The birth of the concept of Spin

Marina Baldissera

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Main outline of conceptual development:

It seems that the main process in the formation of the concept of spin, is that
start from a physical interpretation (Bohr, Sommerfeld)
$\rightarrow$ new anomalous behavior (anomalous Zeeman effect)
$\rightarrow$ abstract mathematical description of behavior (*Ersatzmodells* of Sommerfeld, Lande', Pauli) ca. 1920
$\rightarrow$ new physical interpretation (Lande' (1922, defeated by Stern-Gerlach exp?) but then replaced by Uhlenbeck and Goudsmit 1925-26)

Early observations of the Zeeman Effect:

- 1875 Zeeman-like effect observed in atomic spectra: ‘broadening of lines’.
- 1896 definite effect of magnetic field on atomic spectra

Zeeman effect?

Two types of Zeeman effects observed:

1. The *normal* Zeeman effect, that occurs for singlet spectral lines (i.e spectral lines, that, in modern terms: symmetric spin part of wavefuntction)
   In this case only the orbital magnetic moment couples with the external magnetic field.
2. The *anomalous* Zeeman effect, that occurs for 'multiplet' spectral lines (i.e. spectral lines that in modern terms correspond to states with asymmetric spin wavefuntion)
   In this case the spin and the orbital magnetic moment couple with the external magnetic field.

NB: 'multiplets' seems to be used in different ways. One can have singlets and multiplets for the spectra of atoms that are *not* in a magnetic field, but when a magnetic field is applied, it was thought that multiplets behaved 'anomalously' because their splitting could not be accounted for using only 3 quantum numbers....

1913 model of atom

- At this point in time, it was thought that the atom could be fully described by 3 quantum numbers:
- n = the principal quantum number (size of orbital), k = the subordinate quantum number (shape) , m = the magnetic quantum number
- rules: for fixed n, $k \leq n$; $-k \leq n \leq +k$, + selection rules
- these elements do *not* suffice to account for anomalous Zeeman effect.

It was thought that most of the 'atomic action' when observing spectra would come from one 'radiant electron' (Strahlelektron), rest of system is called 'core' (Tomonaga) or 'nucleus' (everyone else?)

new quantum numbers!

In 1920, a new quantum number was introduced in order to account for the 'extra splitting' (also called fine structure) due to the Zeeman effect.
The *inner* quantum number j, was supposed to determine the splitting of multiplet terms when external magnetic field was applied.
NB: the levels of extra splitting are now accounted for by m, not j.
For fixed n, k, j $\rightarrow$ -j $\leq$ m $\leq$ +j
This however, still did not suffice to account for the anomalous effect. There seemed to be another selection rule tied to the multiplicity of terms. This rule was accounted for by the quantum number R and determined the beginning of the use of the so-called *Ersatzmodells*

Status of theorization

We now have a new set of quantum numbers. Sommerfeld, Lande' and Pauli all used this new set of quantum numbers to construct their models. I will only look at Lande'. It is interesting to note that even if they were different, they could all account for experimental data equally well.

Lande's Ersatzmodell

R=$\frac{Multiplicity}{2}$
K=k-$\frac{1}{2}$
J given by $|K-R|$+$\frac{1}{2}$ $\leq$ J $\leq$ $|K+R|$ -$\frac{1}{2}$
m given by -J+$\frac{1}{2}$ $\leq$ m $\leq$ J -$\frac{1}{2}$

Physical Interpretation

There were two things that Lande' had to explain in the physical interpretation of his model. The multiplicity of the lines with no external magnetic field, and the difference in multiplicity induced by the external field..

- *normal Zeeman effect* $\rightarrow$ have a spherically symmetric core, it is 'magnetically inert' and does not have and effect on the radiant electron, unless an external magnetic field is applied. (singlet, can split in a doublet)
- *anomalous Zeeman effect* $\rightarrow$ core has axially symmetric angular momentum which interacts with angular momentum of radiant electron. This accounts for the multiplicities without external magnetic field. (*internal Zeeman Effect*
  Relevant QN are R, K, J.
  when an external magnetic field is applied, get extra splitting given by m. (note difference when either core or electron angular momentum is larger)

Problems with Physical Interpretation

1. If we use this account for ZE_{int}, calculation of the magnetic moments give wrong result with the experimental data of the ZE_{ext}
2. Lande' has a problem with the 'closure of shells'. He was aware of this. He always needed one radiant electron and a core. This is a major problem for the description of electrons in ionization cases. (Tomonaga p.20)

1922-1925

1. Stern-Gelrach experiment
2. Pauli exclusion principle

The spinning electron (finally!)

Uhlenbeck and Goudsmit were the first to publish their idea about the self-rotating electron. 1925 paper points at three main difficulties

1. (a) Alkali should have a 'magnetically intert' core, which does not agree with experiment
2. (b) Problem of Ionization
3. (c) Vanadium, Titanium calculated value for K does not agree with value predicted by Bohr-Stoner periodic system.

The 1925 paper is still an intermediate paper, but they state that they assign to R the 'self-rotation' of the electron, and agree with Pauli that each quantum number correspond to a 'degree of freedom' of the electron.

1926

It seems that when they published this paper they already knew about the problems that the classically self-rotating electron had:

1. to account for the ratio of the magnetic moment of spin of electron which has to be twice the magnetic moment of orbital rotation, the electron most rotate at $10xc$
2. the splitting of singlet into doublet (relativistische doublette) c.f. Tomonaga pp. 2-3

1926

They start from electron reference frame.
The electron will feel a magnetic field which does not exist in the laboratory reference frame:

$$\vec{H} = \frac{1}{c} \frac{\vec{E} x \vec{v}}{\sqrt{1 - v^2/c^2}} \tag{1}$$

Where v is the velocity of the electron and $\vec{E}$ is the electric field generated by the nucleus.
This should allow for various orientations of the electron w.r.t. the orbiting plane, and will also have an effect when combining with the orbital angular momentum (?).
It seems that they are also saying that this also accounts for corrections to R,K and J terms introduced by Heisenberg (Heisenbergsche Mitteilung, 1925 paper (b))

1926

They then proceed to explain how the QN refer to the electron, and not the electron-core system.
They retain the Lande' rules, but change the physical interpretation radically.
They can now account for screening effects of elements with same J but different K (this is due to how the electrons fill the orbits and how the energy levels are arranged!)
They can now also calculate width of spectra of Alkali atoms and ionization processes (p.257) that works in accordance with Bohr correspondence principle.

1926

The (anomalous) Zeeman effect reformulated:

1. precession of spin axis is not accounted for by Larmor theorem (?)
2. can account for Paschen-Back effect (strong external magnetic field, orbital and spin magnetic moment couple to external field independently)

Problems:

1. spectral line width prediction too large by a factor of 2
2. still need more study in the structure of electron (are they alluding to the speeds of rotation?)