EFFECTS OF PLASMA PHENOMENA ON NEUTRINO MASS MEASUREMENTS PROCESS USING A GASEOUS TRITIUM β-SOURCE

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In the paper the ionization state of molecular tritium and electric potentials in a Windowless Gas Tritium Source (WGTS) of tritium β-decay experiment KATRIN are considered. The ionization processes in WGTS are sustained by β-electrons and so-called „secondary electrons", arising from inelastic and ionization collisions of "primary" β-electrons with tritium molecules. As a result in the WGTS tritium gas volume acts as a low-temperature and slightly ionized gas steady state close to quasi neutrality (the Debye length is small in comparison with the setup characteristical sizes). On the basis of an one-dimensional self-consistent model the WGTS plasma steady state is described and the influence of plasma phenomena on neutrino mass measuring process is discussed. It is found that electric potentials in a main plasma volume can not significantly make worse the measurement process. At the same time the non-equilibrium electron spectrum and fast plasma flow at the end of the tube can result in instabilities which are able to spoil slightly the β-electron spectrum endpoint. This problem must be carefully investigated further. For more reliable conclusions more detailed consideration is required that will include kinetic effects in the WGTS plasma.

I. INTRODUCTION

The problem of neutrino rest mass investigation is one of the fundamental tasks of modern physics as its decision can promote the significant progress in region of particle physics, astrophysics and cosmology. The most simple technique for the neutrino mass measurements is the direct or kinematic approach based on the measuring the end-point energy of electrons arising at tritium β- decay. In the setups of this type a strong magnetic field is created parallel to axis of tube filled by tritium gas to guide β-decay electrons towards the spectrometer. Direct searches of neutrino mass were conducted in a number of laboratories (see, for instance
[1,2]). A crucial requirement for such measurements is a strict control of β-spectrum endpoint position. Any uncontrolled endpoint variation can lead to systematic errors. The losses of β-electron energy at the endpoint and its dispersion can be due to:
(a) a cyclotron radiation by a single electron in a strong magnetic field.
(b) the dispersion of β-electron spectrum at interaction with plasma waves excited in the WGTS plasma column due to instabilities. As it is known the noticeable dispersion of order ~ 1 can be observed at even a slow level of turbulence [3]. These problems should be carefully investigated further.
(c) the effect of electric potential variations (EPV) along the WGTS plasma column. Here, the control of potential profiles on the basis of using external means is quite desirable.

As it will be shown below the EPV effect can be of the order of ~ 10meV. At the same time in a plasma with a non equilibrium electron spectrum this effect can be significantly greater. As a result EPV effect on dispersion of β-electron spectrum at the endpoint can be more significant. Recently, an attention was paid to a possible effect of a space charge formed by tritium β-decay [4]. In fact, fast β-electrons escape the WGTS volume in a short period of time of ~ 100 ns, running away along the magnetic field force lines. At the same time a considerable number of "secondary" electrons ($\sim 10^7 \div 10^8$ cm^{-3}) is produced in WGTS gas. Remaining ions form a positive space charge with, in principle, large potential. β-electron slowdown in this potential can lead to the systematic errors mentioned above.
The considerable number of "secondary" electrons ($\sim 10^7 \div 10^8$ cm^{-3}) produced in WGTS gas result, in the WGTS volume, having an ionization state close to the quasi-neutral one and charges are displaced to the plasma boundaries. In terms of the mentioned above the paper deals with: (1) degraded electron spectrum regarding elastic and inelastic collisions; (2) conditions for formation of quasi neutral plasma; (3) obtaining quantities of potential drops near the solid surface taking into account electron emission; and (4) analysis of electric potential variations along the WGTS plasma column.

II. β-ELECTRON SPECTRUM DEGRADATION AND WGTS IONIZATION STATE

The WGTS is a pipe at cryogenic temperature with tritium injection in the center and differential pumping at open ends. A strong magnetic field parallel to pipe axis is used to guide β-decay electrons toward the spectrometer [5]. The ionization processes in tritium gas are sustained by β-electrons. Set-ups of a similar type were used for the direct measurement of neutrino mass performed previously by several experimental groups. . As is mentioned above a crucial requirement for such a measurement is a strict control of β-spectrum endpoint position. An uncontrolled endpoint variation leads to systematic errors , that is negative neutrino mass square shift.

Unfortunately, the interaction of β-electrons with electrical potentials in WGTS plasma column can result in the inaccuracy of the measurements. Below, problems of compensating space ion charges formed at β-decay and possibilities of controlling space distribution of electrical potentials in WGTS plasma are discussed.

