ATOMIC SPECTRA IN THE ATMOSPHERE OF DENSE STARS

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Abstract

The intense field atomic physics problem is briefly reviewed, in particular those aspects of it which are of astrophysical interest. Theoretical predictions of the spectral features and the polarization in the continuum spectra are discussed from the point of view of measuring static magnetic fields in the atmosphere of white dwarfs. Atomic structure relevant to the study of the atmosphere and surface properties of compact objects such as pulsars, neutron stars and black holes are reviewed. This predicts the unusual surface and atmospheric properties for these objects. Some of the unsolved problems are indicated.

INTRODUCTION

The free atoms and molecules emit their discrete characteristic spectral lines when heated. The same spectral features can also be seen in their absorption spectra when light in these wave length bands is incident on them. Each of these lines has its natural width. We learn about the inaccessible environment by observing the change in the position and width of these lines and the intensity and polarization of the emitted light. The chemical properties of elements, formation of compounds, ionization energies and plasma properties depend on the structure of building blocks, the atoms. The structure and physical properties of solids are also correlated to those of the building blocks. If the environment changes the atomic structure drastically, not only the sprectral lines, their intensities and polarization will be changed but also the chemical properties of elements, the process of formation of compounds, solids and their properties will be very different from that what we know them. In this article we will discuss one such environment of strong magnetic fields.

It is not possible to produce such an environment because sufficiently high magnetic fields have not been attainable in the laboratory. In the past, attempts were made to produce large fields (Fowler 1973). The electromagnets with power consumption of about 2 MW can produce magnetic field $B \simeq 7\times10^{4}$G. The use of superconducting magnets can produce uniform fields $B \simeq 5\text{x}10^{5}$G. However, considerably higher fields have been produced by implosion techniques. A field of $B \simeq 10^{5}$G is first produced which is then rapidly compressed in a few microseconds by an explosive device producing transient field $B \simeq 10^{7}$G. Magnetic fields of this order can produce pressure $\simeq 4\text{x}10^{6}$ atms, which is about the pressure at the centre of the earth.

Nature has provided us much stronger sources of magnetic fields. We recall that magnetic field is of a dipolar character. Therefore, the field becomes stronger at the points closer to the source. In particular if the source is strong and is of very small dimension, the field near it is expected to be very intense. For example, consider an atomic electron moving in a Bohr orbit as a source of magnetic field. The magnetic field arises due to the current produced by its orbital motion (angular momentum) and the spin. Electrons having larger angular momenta and spin polarisabilities produce strong magnetic field at the nucleus of the atom. This hyperfine magnetic field at $\overset{+}{Fe}$ $(l=2)$ nucleus $\simeq 3\text{x}10^{5}$G while it is $\simeq 10^{6}$G at the Gd $(l=3)$ nucleus. Heavy ion motion in sub-Coulomb collisions produces magnetic fields $\simeq 10^{14}$G in the vicinity of colliding nuclei due to the high currents produced by their motion. Let us consider now the larger size sources in astrophysics. It has been found that the magnetic field at the surface of the Sun and outer interior is 1-10 G and 10^{3}G respectively. Recently fields 10^{6}—10^{7}G have been measured at the surface of magnetic white dwarfs. The theory of neutron star requires that $B \simeq 10^{12}$—10^{13}G at its surface.

WHAT DO WE KNOW ABOUT AN ATOM IN A MAGNETIC FIELD ?

As early as 1896, Zeeman discovered the splitting of a line in an external weak magnetic field. In 1897, Lorentz proved that an electron undergoing simple harmonic motion when subjected to an uniform magnetic field, emit spectral lines known as Lorentz triplet. Later on, many more lines were found which showed complex spectra. It became known as anomalous Zeeman effect, It was explained by Uhlenbeck and Goudsmit in 1925 from the spin and magnetic moment of an electron. The Li I spectrum, an exception to Zeeman effect, was explained by Paschen-Back as early as 1912 by assuming that the magnetic field is so strong that the splitting caused by it is much larger than the doublet intervals in lithium. The splitting in large magnetic fields became known as Paschen-Back effect, Because of the lack of availability of high fields not many atomic species have been studied. At still higher fields, the quadratic field term in the interaction, neglected so far, influences the spectral lines. This quadratic Zeeman effect is complex and has to be solved numerically. In solid state physics there are situations where electrons can be treated almost as free particles. In such a situation even the fields $\simeq 10^4$G are relatively very intense. Landau in 1930, propose a theory to solve the problem of an electron motion in such intense fields.

