find $\bar{\epsilon}_0=\mu-1.2kT$. The determination of the 1.2 is necessarily an approximation but is good to better than four percent. They then proceed to compute the heat carried away by electrons emitted in an accelerating field as though the emission current were supplied at the cool part of the filament at the level $\bar{\epsilon}_0$ instead of μ. This leads to the result $\bar{w}=\phi+3.2kT$ for the average energy carried away per electron when emitted thermionically. Here ϕ is the work function $(C-\mu)$ and C is essentially the potential energy of an electron just outside of the emitter relative to the bottom of the Fermi band as zero.

Consider the receiving plate of a tube for studying thermionic emission to be at 0°K. Then the electrons in the emission current cannot fall into quantum states lower than μ upon being received because all of those states are filled. The electric current flows around the circuit at the level μ (except for batteries) and flows into the emitter at this level. Richardson[2] visualized a situation essentially no different from this and showed that the true heat loss per electron attending thermionic emission is $\bar{w}=\phi+2kT$. A reflection effect, or a transmission coefficient $D(W)$ which is constant and therefore independent of W for all values of $W>C$, does not alter $\bar{w}$ where W is the energy associated with the motion normal to the surface. Thermionic studies[3] indicate that $D(W)=1-\exp(W-C)/R$ represents the experimentally determined energy distributions accurately where R is an empirical constant equal to 0.191 electron volt. A paper is being prepared which shows that with this transmission coefficient, $\bar{w}=\phi+kT[2+1/(1+kT/R)]$. For the temperature range 1500°K to 2200°K this coefficient of kT varies from 2.6 to 2.5 as compared with 2 for non-selective transmission.

The possibility that there are misprints on page 893 of Fleming and Henderson makes a detailed checking of their results difficult since three of the integrations have limits μ to ∞ instead of those expected of 0 to ∞ and the brackets are not completed in front of the exponentials as it seems they should be. Although the writer has not yet been able to duplicate the final equation giving $\bar{w}$ as computed for the case of field emission using the indicated limits of μ to ∞, there can be no doubt concerning the final result that an inappreciable heat loss is to be expected for the electrons emitted even though the temperature of the emitter is fairly high. In fact it seems likely that one would find a detectable heating effect when a strong emission takes place from a very sharp point. If one uses integration limits 0 to ∞ and assumes that the electrons enter the emitter at the μ level, the calculation of such heating, if it exists, is straightforward.

It should be clear that the above criticisms apply to aspects of the theory which are on the borderline of the experimental accuracy that one may hope to attain. The main general conclusions, that in the case of thermionic emission the heat loss is largely dominated by an energy very nearly $\phi+2kT$, and that very little heat loss is to be expected in the case of field emission, are well borne out by the experiments.

[1] G. M. Fleming and J. E. Henderson, Phys. Rev. 58, 887 (1940).
[2] O. W. Richardson, Phil. Trans. A201, 497 (1903).
[3] W. B. Nottingham, Phys. Rev. 49, 78 (1936).

On the Energy Losses Attending Thermionic and Field Emission

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May 15, 1941

In the preceding letter Professor Nottingham is concerned about a calculation performed in a paper[1] by us to evaluate the energy loss in thermionic emission. The essential difference in viewpoint, as Professor Nottingham chooses to discuss it, depends upon whether the electrical conduction in a metal can occur at levels lower than μ, the Fermi parameter; Professor Nottingham's contention being that conduction physically occurs only at the level μ.

Other than the experimental results themselves, the most important conclusion to be drawn from the paper[1] under discussion is that conduction can occur at levels below μ. This conclusion rests upon the validity of two experimental results: first, the conclusion of the paper in question that there is no measurable temperature change of a field current emitter, and second, that there exists an energy distribution[2] for the electrons involved in field emission, which exhibits a maximum often two volts below the maximum energy corresponding to μ.

To make this conclusion more evident, consider a piece of metal with electrons being emitted at one end and supplied by conduction at the other end. Let $N(E)$ be the rate at which electrons of energy E are emitted, and let the average energy in the current of electrons entering the metal be E_1. Then the rate at which energy is acquired during emission by the metal is $\int_0^\infty(E_1-E)N(E)dE$. Since the experimentally determined energy distribution for field electrons emitted near room temperature shows that $N(E)$ has a maximum for an energy, E, of the order[2] of a volt or more below μ, if E equals μ the integral is essentially positive and equal to at least one electron volt/electron. The temperature change of any point in the emitter depends on the degree of concentration of energy released in the vicinity of the point. For field emission at room temperature an average energy transfer of 0.002 electron volts per electron would, if concentrated at the emitting surface, have been detectable. Thus the experiments[1] show that not more than 1/500 of the energy release is concentrated at the emitting surface. Therefore, either the electrons in the net current are not supplied at the level μ, or their transition from higher to lower levels occurs on the average at a large distance from the emitting surface.

The usual perturbation methods used in the kinetic theory evaluation of conduction take into account three kinds of perturbations (density, temperature and potential variations). It is further required that these perturbations be small. The condition in the vicinity of a boundary may be regarded as a perturbation of another kind and in this case the perturbation is not necessarily small. In view of the deficiency of the theory for this kind of problem, the calculation in the paper[1] is necessarily a rough estimate of the phenomena occurring in the neighborhood of the boundary.

The three integration lower limits, μ, on page 893 are not misprints. However, the brackets should be closed in front of the exponential factor in the second equation for w, and the last equation on page 894 should read $w=\phi+3.2kT$.