At β-decay fast electrons are created which have an energy of up to 18.6 keV. For the molecular tritium density $n_m \sim 10^{15}$ cm^{-3} (KATRIN Project) the number density rate of producing β-electrons is $N_\beta \sim 3.6 \cdot 10^6$ cm^{-3} s^{-1}. Fast β-electrons moving along force lines of magnetic field escape the WGTS plasma column in a short time of an order of ~ 100 ns. At the first sight, the space ion charge remains non compensated; hence, in the plasma column electric fields of a high strength can arise. At the same time it is necessary to take into account the so-called " secondary electrons" which are produced at degradation of the β-electron spectrum due to inelastic collisions of fast electrons with molecules. The secondary electrons mentioned above can, in principle, compensate an ion space charge. Consequently, one can realize plasma quasi neutrality which essentially depends on the number of electrons produced at ionization of molecule gas by fast ("primary") and secondary electrons.

According to the calculations one primary electron can create about 13 secondary electrons. As the secondary electrons have an energy of the order of ~ 15 ÷100 eV it is possible to estimate the number of "slow" electrons created by every secondary electron; as a result, we find the general number of electrons created by one fast electron; it is ~15. So, for a plasma density we will have: $n \sim 3 \div 5 \cdot 10^8$ cm^{-3} if life time is defined by the gas flux velocity (the recombination coefficient $\alpha_r \leq 2 \cdot 10^{-8}$ $cm^{-3}s^{-1}$). Unfortunately more accuracy estimating plasma density is impossible of a great scatter of experimental data for the recombination coefficient. Slow electrons arising at ionization collisions can support a quasi neutrality, $n_e \approx n_i$, with an accuracy not less than 10^{-5}.

The characteristic time of energy exchange with the molecule gas for these electrons is $t_E \sim 10^{-4}$ s. At the same time their life time relative to diffusion along the tube length ($t_D \sim 10^{-1}$ s) is quite sufficient to slow down. So, the slow electrons can again the temperature which is equal gas one. As is mentioned above intermediate electrons arising after ionized collisions of the fast electrons with gas molecules (their energy is from 15 to ~ 100 eV) are able to ionize the tritium molecules. They also slow-down to acquire the gas temperature.

Our Monte Carlo calculations show that most of these electrons, at least in the plasma column centre, cool down to gas temperature (Fig.1).We included into our computer program the most important e-T_2 scattering cross-sections: ionization, electronic excitation, vibrational and rotational excitation, and elastic scattering [6]. The β-decay events were generated according to the Fermi spectrum, with isotropic angle distribution, and proportionally to the gas density. Then, the path of these electrons inside the WGTS system was followed, and their ionization processes were recorded. The path and interaction of the secondary electrons created by ionization was then also followed, until they left the WGTS system.

The main results of these computations are the following. The largest part of the secondary electrons cools down to gas temperature (30 K, corresponding to 2.6 meV) within a time interval of 1-2 ms, and during this cooling time the slow electrons diffuse along the magnetic field lines about 1 m distance. Since the length of the WGTS system is 10 m, the average escaping time of the electrons from the system is about 100 ms. So, most of the electrons present inside the system have an energy distribution with a characteristic energy of a few meV.

Using this Monte Carlo program, we have computed an estimate for the electron energy distribution function $f=dN/d(\log_{10} E)$ inside the WGTS system (Fig.1, on a log-log scale).There is a large peak at low energies, with rough agreement with the Maxwell distribution corresponding to 30 K gas temperature, and in addition the distribution function has a long tail, which is due to the large starting energies of the primary (β-decay) and secondary (ionization) electrons. The computation was performed without space charge potential and without electron-ion recombination.

III. ELECTRICAL POTENTIAL JUMPS IN WGTS PLASMA

III.A. Space ion charge compensation and plasma quasi neutrality.

What accuracy is required to compensate an ion charge in order to avoid formation of high electric potentials in plasma? As is known, in a plasma of sufficiently large sizes (compared with a screening radius) quasi neutrality is usually observed. However, even at an almost entire charge compensation when electron and ion densities are practically equal, nevertheless there can occur electric fields (E) of high amplitude. So, at a fairly insignificant (~ 10^{-4}) plasma deviation from quasi neutrality there can appear rather high difference of potentials in the plasma. Thus, the problem of both the spatial charge compensation in the WGTS plasma column and control of the electric potential

profiles are of important significance. Fortunately, numerous experiments in plasma physics confirm the fact of displacing spatial charges towards the borders of the plasma volume where potential jumps are observed.

