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Mean Excitation Potentials*

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Previous experimental results of the present authors on the energy loss of 18-Mev protons in aluminum are corrected to give a value for the mean excitation potential $I=168$ ev. It is pointed out that recent work on the range-energy relationship for protons in aluminum may indicate a variation of I with proton energy which is considerably larger than that to be attributed to the nonparticipation of the K electrons.

THE results of a measurement of the absolute energy loss of protons upon passing through various materials have been recently published.[1] Since that time, it has become evident that an out-of-date and inaccurate value of the constant e^2/mc^2 was used[2] in computing the mean excitation potentials of these materials. In the light of new work[3–5] that has been done in the field of proton ranges and excitation potentials, it was thought worth while to correct the previous computations.

In Bethe's energy loss formula,[6]

$$-dE/dx=(4\pi NZ^2e^4/mv^2)B, \quad B=Z\ln(2mv^2/I)-C_k,$$

the atomic stopping number B can be obtained from the experimentally determined $dE/d\sigma$ by using the relation

$$B=\frac{\beta^2A}{4\pi mc^2r_0^2N_0}\left(\frac{-dE}{d\sigma}\right).$$

Here $\beta=v/c$, $r_0=e^2/mc^2$, $A=$atomic weight of the absorber, $N_0=$Avogadro's number, and $-dE/d\sigma$ is the energy loss per unit surface density of the absorbing foil. Negligible error is introduced in this experiment by using the average value of β^2 during the energy loss. Also the mean excitation potential

$$I=2\beta^2mc^2\exp[(-B+C_k)/Z].$$

It is to be noted from these relations that a half-percent error in r_0 will be reflected as a six percent error in I.

Using the value 2.818×10^{-13} cm for r_0 we obtain the corrected results for aluminum which are shown in Table I. The values of the other constants used are $mc^2=0.5108$ Mev, $N_0=6.0228\times10^{23}$ atoms per gram atom (chemical scale), $A=26.98$ g for aluminum. The weighted average for aluminum becomes $I=168$ electron volts.

TABLE I. Mean excitation potential of aluminum.

Surface density (mg/cm²)	Most probable energy loss (Mev)	Mean excitation potential (ev) (with probable error)
7.153	0.153	179.3±21.5
14.054	0.301	181.3±13.6
21.432	0.465	172.7± 8.6
21.532	0.470	167.0± 9.6
33.875	0.737	175.8± 7.0
38.395	0.839	173.8± 5.0
47.457	1.048	168.7± 8.3
57.493	1.276	168.6± 5.9
67.294	1.515	160.9± 5.4
76.849	1.737	161.6± 4.1

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[1] D. C. Sachs and J. R. Richardson, Phys. Rev. 83, 834 (1951).

[2] We are greatly indebted to Dr. Joseph E. Perry for bringing this discrepancy to our attention.

[3] N. Bloemberger and P. J. van Heerden, Phys. Rev. 83, 561 (1951).

[4] K. B. Mather and E. Segrè, Phys. Rev. 84, 191 (1951).

[5] E. L. Hubbard and K. R. MacKenzie, Phys. Rev. 85, 107 (1952).

[6] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. 9, 262 (1937). See this paper for notation.

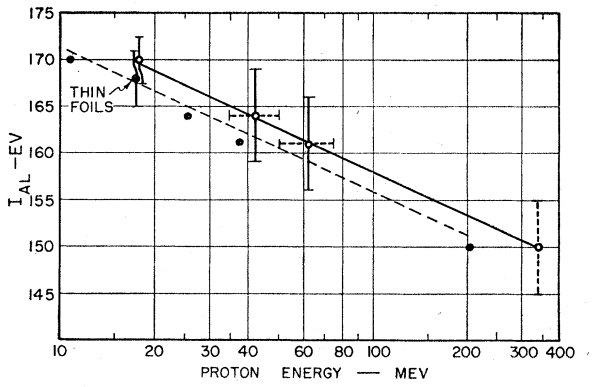

FIG. 1. Mean excitation potential of aluminum as a function of proton energy. The solid curve connects points obtained from proton range-energy experiments. The dotted curve represents an approximate thin-foil energy loss function.

Table II presents a summary of the results of recent experiments[7] which determined the mean excitation potential of aluminum. Our experiment (Sachs-Richardson) was performed with thin foils of material where the loss of proton energy in the foils was a small fraction of the incident energy (see Table I). In contrast, the remaining experimenters measured the complete proton ranges in aluminum. Assuming for the moment that there is a real variation of I with proton energy, Kaus has calculated the value of the proton energy which represents an effective value for the entire energy loss. He assumes that

$$I(E)=I_0-a\log E$$

is the functional relationship between I and the proton energy and that $a/I_0\leqslant 0.1$. From this, one obtains the result that $E_{\text{eff}}\simeq 0.6E_{\text{inc}}$. This E_{eff} for each experiment is shown in column 3 of Table II. Of course, for thin foils we have $E_{\text{eff}}\simeq E_{\text{inc}}$. In column 4 of this table, the I_{Al} values (with standard deviations) are listed. The standard deviations to the excitation potentials were obtained from the respective papers with the exception of that of Mather and Segrè. In this case the standard deviation had to be computed from their statements[8] of the approximate deviations (i.e., about 1 Mev for the energy and 0.2 g/cm² for the ranges).

Figure 1 shows a semi-log plot of the mean excitation potential of aluminum *vs* proton energy. The open circles refer to the incident proton energies (column 2 of Table II), while the solid circles represent the effective energies as defined above. The point corresponding to the thin foil result is not changed when account is taken of the effective proton energy. Upon consideration of the results in the figure, it is clear that better experimental data would be desirable before deciding that the variation of I with energy is real. It should also be pointed out that the effect of I of the nonparticipation of K electrons[6] has been taken into account in the treatment of the experimental data when use is made of C_k. Even if these calculated corrections were ignored entirely, the apparent variation of I over this energy range would only be of the order of 6 ev, which is small compared to the indicated experimental variation.

The thin foil mean ionization potentials for some other materials are shown in Table III. These results were computed using C_k, C_l, $\cdots=0$, i.e., no corrections for nonparticipating electrons were made. These corrections, if they were known, would tend to lower the values of the potentials.

TABLE II. The results of recent experiments which measured the mean excitation potential of aluminum.

Experiment	Incident proton energy (Mev)	Effective proton energy (Mev)	Mean excitation potential of aluminum (ev)
Sachs-Richardson[a]	17.8	17.8	168±3
Hubbard-MacKenzie[b]	18.0	10.8	170±2.5
Bloembergen-van Heerden[c]	35–50	21–30	164±5
	50–75	30–45	161±5
Mather-Segrè[d]	340	204	150±5

[a] See reference 1.
[b] See reference 5.
[c] See reference 3.
[d] See reference 4.

TABLE III. Weighted averages of the mean excitation potentials of various materials.

Material	Weighted average mean excitation potential (ev)
Nickel	399
Copper	435
Rhodium	799
Silver	796
Cadmium	792
Tin	853
Tantalum	1148
Gold	1383
Nylon	41.3

[7] See also D. H. Simmons, Proc. Phys. Soc. (London) **A65**, 454 (1952).

[8] See reference 4, p. 193.