Why revival of interest in this problem ?

Historically, interest in the strong magnetic fields was revived in solid state physics in connection with isotropic excitons in insulators, semi-conductors donor and acceptor impurities which behave like hydrogen atom. The magneto-optical absorption edge of these materials showed structure which has been interpreted as due to the formation of bound states of an electron and hole pairs, the excitons. The Coulomb interaction between the pair is effectively reduced due to the dielectric medium surrounding them. The effective mass of the pair in the medium also decreases. The electron-hole pair in such an environment requires fields only $\simeq 10^4$G to completely change its hydrogenic spectrum. Here, we will not be discussing this problem.

In astrophysics, the interest in measuring magnetic fields dates back to 1908 when Hale discovered magnetic fields in sunspots from Zeeman splitting of their spectral lines. In 1947, Babcock reported the presence of magnetic fields in some A-type stars. The existence of large fields in neutron stars has stimulated new interest in this problem. The discovery of polarized continuum radiation from white dwarf stars by Kemp has given an impetus to the work on this problem (Kemp 1970).

Definition of strong magnetic field

Whether a given problem is to be treated in a weak or a strong field approximation depends on the energy scale of a problem. As an illustration, let us take an example of a hydrogen atom in magnetic field. The lower few energy states of the H atom are widely spaced relative to those states say for principal quantum numbers between $6 < n < 10$. Therefore, the fields required to change the spectral lines in the lower Lyman series (which involve the few lower H atom states) will be much stronger than that required to change the lines at the wings of the Balmer series (states with larger n). Another example is of an exciton in magnetic field stated above.

A free electron in magnetic field **B** has a uniform straight line motion in the direction of the field. In the transverse direction the centrifugal force balances the Lorentz force to give $\mu v^2/\rho = evB/c$, where v is the tangential velocity of the electron in its circular orbit of radius ρ (e and μ are its charge and mass respectively). These two motions superposed on each other gives rise to a resultant cycloidal electron motion. From above its transverse velocity $v = eB\,\rho/\mu c$. In terms of the electromagnetic vector potential $\mathbf{A} = \rho \times \mathbf{B}/2$, the electron conjugate momentum $\rho = \mu\,\mathbf{v} + e\mathbf{A}/c$. With the choice of z-axis along the field direction, the Bohr quantization of the z-component of electron angular momentum gives $\rho^2/2c = m\hbar$ or the quantized orbital radius $\rho = \sqrt{2m}\,\rho_c$, the cyclotron radius $\rho_c = (\hbar c/eB)^{\frac{1}{2}}$. This gives the quantized energy $E = \mu v^2/2 = \mu\,(eB\,\rho/\mu c)^2/2 = (eB/\mu c)\ m\hbar = m\,\hbar\,\omega_c$, the cyclotron frequency $\omega_c = (eB/\mu c)$. From the expression of ρ above, we note that the radius of the transverse circular orbit of an electron decreases as $1/\sqrt{B}$, as B increases while the energy increases linearly with B.

Let us now consider a hydrogen atom. In the absence of a magnetic field, the separation of the lowest Lyman lines are of the order of $\sim \mu e^4/\hbar^2$. The strong magnetic field can now be defined by the ratio of the electron energies $\hbar\omega_c$ and $\mu e^4/\hbar^2$, $\hbar\omega_c/(\mu e^4/\hbar^2) > 1$ which gives $B > e^3\mu^2/\hbar^3$. Furthermore, the validity of the non-relativistic quantum mechanics used in describing the electron motion puts the upper limit on B, $\mu c^2 > \hbar\omega_c$, which restricts B to $B < \mu^2 c^3/\hbar e$. Using known values of the physical constants, the strong field, required to change drastically the few lower hydrogen atom states has the range $4\times10^9\text{G} < B < 5\times10^{13}\text{G}$. We will discuss the effect of such strong fields later. First we will consider the effect of magnetic fields $\simeq 10^7$G on the hydrogen atom spectrum and the polarization of the emitted light.