III.B. Potential jumps near the plasma-surface boundary.

If there is no magnetic field for the potential jump near the surface we have the expression from [7-9]

$$e\Delta\varphi \approx T_e \ln \sqrt{(m_i/m_e)} \qquad (1)$$

where m_i ,m_e are ion (electron) masses, respectively and T_e is electron temperature. For a plasma in molecular tritium we will have $e\Delta\varphi \approx 5\ T_e \sim 12$ meV. Below we assume that electron temperature equals the gas one. In the case of the plasma in the magnetic field with its force lines directed parallel with the surface the description of the layer become more complex. The similar situation is realized, for instance, in tokamaks and stellarators [7].

In terms of fundamental physical insights we will try to find a value of the potential jump near the surface and to discuss the effect of electron emission from the surface.

Note that in a transverse magnetic field, ions have a much higher mobility than electrons. It follows that to equalize electron and ion fluxes the potential jump near the surface must be of opposite sign (plus) compared with the case of no magnetic field. Now the ion distribution is described by the Boltzmann equation

$$n_i = n_0 \exp(-e\varphi/T) \qquad (2)$$

where n_0 is the plasma density on the border of the quasi neutral plasma. It is still assumed that a quasi neutrality is kept in basic volume. For the ion fluxes towards the wall, in accordance with (2), we shall have

$$j_i = _\ n_0 \exp(-e\Delta\varphi/T)\ r_c/\tau_i \qquad (3)$$

where $\Delta\varphi$ is the potential jump, r_c is the cyclotron radius and τ_i is the time between two sequential collisions of ion and molecules. As is seen from (3) the velocity of the directed ion motion at the border of the quasi neutral region is not equal the ion sound velocity. So, in this case the Bohm criterion is not valid.

To calculate the electron flux towards the surface we make use of the equation of continuity for electrons

$$\mathrm{div}\ j_e = s - \alpha_r n_e n_i \qquad (4)$$

where s is the ionization rate and α_r is the coefficient of recombination. We assume that in the basic plasma volume balance between ionization and recombination processes takes place, which, however, is violated at a certain distance Δx from the surface where diffusion losses of the particles onto the wall break the equilibrium of ionization.

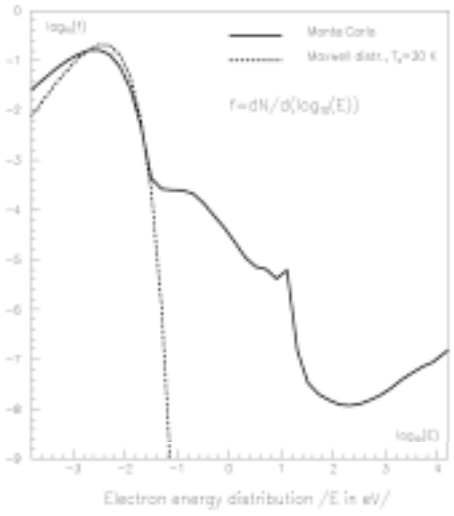


Fig. 1.

This is observed at $\Delta x^2/2D_\perp < \tau_r$, where $D_\perp$ is the coefficient of electron diffusion transverse to the magnetic field and τ_r is the characteristic time of recombination. At the mentioned condition the second term in right side of equation (4) can be neglected. It is also easy to show that $\Delta x << a$, where a is the plasma column radius. In this case one can use an one-dimensional approximation when calculating the electron current onto the wall. Assuming $j_e(0) = 0$ on the axis of the plasma column, we find for the electron current near the surface

$$J_e \approx s\ \Delta x \approx s \sqrt{(2\ D_\perp \tau_r)} \qquad (5)$$

By equating ion flux (3) to electron ones (5) we have the following value for the potential jump near the solid surface

$$e\Delta\varphi \approx T \ln [n_0\ r_c/\ (2\tau_i\ s \sqrt{(2\ D_\perp \tau_r)})] \qquad (6)$$

As is seen from (6) in the case of plasma in the magnetic field with its force lines parallel to the surface the potential jump depends on many parameters, e.g. plasma temperature and density, electron production rate, s, coefficient of transverse diffusion $D_\perp$, characteristic rate of recombination, etc. For KATRIN plasma parameters we have the estimate $e\Delta\varphi \approx 10$ T ~25 meV.

