Heavy Electrons from Radium E—Discussion of the Evidence

The evidence for the existence of heavy beta-rays as given in the previous two letters[1, 2] has been subject to the following objections: (a) the voltage across the velocity selector is not that determined by the voltage measuring device, (b) the resolving power of the velocity selector is zero, and/or (c) the "heavy electron" band on the film is due to ordinary electrons being multiply reflected or scattered within the selector.

Objection (a) is ruled out by the presence of the line due to the ordinary electrons in the photograph shown in my last letter.[2] This line occurs at the position on the film required by the selector velocity, $\beta_s c = E/H$.

To answer (b), we consider the velocity selector.[3] Making the approximations that the force Ee on the electron is opposite to the force $He\beta c$ on it and that the curvature $1/\rho'$ inside the selector is constant, we obtain

$$\beta_s = \beta + pm_0\beta^2 c/He\rho'(1-\beta^2)^{\frac{1}{2}}, \qquad (1)$$

where pm_0 is the mass of the electron. To obtain the resolving power, we put $\rho' = \pm l^2/8w = \pm 29.8$ cm (see previous letter). At the moment it is only necessary to show that the "heavy electron" band is not produced by ordinary electrons. The ranges of $\beta = v/c$ for the ordinary electrons allowed through the selector for the films described in my last letter are from β_1 to β_2 and from β_3 to unity, as follows:

FILM	β_s	β_1	β_2	β_3	s_1	s_2	s_3	s_h
5	0.34	0.33	0.37	0.96	—	—	0.32	1.02
8	0.33	0.29	0.43	0.77	1.95	1.05	0.40	0.47

The corresponding displacements on the films are shown under s_1, s_2, and s_3. The blanks indicate that the magnetic field was great enough to prevent the ordinaries from reaching the film. The displacement of the center of the "heavy electron" band is shown under s_h. *Obviously this band could not have been produced by ordinary electrons.* Although for film 8 the selector will pass ordinaries of β from 0.29 to 0.43 and so should give a width of 0.90 cm for the ordinary line, yet the observed width is about 0.2 cm. In agreement with the theory of the selector, this indicates that the probability of the selector passing ordinary electrons is highest when $\beta = \beta_s$. For the heavies the range of β depends on the mass pm_0. Consider film 5. For $p = 2$, the range of β is from 0.30 to 0.41 and from 0.85 to 1.0, while for $p = 3.33$ the range is from 0.29 to 1.0. In the latter case the resolving power may be said to approach zero. In this case the magnetic field outside the selector spreads the heavies out into a combination of mass and velocity spectrum. The distribution in this spectrum depends upon the probability that an electron of a certain velocity will get through the selector and upon the relative prevalence of the beta-rays with the mass corresponding to this velocity. Although the values of p in the previous letters are not exact, they cannot be very far wrong since they are calculated from the displacement of the center of the "heavy" band. I am now using higher resolving power and shall report my results shortly.

To answer (c), I need only report the following: Using a new selector with $E = 100{,}000$ volts/cm, I have found that with $H = 740$ gauss ($\beta_s = 0.45$) both ordinary and heavy electrons are recorded, but that with $H = 830$ gauss ($\beta_s = 0.40$) no heavy electrons (or very few) are recorded although the ordinary line was quite distinct. This means that the selector was passing very few or no heavies. It also means that the multiple reflection of ordinaries is not responsible for the "heavy" band.

G. E. M. JAUNCEY

Wayman Crow Hall of Physics,
Washington University,
St. Louis, Missouri,
January 31, 1938.

---

[1] Jauncey, Phys. Rev. **53**, 197 (1938).

[2] Jauncey, Phys. Rev. **53**, 265 (1938).

[3] Dr. C. Zahn gave an excellent description of the theory of the selector at an informal meeting on January 30, 1937.

On Magnetic Anisotropy in Ferromagnetic Crystals in Weak Fields

The *Physical Review* recently published important results of Williams[1] who first studied the magnetic properties of crystals in specimens of closed form. Williams showed that the magnetization curves of crystals are different along different directions even in weak fields. The initial magnetic susceptibilities along the [100], [110] and [111] directions were found to be approximately in the ratio 6 : 3 : 2.

The fact that magnetic anisotropy may exist, even in weak fields, was indicated by Akulov.[2] Akulov came to this conclusion on the basis of the assumption that the work expended on magnetization in any direction is one and the same function of the sum of the components of the magnetization vector along the axes of easy magnetization. From this Akulov finds that in weak fields the values of the susceptibilities along the [100], [110] and [111] axes should be in the ratio of 6 : 3 : 2.

In order to explain magnetic anisotropy in weak fields Bozorth[3] assumed that when H is applied, for example, along the [110] direction the component of H along [100] will produce a magnetization in that direction given by the [100] magnetization curves. On the basis of this assumption Bozorth also comes to the conclusion that the initial susceptibility along the [100], [110] and [111] axes should be as 6 : 3 : 2.