HYDROGEN ATOM IN THE ATMOSPHERE OF WHITE DWARFS

It is believed that white dwarfs, pulsars and neutron stars have evolved from normal stars and that they are in the late stages of their evolution. In order to explain the observed properties of pulsars, the theories require that the magnetic fields $\simeq 10^{13}$G exist in the neutron stars, whose radii $R \simeq 10^4$m. The possible mechanism of such strong fields is the validity of the conservation of magnetic flux during the evolution of the star. It is observed that the field in the outer layers of the Sun $\simeq 10^2$G. The magnetic fields of this order may be common for all main sequence stars is supported by the abundance of pulsars, as can be seen from what follows. The conservation of magnetic flux during the collapse of a star implies that its magnetic field $B \propto 1/R^2$, (R being its radius). The normal main sequence star has a radius $R \simeq 10^9$m ($\simeq$ that of the Sun), and $B \simeq 10^2$G (assumed above). When it collapses to a pulsar of radius $R \simeq 10^4$m, its magnetic field $B \simeq (10^2\text{G}) \times (10^5)^2 \simeq 10^{12}$G. White dwarfs are denser stars whose masses are $\simeq$ one solar mass and radii close to Earth's radius. Again from the above discussion it is expected that the magnetic fields of the white dwarfs $B \simeq 10^2\text{G} \times (10^9/10^7)^2 = 10^6$G. The question that created a great interest soon after the discovery of pulsars was 'Can we measure these magnetic fields ?' This led astronomers to measure field in white dwarfs (Garstang 1977).

In the atmosphere of white dwarfs the abundance of H and He is expected to be the largest. If the temperature of the star is large enough, one may observe characteristics of the light emitted (or absorbed) by these atoms in the presence of the magnetic environment. The light from the star traverses through the outer atmosphere of the star which may contain H and He atoms and molecules.

such as CH and C_2 particularly if it is a cool star. This may change the polarization of the light and introduce the absorption bands characteristics of these atoms and molecules. In order to study this problm one has to know the molecular structure in the magnetic field and its transition properties (de Melo etal 1976; Warke etal 1977). It is clear that the understanding of the observed data may require the theoretical study of the structure of H and He atoms (Rou 1976, 1979), besides some complex systems such as CH, C_2, H^-, He^- in strong magnetic field, because in laboratory, we are unable to produce such strong fields required to carry out such a study.

The interaction energy of an electron with the magnetic field has two terms, V_1 and V_2, which are linear and quadratic in B. The first term V_1 arises from the interaction of B with the electron magnetic dipole moments, spin: $\frac{e\hbar}{2mc}$ 2 s and the moment arising from its orbital motion: $\mathbf{r} \times \mathbf{j}/2c = \frac{er \times \mathbf{p}}{2mc} = \frac{e\hbar}{2mc}\mathbf{l}$. This gives