As known the electron emission can result in reducing (in the case of plasma with no magnetic field) a value of the near-surface potential jump. In the case of plasma in a magnetic field the given effect of the electron emission needs further investigations.

In the WGTS plasma column (the KATRIN project) the pipe walls are kept at a low temperature of ≈ 30 K, and the electron emission from the surface is almost entirely ruled out. Electron emission can be artificially created (f.e., photo- and secondary electron emission) but this method is fraught with technological problems. J.Bonn [10] paid attention to a specific feature of a cold tritium plasma inside the WGTS pipe: on cold solid surfaces there forms a

layer of molecular tritium which is a source of β-electrons. In the case of a mono molecular layer with a molecule concentration of ~ 10^{16} cm^{-2} the intensity of the β-electron source is ~$10^{7}cm^{-2}$ s^{-1}. These electrons penetrate deep into the material of the pipe wall and in interacting with metal transfer their energy to free and bound electrons which causes secondary electron emission. The intensity of this electron emission depends on material of the wall, in particular, on its surface state and may widely range up to ~ 10 secondary electrons per one primary β-electron. With allowance for the secondary electron emission j_E^s the resulting electron current towards the surface is decreased by j_E^s. From here we find the value of the potential jump

$$e\Delta\varphi \approx T \ln [\quad n_0 r_c / 2\tau_i (s \sqrt{(2 D_\perp \tau_r - j_E^s)}] \qquad (7)$$

The estimates show that even at a coefficient of ~ 10^{-2} for the secondary electron emission, according to (7) an increase of the potential jump can be considerable. Thus, the effect involving emission of β-electrons by a tritium mono layer requires detailed study.

IV. ELECTRIC POTENTIAL DISTRIBUTION ALONG THE WGTS PLASMA COLUMN

In a homogeneous plasma, as is known, spatial charges do not arise. An electric field in such plasma can be generated due to an external source. In a spatially non uniform plasma spatial charges are produced, first of all, in the places with a large gradients of plasma density. Let us consider spatial distribution of an electric potential along the WGTS plasma column (along force lines of the magnetic field) In terms of the equation set describing electron (j_e) and ion (j_i) currents we have

$$j_e = - \mu_e (enE + T \nabla n) + nV \qquad (8)$$

$$j_i = + \mu_i (enE - T \nabla n) + nV \qquad (9)$$

where $\mu_{e,i}$ is the mobility of electrons (ions) and V is the hydro dynamical gas velocity. Here the frequency of collisions for ion and electron with neutrals is assumed to be non depended from temperature.

For resulting current $j = e(j_i - j_e)$ we have

$$j \approx \mu_e (enE + T\nabla n) \qquad (10)$$

With no current $enE = - T\nabla n$, thus $\varphi = T \ln (n/n_0)$. Assuming $n/n_0 \sim 10^{-2}$ for the required electric potential difference we find $\Delta\varphi \sim 5$ T. So, the value of $\Delta\varphi$ obtained cannot affect essentially on β-electron spectrum. A more accurate value of $e\Delta\varphi$ can be found within a self-consistent numerical model with due to account for spatial gas distribution $n_m = n_m (x)$ and corresponding values of the recombination coefficient (unfortunately, the experimental values of α_r have a considerable spread in magnitude; analysis to be necessary).

V. CONCLUSION

Molecular tritium in the WGTS system is ionized by β-electrons and secondary electrons forming a low-temperature slightly ionized plasma at an electron concentration of up to 10^{8} cm^{-3}. The Monte Carlo calculations show that the greatest part of these electrons slow down due to inelastic and super elastic collisions to the gas temperature. In the main WGTS volume the plasma is quasi neutral, and spatial charges are displaced to the plasma boundaries forming potential jumps. As a result of plasma non uniformity along the WGTS axis potential differences occur with their amplitude of ~ 10 meV that cannot essentially influence the results of neutrino mass measurements.

In conclusion we would like to emphasize that for a better understanding of the processes which can effect the accuracy of measurements of the fast β-electron spectrum at its end and quantitative evaluation of corresponding effects it is desirable to solve a two-dimensional self-consistent task: (1) plasma state in a moving flow of molecular gas where ionization is produced by β-electrons and s.c." intermediate electrons" created by the primary ones; (2) potential distribution along the WGTS pipe and in a radial direction including potential jumps near the solid surfaces; (3) processes of electron deceleration and degradation of β-electron spectrum.

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