	6

A tentative explanation for the decrease of B' with energy may be that at high energies the outer electrons play a much subdued role in ionization and only the K-shell electrons are principally effective. (This idea was questioned in the ensuing discussion).

The stopping power of aluminum as measured was K=8.7. According to W. Aron's range-energy curves K=8.8. This bears out the good agreement between the tables and measurement that was found throughout the work.

In order to investigate straggling in the Bragg curve for protons, it was assumed that the ranges R of particles of the same energy are scattered around a mean value R_o according to a Gaussian distribution:

$$P(R)= \frac{1}{\sqrt{2\pi\,\overline{(R-R_o)^2}_{aver.}}}\; e^{-\frac{(R-R_o)^2}{2\overline{(R-R_o)^2}_{aver.}}}$$

To find the ionization corresponding to a range R, the contributions in ionization of all particles that stop at $R' \geq R$ must be summed in the fashion sketched in Fig. 3. For a value of the parameter $\sqrt{\overline{(R-R_o)^2}_{aver.}}=1.5$ gm/cm^2 one obtains an excellent fit to the experimental Bragg curve. The theoretical formula for straggling

$$\overline{(R-R_o)^2}_{aver.} = 4\pi e^4 NZ \int_0^{E_o} \left(\frac{\partial E}{\partial x}\right)^{-3} dE,$$

derived by Bohr, with the stopping power of copper obtained from Aron's range energy curves yields $\sqrt{(R-R_o)^2} = 0.8$ gm/cm^2. The divergence between the two results is readily explained by a 1 percent spread in beam energy which is entirely plausible on the basis of the deflector geometry.

Finally, the energy lost per ion pair produced in various gases was measured relative to argon, and from an absolute determination on argon by E. Segrè et al, the energy lost per number of ion pairs produced W was obtained for these gases. The measured quantities were I_x, the ionization read off an ionization chamber filled with gas x and I_a, the ionization produced in an argon filled chamber, when both chambers were traversed by a beam of 340 Mev protons. Since the number of ion pairs produced is proportional to the ionization,

$$W_x/W_a \sim \frac{\left(\frac{\partial E}{\partial x}\right)_x}{\left(\frac{\partial E}{\partial x}\right)_a} \cdot \frac{k_a I_a}{k_x I_x} .$$

where the k_x and k_a are the constants that convert ionization to number of ion pairs. The results of these measurements are set down in Table 2.

Table 1

Z	Element	Cu equivalent gm/cm^2	Al equivalent gm/cm^2 (300 Mev p^+)	Al equivalent gm/cm^2 190 Mev d^+	Stopping power/per electron rel to Al 300 Mev	95 Mev
1	H (inCH_2)	.36	.41		1.16	.95
3	Li	.82	.94		1.18	
4	Be	.85	.99		1.12	1.11
6	C	.75	.86	.88	1.12	1.08
13	Al	.87	1.00	1.00	1.00	1.00
26	Fe	.96	1.10		.94	.92
29	Cu	1.00	1.14	1.22	.92	.91
47	Ag	1.11	1.27	1.37	.87	.85
50	Sn	1.16	1.33		.86	.82
74	W	1.28	1.47		.81	.77
82	Pb	1.32	1.52	1.69	.80	.75
92	U	1.39	1.59	1.74	.79	.73

Table 2

	W_x/W_a	W_x 340 Mev p^+	W_x Po$^{\alpha}$
H_2	1.40	34.9	35.1
H_e	1.02	25.3	30.2
N_2	1.31	32.7	36.3
O_2	1.23	30.5	34.5
A^2	1	24.8	27.6

Production of Be^7 in Light Nuclei with 335 Mev Protons. L. Marquez.

Experiments are being carried out to determine the probability that particles heavier than helium ions are boiled off from nuclei on excitation with high energy protons. The curve of Fig. 1 shows the variation of the cross section for the boiling off of Be^7 nuclei with atomic weight. The momentum that the Be^7 nucleus acquires varies considerably with A since in light elements, the Be^7 nucleus is left behind after light particles are boiled off whereas the converse takes place in heavier elements. The yields were higher than would be expected on the basis of the liquid drop model of the nucleus.

Mass of the Neutral Meson. W. Panofsky.

From the observation of γ-rays believed to be produced in the reaction

$$\pi^- + p^+ \longrightarrow n + \pi^0 \quad (\pi^0 \downarrow 2\gamma)$$

The mass difference between the heavy negative and neutral mesons has been determined to be $\pi^- - \pi^0 = 5.7 \pm 1.2$ Mev. Using the presently accepted value of 276 ± 6 e.m. for the mass of the negative heavy meson one finds for the neutral meson $\pi^0 = 265 \pm 6$ e.m.