$V_1 = -\frac{e\hbar}{2mc}(2s+l) \cdot \mathbf{B} = \mu_B(2s+l) \cdot \mathbf{B}$, $\mu_B = (|e|\hbar/2mc)$ the Bohr magneton. The quadratic term $V_2 = e^2B^2r^2 \sin^2\theta/8\mu c^2$ is the current interaction energy. The electron spin-orbit interaction term V_{ls} can also become of the order of V_1 and V_2 for weaker fields. In the magnetic field $B \simeq 10^7$G, the Coulomb interaction between the electron and the proton remains the strongest. This is the range of the field covered by the quadratic Zeeman effect. Now, depending on the value of B, V_{ls} can be smaller or larger than the magnetic interaction energy. In the former case, one has to use the j-j coupling and then treat V_1 (in this case $V_2 \simeq 0$ and can be neglected) as the perturbation. This splits the lines and gives rise to a complex spectrum known as anomalous Zeeman effect. While in the latter case, the field being stronger, V_{ls} is much smaller than the magnetic energy. One uses the L-S coupling to obtain the line splitting arising from V_1 (again V_2 is still negligible). This is known as the Paschen-Back effect (same as the classical Lorentz triplet). When the field is further increased to 10^7G, the V_2 term becomes significant. As seen from the form of V_2, this term will involve the matrix element of $< r^2 >_{nl}$ which is proportional to n^4, where n is the principal quantum number. This indicates that its contribution is more to the excited states for which n is larger. We also observe from above that the Lyman series will not be affected much by this term, however for the wings of the Balmer series, for which n is larger, this term will play an important role. As $V_2 > 0$ and the higher levels are shifted more than the lower levels, V_2 always gives rise to the blue shift. At $B \simeq 10^6$G, this shift ranges from 0.025 nm for $H\alpha$ to 0.46 nm for the sixth line of the Balmer series. The quadratic Zeeman effect which becomes operative at $B \simeq 10^6$G splits each line into 5-6 components which spread as B increases. Another important effect of the strong fields on the spectrum is the introduction of the forbidden lines. For example, in weak field, a 2s-nf transition will be forbidden. However, the V_2 term will introduce the mixing of p and fs states. The effect of this mixing at $B \simeq 10^7$G is that the forbidden 2s-5f transitions become as strong as 2s-5p transitions.

The experimental observations (Rosi 1976; Degl 1976; Elias et al 1974; Angel 1974) on DA stars did not show any of the expected shifts in the lines of the Balmer series of hydrogen atom. When the Zeeman analyser was used to measure the field in 8 white dwarfs, 5 of them did not show any significant effect. Later, sensitive polarimeter measurements were carried out. It is expected that in the strong B, the sum of the intensities of the separate Zeeman components is equal to the total intensity of the line, and they would show a net polarization. The observations in the wings of the $H\gamma$ line show the polarization <0.8 per cent. All these measurements could only put the limit that $B < 10^5$G in the atmosphere of these stars.

In the strong fields $\simeq 10^7$G, the lines will be split and the intensity distributed over a wider region. It will wash out the spectral features or at least weaken spectral features of these stars. This expectation is borne out from the observed spectra of some of these stars and from the fact that most of the DA stars and white dwarfs do not show any features in the visible and infrared region. From the colour of these objects, their temperature is $\simeq$ 11,000°K. The continuum light passing through the atmosphere of the star will get absorbed at the characteristic wave lengths of the constituent atoms and molecules of the atmosphere. As they are in the environment of a strong magnetic field of the star, these absorption lines will provide information about the strength of B. The general feature of the spectra is one or two shallow absorption regions (known as Minkowski bands) with a depth of a few per cent of the continuum. In $Gr\omega$ + 70°, 8247, this shallow region is 12 per cent below the continuum at 413.5 nm, besides a few more regions nearby which are not so strong. The explanation could be that the molecular He in the upper atmosphere is responsible for this absorption; however, it is hard to build up so much molecular He to produce the required effect. In GD-229, the strong absorption is observed at 418.5nm with a few weaker absorptions nearby. While the strong broad absorption in G99-37 is observed at 430 nm with weaker regions at 438 nm is attributed to the G band of CH and the others to the Swam bands of C_2. The calculated absorption profile could be fitted to the observed profile for $B \simeq 3.6 \times 10^8$G. The comparison of the calculated spectra with the GD-90 broad absorption features resolved from Paschen-Back spectra in the Balmer lines H_β, H_γ, H_δ gave $B \simeq 5 \times 10^6$G. Similar comparison with the shift of the Paschen-Back component of the H_α line of the cool star DG 99-47 due to quadratic Zeeman effect gave $B \simeq 1.6 \times 10^7$G. The observed splitting of the H and He I lines from Fiege-7 gave $B \simeq 5 \times 10^6$G.