It should be noticed that these conclusions inevitably contain certain implicit assumptions concerning the initial state of the crystal before magnetization. It is interesting to examine this question from the viewpoint of a model of the process of magnetization in weak fields, as a process of displacement of boundaries between regions of spontaneous magnetization. The model was originated in the works of Sixtus and Tonks[4] and was further developed theoretically by Becker[5] and Bloch,[6] and also in part in a recent work of the writer.[7] Starting with this model we find that in weak fields, when the spins remain directed along the axes of easy magnetization, the susceptibility of iron may be divided into two parts, $\kappa_{||}=I_{||}/H$ and $\kappa_{\perp}=I_{\perp}/H$, where $I_{||}$ is the magnetization arising from the displacement of boundaries between regions with antiparallel resultant spins; and $I_{\perp}$ is the magnetization arising from the displacement of boundaries between regions with resultant spins forming an angle of 90°.[8] To obtain formulae for magnetic anisotropy in weak fields it is necessary to calculate $\kappa_{||}$ and $\kappa_{\perp}$ for an arbitrary direction in the crystal. After carrying out the corresponding calculations the following formula for initial susceptibility κ_0 is obtained:

$$\begin{aligned}&\kappa_0=\kappa_{||}+\kappa_{\perp},\\&\kappa_{||}=\kappa_1(n_1h_1^2+n_2h_2^2+n_3h_3^2),\\&\kappa_{\perp}=\kappa_2[n_2n_3(h_2^2+h_3^2)+n_3n_1(h_3^2+h_1^2)+n_1n_2(h_1^2+h_2^2)].\end{aligned}\tag{1}$$

where: n_1, n_2, n_3 are the parts of unit volume of the crystals in which the spins are parallel or antiparallel to the axes of easy magnetization [100], [010], [001], respectively: h_1, h_2, h_3, are the cosines of the angles between the directions of the magnetic field and these axes; κ_1 and κ_2 are coefficients independent of the direction of magnetization, provided that in any one direction of easy magnetization the magnitudes of the stress gradients, and their spatial distribution, are on an average the same as in any other.

It follows from (1) that if there is uniform distribution of the spins, i.e., if $n_1=n_2=n_3$, the susceptibility should not depend on the direction of the field. Thus the presence of magnetic anisotropy in Williams' crystals should, from the viewpoint of the model under consideration, be explained as a result of the presence of preferential spin orientations. From the calculations of Kaya and Takaki,[9] made on the basis of measurements of magnetization in crystals of iron, it follows that in the initial condition, the spins are preferentially orientated along the directions of easy magnetization for which the demagnetizing factor has the least value (in a specimen of the given form). From this it follows that in Williams' specimens, the values of n_1, n_2, n_3 could hardly be equal to one another. It is extremely possible that in specimens cut along the direction [100] the greater part of the spins were orientated parallel or antiparallel to this direction, particularly after the specimen has been magnetized once. If it happens that for $H\|[100]$ we have $n_1=1$, $n_2=n_3=0$; for $H\|[110]$ $n_1=n_2$, $n_3=0$ and for $H\|[111]$, $n_1=n_2=n_3$, i.e., if there is a most preferential orientation it follows from (1) that the initial susceptibilities in these cases should be as

$$6:\left(3+\frac{3}{2}\frac{\kappa_2}{\kappa_1}\right):\left(2+\frac{4}{3}\frac{\kappa_2}{\kappa_1}\right).$$

When $\kappa_1 \gg \kappa_2$ this gives the ratio 6 : 3 : 2.

There is reason to suppose that $I_{||}$ is either entirely, or to a considerable degree irreversible and $\kappa_{||}$ represents the initial irreversible susceptibility (up to the present time, the initial susceptibility has been supposed equal to the initial reversible susceptibility). Therefore, measurements of the reversible susceptibility of these crystals would be of interest.

E. Kondorsky

Physical Institute of the State University,
Moscow, U. S. S. R.,
December 21, 1937.

[1] H. J. Williams, Phys. Rev. **52**, 747, 1004 (1937).

[2] N. Akulov, Zeits. f. Physik **69**, 78 (1931).

[3] R. M. Bozorth, J. App. Phys. **8**, 575 (1937).

[4] K. J. Sixtus and L. Tonks, Phys. Rev. **37**, 930 (1931); **42**, 419 (1932); L. Tonks and K. J. Sixtus, **43**, 70, 931 (1933).

[5] R. Becker, Physik. Zeits. **33**, 905 (1932).

[6] F. Bloch, Zeits. f. Physik **74**, 295 (1932).

[7] E. Kondorsky, Physik. Zeits. Sowjetunion **11**, 597 (1937).

[8] It should be noticed, that in his work Akulov also divided the magnetization into two parts, the first being the magnetization arising from longitudinal inversions of spins, and the second from transverse ones, but this author considered the process of inversions of spins from a different point of view.

[9] S. Kaya and H. Takaki, J. Hokkaido. Univ. **1**, 227 (1935).