In the same experiment γ-rays have also been observed that are believed to be produced according to the scheme $\pi^- + p^+ \longrightarrow n + \gamma$. The probability of the production of a neutral meson relative to that of a direct γ-ray is estimated to be $\frac{\Gamma_{\pi^0}}{\Gamma_{\gamma}} = 0.74 \pm 0.2$.

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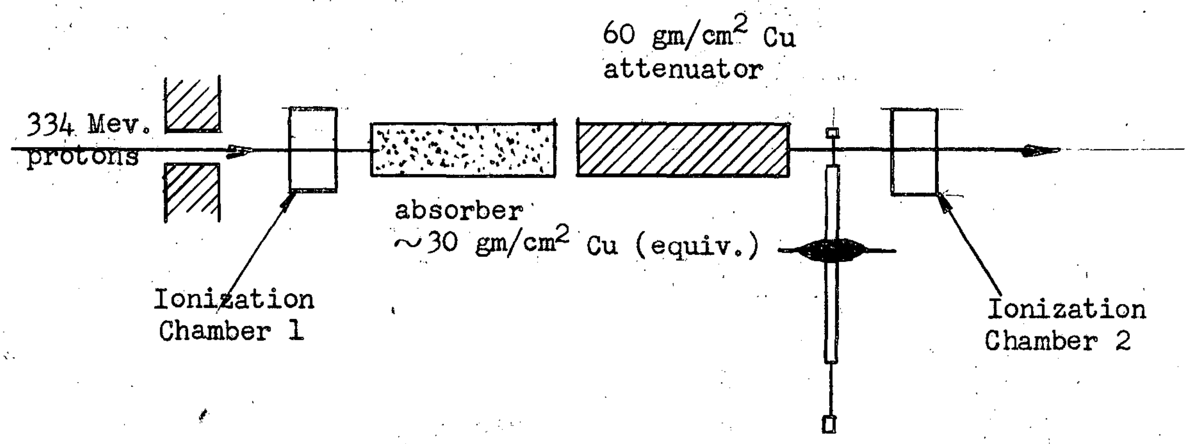
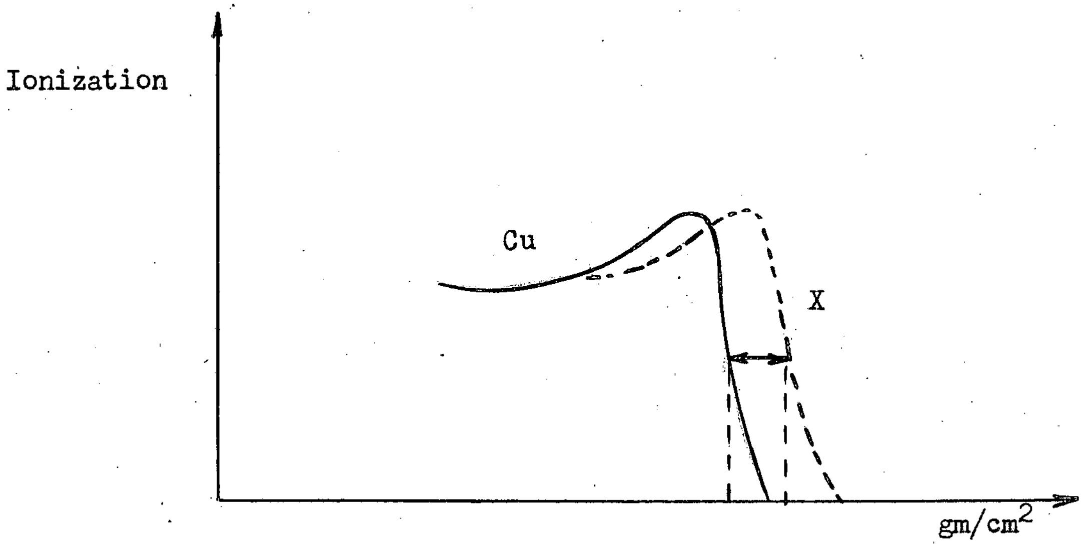
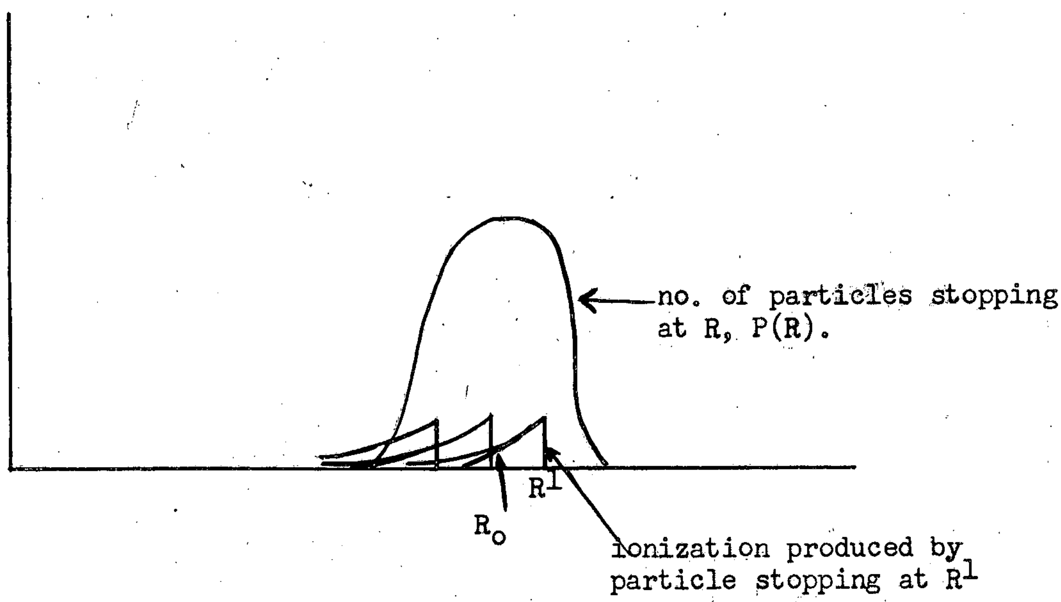