Kemp in 1970 proposed a theory of fractional circular polarization of continuum light arising from the magneto-emission from a thermal source. He assumed an uniform distribution of the assembly of radiating oscillators. Let ω_0 be the frequency of the observed light. In the presence of magnetic field, light of this frequency can come from two frequency regions

$\omega_0 - \omega_c/2$ and $\omega_0 + \omega_c/2$ (corresponding to the $B=O$ frequency range). In the presence of the field B, the blue shifted component of the former and the red shifted component of the latter, both contribute to the light observed at ω_0. The intensity of the emitted light is proportional to $\omega_0^4 \mid <i \mid x \mid f> \mid^2 \alpha\ \omega_0^4 / (\varepsilon_i - \varepsilon_f)$. In the zeroth order $\varepsilon_i - \varepsilon_f = \omega_0 \pm \omega_c/2$. Thus the intensities of the two transitions $(\omega_0 \pm \omega_c/2 \rightarrow \omega_0)$ is proportional to $1/(\omega_0 \pm \omega_c/2)$. These two transitions will have opposite polarization. Therefore, the fractional circular polarization.

$$q(\omega_0) = [I_r(\omega_0) - I_l(\omega_0)] / [I_r(\omega_0) + I_l(\omega_0)] \simeq -\frac{\omega_c}{2\omega_0}$$

From the measured fractional circular polarization q and the known frequency ω_0 of the continuum observed light, one obtains ω_c from which the field B can be calculated. It is to be remarked here that a Bremsstrahlung model also predicts $q(\omega_0)\ \alpha\ \omega_c/\omega_0$. The predicted variation of $q\ \alpha\ 1/\omega_0$ does not agree with the observed data. This undesirable feature is attributed to the spectral features of the star. The other suggestions (Garstang 1977) are (1) in strong field Landau levels may play an important role, and (2) the synchroton radiation from relativistic electrons in the magneto sphere will be polarized. The fractional circular polarization is observed in the visible and ultra-violet spectrum. The linear polarization was almost absent in most of the above cases. The measured values of $q(\omega)$ showed considerable structure as a function of λ. In case of Grω - 70', 8247, q varied between 0.8 per cent at 330 nm to -3.7 per cent at 415 nm. In the infrared region, it was -8.5 and -15 per cent at 1.15 μm and 1.25 μm respectively. The calculated field strength is $\simeq 10^7$G. The fractional polarization of $q = -0.4$ per cent was observed in the case of G195-19 while it was 0.3 per cent for Fiege-7. Similar observations were carried out on a few more stars. These observations predicted fields $\simeq 10^7$G at the surface of these stars. Another striking feature of the observed fractional circular polarization is its periodicity. In the case of G195-19 the period of variation of q is T= 1.331 d while in the case of Fiege-7 T $\simeq$ 2.2 h. Periodicity of q of this order is observed in a few other stars. The periodicity can be explained by postulating that these are the rotating stars with the strong oblique magnetic field axis. There have been suggestions invoking presence of spots on the steller surface to explain the observations. (Garstang 1977).

ATOMIC STRUCTURE IN INTENSE MAGNETIC FIELDS

We can use the usual perturbation methods to study the effect of weak magnetic fields on atomic structure. In the intermediate range of B, one has to use complex variational methods to study it. We do not want to discuss these methods here. However, we want to discuss qualitatively the effect of very intense fields on the atomic structure. The situation nearest to this would be that on the surface of a neutron star. In such intense fields we have no other way but to use variational method to study the hydrogen atom structure. From the earlier discussion, we know that a free electron moves on a cycloid of radius P and with axis along **B**. Even though there is an additional attraction due to the proton in the intense magnetic field, the electron motion is expected to be very close to it. Only the location of the axis is to be determined by minimising the electron energy. Now that there is a massive proton located say at the origin, in addition to magnetic energy, electron also has an attractive Coulomb energy. In order to gain the Coulomb attraction, the cycloid axis has to pass through the proton position. Because of our interest in the bound localized electron orbitals, the cycloid has to be of some finite length L, with its axis parallel to **B** and passing through the origin. Consistent with this classical picture, we now choose the electron wave function ψ, which is constant on the surface of a cylinder (on which the classical cycloidal motion was confined) of radius P and length L and is zero everywhere else. The quantized motion in the transverse plane is a circle of radius $P = \sqrt{2m}P_c$ and the transverse enrgy $\hbar\omega_c$. To the first approximation, the Coulomb interaction will have very little effect on this transverse motion in intense field. However it will affect the longitudinal electron motion dratically as we want to localize electrons in bound orbitals instead of cycloids extending upto infinity. The variational parameter L is to be determined by minimising its total energy for a given $P = P_c\sqrt{2m}$. The electron-proton Coulomb energy calculation is reduced to that of calculating the electrostatic potential at the center of the cylinder due to a uniformly charged cylindrical surface of total charge e; because of the choice of ψ, the electron density $|\psi|^2$ is uniform on the cylindrical surface S and zero elese where. The potential energy