[1] G. M. Fleming and J. E. Henderson, Phys. Rev. **58**, 887 (1940).
[2] J. E. Henderson and R. K. Dahlstrom, Phys. Rev. **55**, 473 (1939).

On the Selection Rules in Beta-Decay

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April 25, 1941

THE rapid decay of a presumably largely ^1S He^6 to a $^3S+^3D$ Li^6 has always been regarded as strong evidence for the Gamow-Teller selection rules in beta-decay. The analogous disintegration $C^{10}\rightarrow B^{10}$ is also rapid and obviously allowed. However the three further at first sight similar disintegrations

$$(S) \qquad H+H\rightarrow D; \quad Be^{10}\rightarrow B^{10}; \quad C^{14}\rightarrow N^{14},$$

where in every case the parent nucleus would be expected to be largely ^1S, and the product nuclei are known to be predominantly $^3S+^3D$, are slower than would be expected for allowed transitions of the observed energy by factors of the order 10^4-10^7. The activity $O^{14}\rightarrow N^{14}$, homologous to that of C^{14}, is not known; the activity of F^{18}, where normal states can perhaps be less unambiguously assigned, is allowed.

The assumption that the initial states in the disintegrations (S) have been incorrectly assigned is very unsatisfactory. For the reaction $H+H\rightarrow D$ there can be no question that the initial state is ^1S; and the astrophysical evidence that this reaction is slow seems excellent. For Be^{10} and C^{14} states of very high angular momentum (^1G) would be required to account, with Gamow-Teller selection rules, for their extremely long life; this is not only highly implausible on the basis of any known nuclear theory, but in gross contradiction with the expected proton-neutron symmetry of the nuclei C^{10} and Be^{10}. Almost equally unsatisfactory is the assumption that He^6 and C^{10} are ^3S or ^3D, and the Gamow-Teller selection rules wrong; for this too, in addition to leaving unexplained the many less direct evidences for spin change in allowed transitions, would grossly violate theoretical expectations on the symmetry of normal states and on the proton-neutron symmetry in C^{10} and Be^{10}.

The fast reactions

$$(F) \qquad He^6\rightarrow Li^6; \quad C^{10}\rightarrow B^{10}$$

differ from the slow reactions (S) systematically, in that for (F) energies of over 3 Mev are available, whereas for (S) the energies are 350 kev, 550 kev, and 150 kev, respectively. This suggests that the Gamow-Teller selection rules have a "threshold," such as would be involved if the corresponding neutrino had a rest mass. This rest mass would have to be at least of the order of that of an electron, and might for instance characterize a neutrino of spin $\frac{3}{2}$. On this theory the reactions (S) would be governed by Fermi selection rules, and there would then be no difficulty, on taking into account the small amount of ^3P to be expected in the initial states, and of ^1P in B^{10} and N^{14}, in accounting for their very long lifetimes. The reactions (F) on the other hand would involve the emission of a heavy neutrino and be allowed by Gamow-Teller selection rules.

This suggestion has three simple consequences: (I) There should be a discrepancy, given by the mass of the heavy neutrino, in the energy balance of the reactions (F).[1] (II) The shape of the upper end of the He^6 and C^{10} spectra should correspond to a finite neutrino mass. (III) The disintegration $O^{14}\rightarrow N^{14}$, that has an estimated upper limit 3.8 Mev$-\mu c^2$, with μ the heavy neutrino mass, should decay rapidly. If we take N^{14} as 15 percent ^3S, and $\mu c^2\sim\frac{1}{2}$ Mev, the lifetime should be about 20″.[2]

It would appear that published evidence was neither sufficient to check nor disprove these expectations. If we suggest the *a priori*, highly improbable existence of the heavy neutrino, it is in part because these three points can so readily be settled, but even more again to call attention to the very puzzling difficulties that have arisen in interpreting these activities.

[1] The Wigner and Hartree estimates of the $C^{10}-Be^{10}$ Coulomb difference themselves differ by several hundred kilovolts, and are presumably of insufficient accuracy to afford a test of the C^{10} energy balance.
[2] The bombardment of C with alpha-particles, of N with deuterons, both lead to strong O^{15} activity; the bombardment of N with protons leads to a strong C^{11}. All these reactions have been tried in Berkeley, by Dr. Kamen, Dr. Segrè, and Mr. Wright, as sources for O^{14}; in every case the results of a preliminary survey were negative. These investigations are not yet concluded, and I am grateful to these workers for telling me of their findings.

Non-Laue Diffraction Maxima from Rocksalt—Non-Equatorial Maxima

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May 15, 1941

PROFESSOR W. H. Zachariasen has been kind enough to send the senior author a copy of his Letter to the Editor which appears in this issue of *The Physical Review*. Non-equatorial associated Bragg spots appeared on the films which were used in Jauncey and Baltzer's paper.[1] A correction for the position of these spots on the film must be made if the l axis of the crystal and the axis of the cylinder of photographic film are not parallel. Making this correction, which will be described later, we find the experimental shifts, $2\theta_m-2\theta_B$, shown in the second column of Table I. The shifts are for the 402 associated Bragg spots

TABLE I. *Values of $2\theta_m-2\theta_B$.*

Δ	EXP.	FORMULA	
		ORIG.	REV.
−3°20′	−1°19′	−2°29′	−1°37′
−2°25′	−0°55′	−1°48′	−1°10′
−1°39′	−0°47′	−1°14′	−0°48′
−0°44′	−0°09′	−0°33′	−0°21′
+0°12′	−0°00′	+0°09′	+0°06′
+1°01′	−0°28′	+0°45′	+0°29′
+1°49′	−0°45′	+1°21′	+0°52′