Experimental Scheme
Fig.1



Typical Bragg Curves
Fig. 2



no. of particles stopping
at R, P(R).
R¹
R_o
ionization produced by
particle stopping at R^1

Fig.3

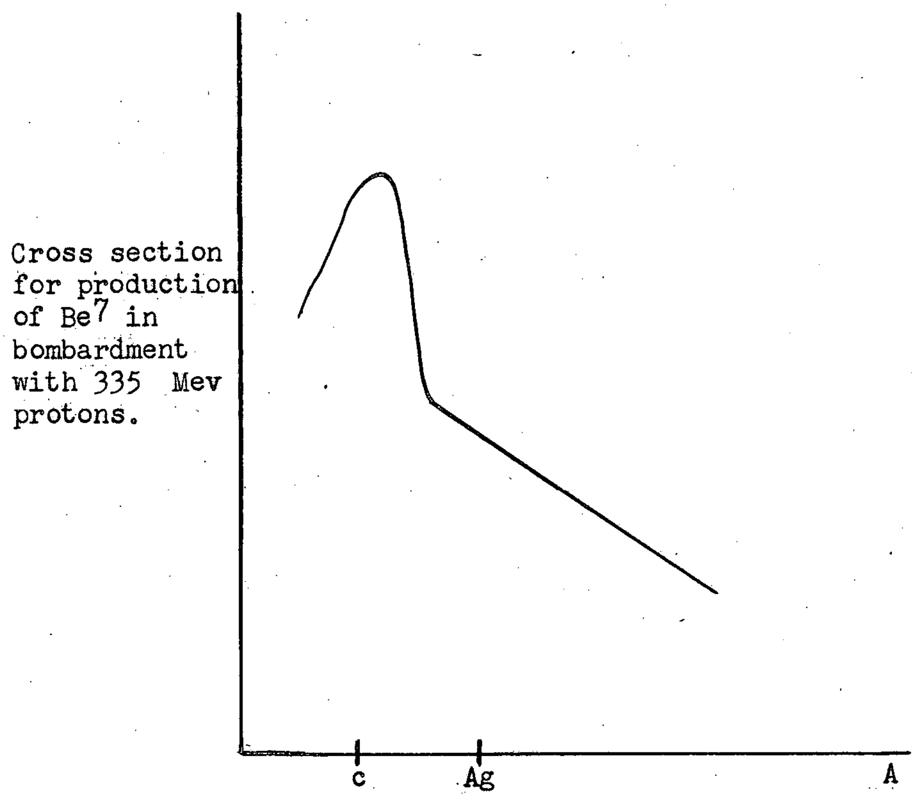

Cross section for production of Be7 in bombardment with 335 Mev protons.
C
Ag
A

Fig.4