$$V = -e\int \frac{\sigma\, ds}{\xi_s} = -4e^2 \log(L/\rho)\, L$$

The electon confinement in z-direction within a distance L will give rise to an uncertainty in its momentum $\simeq \hbar/L$, so that its maximum kinetic energy $K.E. = \hbar^2/2\mu L^2$. Minimising the total energy $E = K.E. + V$, with respect to variations of L, one obtains $L = a_0/\log(a_0/\rho)$. From which we observe that $a_0 > L > \rho$, and the binding energy $B = (\hbar^2/\mu a_0^2)\log^2(a_0/\rho)$ becomes very large. As $\rho\ \alpha\ \sqrt{2m}$, the minimum energy obtained above is the lowest energy of the longitudinal motion (parallel to **B**) for a given value of m (the eigen value of l_z which is conserved). Let us recollect the results derived so far. An electron in intense magnetic field is confined to move on Landau orbits and is effectively tied up to the magnetic lines of force. The electric field due to proton can be resolved along **B** and in the transverse direction. The effect of transverse electric field on the transverse electron motion, which is due to intense **B**., can be neglected. Thus, the electron confinement in transverse direction is due to magnetic field, while the electron binding in the z-direction is caused by the Coulomb attraction, which on the average is $-e^2/\sqrt{\rho^2\ z^2}$. Thus the motion in intense field gets decoupled in the transverse and longitudinal direction We also saw that for intense magnetic fields $L > \rho \simeq 0$. To a good approximation, the motion along the z-direction is described by the wave equation

$$\frac{\hbar^2}{2\mu}\frac{d^2\varphi}{dz^2} - \frac{e^2}{|z|}\varphi = E\varphi$$

The electron energy corresponding to quantum number) m, m_s (the eigen-values of l_z and S_z of an electrons and n the number of nodes of $\varphi(z)$ is

$$E(m, m_s, n) = \tfrac{1}{2}\hbar\omega_c(|m| + 1) + \frac{\hbar\omega_c}{2}(m + 2m_s) + E_c(n)$$

The low lying eigen-values are obtained by minimising E with the variations of the allowed values of m, m_s and n. This requires that $m = -m$ and $m_s = -\frac{1}{2}$, and the corresponding minimum $E = \hbar\omega_c/2 + E_c(n)$. The important property of the spectrum to be noticed is that it is degenerate with respect to m (independent of m). In the above equation, $E_C(n)$ are the eigen values of the above wave equation of $\varphi(z)$. We already saw that the lowest eigen value corresponding to $n = 0$ is very large, for example for $B = 2.35 \times 10^9$G, $E(0,0) = -185$ eV[7]. The excited state corresponding to othe values (>0) of m and m_s are of the order of $\hbar\omega_c > |E_{ex}(m, n)|$ for intense fields. Therefore, they lie in the continuum and are not bound. We have almost derived the low lying spectrum of H atom, except for the excited states $E_c(n)$. This can be understood from the following qualitative arguments. The wave equation for $\varphi(z)$ is the same as that for φ in the three dimensinal, S-state equation of the H atom wave function $\phi_S(r) = r\,\psi_S(r)$. The first excited state $\varphi_{n=1}(z)$ will be odd in z (as the z-parity of $\varphi(z)$ is a constant of motion) therefore vanishes at $z = 0$, $\varphi_1(z = 0) = 0$ since φ_1 as in satisfies the same equation as $\phi_S(r)$ of the H atom with the bondary condition $\varphi_S(r) = 0) = 0$, the eigen value of $\varphi_1(z)$ is expected to be very close to that of $\varphi_S(r)$ which $\simeq -13$ eV. The ground state wave function $\varphi_0(z)$ has no analogue to the three dimensional H atom problem and we found that its eigen value is very large and negative. The other excited bound states corresponding to $n > 1$ will lie between -13 eV and 0. We summarise the two main properties of the spectrum : (1) it is nearly degenerate with respect to the values of m (2) the excited states $E_c(n \gg 1)$ are very far separated from the ground state energy $E_c(0)$ and all lie between -13 eV and 0.

MATTER ON THE SURFACE OF NEUTRON STARS-ATOMS :

In the independent electron approach, the structure of a many-electron atom will be similar to that of the hydrogen atom discussed above. (Rederman 74; Bayfield79) Using this structure, we can now study the properties of matter existing on the surface of neutron stars where sucn intense fields do exist. It is natural to investigate first the structure of atoms existing in the from of gas either on the surface or in the atmosphere of such objects. The spins of all the electrons are aligned in the direction opposite to that of the magnetic field . The low lying states of the atoms can be found by filling the electrons in the lowest energy levels of the hydrogenic atom allowed by the Pauli principle. This is achieved by electrons occupying the degenerate states m for $n = 0$. We saw that the radii of these Landau orbits increase with m as $\rho = \sqrt{2m}\,\rho_c$. Thus in the lowest atomic state, the lectrons in the atom are confined to coaxial cylinders of increasing radii but of the same length L, oriented along the direction of the magnetic field. We have already observed some unusual properties of these atoms (1) The ionization energy of an atom is the amount of energy required to separate it from an atom in the same environment. All the m levels are nearly degenerate, the energy required to take out the most loosly bound electron is two orders of magnitude higher than the usual atomic ionization energies. This clearly indicates that the process of atomic plasma formation and its properties are very different from those of the weak field case. (2) The ground state energy of the atom of atomic number Z changes smoothly with Z, because filling of additional electrons does not change $E_{g.s.}(Z)$ abruptly as they occupy m orbitals with $n = 0$, which are all nearly degnerate. This shows that atomic shell formation does not take place, implying thereby that the chemical properties of all the elements are the same. (3) Because of the compressed cylindrical structure (relative to the size of a_0) of a neutral atom, they have large electric quadrupole moments arising from the cylindrical charge distribution of the electrons. Two such atoms when brought together will strongly attract each other for certain orientations.

MOLECULES AND SOLIDS :

Let us first recollect the elementary physics involved in the formation of molecules and solids from their constituents, the atoms. The binding energy of two or more atoms is essentially determined by the orbitals of least bound (valence) electrons in the atom. When these electrons are shared between the neighbouring atoms, the energy of the system is lowered due to the attractive interaction between the electrons and the ionized atoms. As a result, the binding energy derived from it is more than the sum of the binding energies of the separate atoms. Other electrons in the atom are tightly bound and therefore not affected very much by the environment of the atoms which contain them. Thus core electrons do not contribute to the molecular or solid binding. In order to minimize the total energy of a solid, we choose the strongly bound cluster of atoms to build up its structure instead of the atoms of those species. The solids of the later kind normally require some sort of external energy to change its structure from the strongest bound structure. Keeping in mind these points, let us discuss the structure of molecules in intense magnetic fields. From point (3) above, we note that the strong electrostatic attraction between atoms arising from their large quadrupole moments will have an important effect on the formation and properties of molecules and solids. For example, hydrogen molecule H_2 in the electronic spin state $S = 1$, is not bound in the $B = 0$ case. We know that this happens due to Pauli principle.

When two H atoms, each in one S state, are brought nearer to each other to form a H_2 molecule in $S = 1$ state, one of the electrons has to be promoted to the excited 2s-2p state, as the two electrons with their spins parallel cannot occupy the same orbitals. This costs energy which is greater than the gain in energy coming from the attraction between two electrons and two protons. Thus it becomes energetically unstable. However the situation is different in intense magnetic field. Each of the electrons in cylindrical hydrogen atoms is in the m = 0 state. When they are brought together to form a H_2 molecule in S = 1 state, Pauli principle will demand the promotion of one of the electrons to the next excited state m = 1, n = 1 of the H atom. These states are nearly degenerate and it does not cost energy to promote one of the electrons to the higher orbit. On the other hand, there is a large gain in energy due to the attractive electrostatic interaction between the two large quadrupole moments. It is to be remembered that in order to reduce the Coulomb repulsion between two protons, we have to join the two identical cylindrical atoms to form a longer cylinder oriented along B. The losely bound H_2 molecule acquires a large binding due to strong van der Waals forces (Lozovik etal 1978; Luc-Koenig 1979]. Because of the compressed sizes of these cylinders, the electrostatic attraction is so large that it even prefers energetically to form the bound linear chain of atoms. If we bring N hydrogen atoms together, N electrons have to be promoted to N energetically lowest orbitals as their spins are all aligned. At the same time, we must also minimize the Coulomb repulsion between the N protons by separating them apart. This can easily be done by joining the cylindrical H atoms to form a chain oriented along B with each electron occupying m = 0, 1, 2,....... N and n = 0 states. Because of near degeneracy of these orbitals, it does not cost any energy, while there is a net gain in the electrostatic attraction coming from the quadrupole-quadrupole interaction between the pairs of H atoms. The length (lattice spacing) of the chain can be calculated by minimising the total energy of the chain. In the case of heavier atoms, diatomic molecules are the strongest bound objects. In fact, their binding energy is very much larger than the sum of the separated atomic binding. In this case, the chain structure is not energetically preferred as many of the m states are already occupied by the electrons in heavy atoms and when we bring in more than two such atoms together, the empty n = 0, m states available are smaller than the number of electrons to be promoted. Secondly, their mutual repulsion also becomes large due to the increased number of electrons. Thus, if there is a homogeneous gas of atoms, one heavy (denoted by h) and other light (denoted by l), energetically the following molecules are favoured hl_n and h_2l_n in the form of linear polymer chains with $n = Z_n / Z_l$. Let us discuss now the consequences of such a molecular structure on their properties and on the properties of solids. As follows from the above discussion, the binding energy (dissociation enregy) of a molecule $\gg$ that of the separated atoms > ionization energy of the molecules. Thus at high temperature, the plasma of molecular ions will be formed instead of the atomic ions as in weak fields. Because of their tight binding they cannot be easily distorted by external forces or pressures. They can sustain the large magnetic pressures exerted upon them. These polymer chain are electrically neutral and can easily be bound together to form a sheet of polymer chains, by joining the neighbouring chains together such that the nuclear charge in these chains are displaced by the lattice spacing to gain the attractive interaction between them. These sheets further can be bound together in the same way to form a bundle of the polymer chains. When the calculations are carried out it is found that the density of such matter is $\simeq 10^4 - 10^5$ gm/cm^3. It is a very hard material with Young's modulus $\simeq 10^7$ times that of the steel, which is of course required to sustain the large magnetic pressure exerted on it. The large magnetic fields help in condensing the matter in small volume.

Conclusions

The measurement of magnetic fields in the atomosphere of stars requires the theoretical predictions of spectral features, polarizations and intensities of discrete and continuous spectra of atoms and molecules in these fileds. For regions near black holes, pulsars and neutron stars may have abnormally high magnetic fields which still keeps the interest in the problem high. We discussed only some aspects of this problems here. The problem of intensities, widths and polarization of light emitted or absorbed by atoms in the atomosphere of such stars is not investigated thoroughly. In order to look for a signature of magnetic fields, the study of complex positive and negative ions in magnetic field is already gaining momentum. (Avron et al 1977, Dmitrieva et al 1979) A lot more work is to be done to find out the role of the center of mass motion and the relativistic corrections in the above predicted properties (Virmato et al 1979; 1978). Intense field atomic and molecular physics is a somewhat fragmented subject with many basic questions poorly developed or not clearly understood. The reason being the theoretical difficulty of treating the electronic motion when both the Coulomb attraction and the field interaction can not be treated by perturbative approach. The detailed quantum mechanical treatment of hydrogen atom in such fields for its states close to n = 80 has not yet been developed. Transitions involving such states in the H-II regions of low particle density, intermediate temperature and fairly high ionization level are observed. These can be a useful probe of interstellar electric and magnetic fields. This may also stimulate interest in the study of complex atoms and molecules and their positive and negative ions in strong fields.

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