VACUUM OSCILLATIONS AROUND A LARGE-Z "NUCLEUS"*

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CONF-890161--2

DE89 006633

for presentation at

GROSS PROPERTIES OF NUCLEI AND NUCLEAR EXCITATIONS

INTERNATIONAL WORKSHOP XVII

Hirschegg, Kleinwalsertal, Austria

January 16-21, 1989

*Research sponsored by the Division of Nuclear Physics, U.S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and by the State of Tennessee Science Alliance Center of Excellence Program under Contract No. R01-1061-68.

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Abstract

We investigate a possible explanation of sharp e^+ peaks in heavy-ion collisions by analyzing QED with a large atomic number external source. We show that a highly polarized vacuum around a large Z "nucleus" has at least two neutral oscillation modes, whose energies are calculated to be 1.8 MeV and 1.5 MeV with an appropriate choice of the nuclear radius. They decay into a pair of $e^{\pm}$ through electromagnetic interactions.

Sharp positron peaks[1] observed at GSI have not been well explained for several years. These peaks are around 300 keV in the spectrum of positron kinetic energy, and their widths are very small. In the e^+e^- coincident experiments, it was found that there is an electron peak at an energy almost identical to that of the positrons. Several models have been proposed to explain these peaks, however none of them is very satisfactory[2].

In our research, we would rather take a conservative attitude than to propose an exotic explanation. Because there are several observed positron peaks, we speculate that the peaks might be naturally understood by some kind of collective phenomenon. Here we try to explain them in terms of collective excitations in QED. Recently, oscillations of the polarized vacuum around a large $Z(\simeq 180)$ "nucleus" have been investigated[3],[4]. Although QED has been tested by many experiments, QED of strong fields has not been well tested yet. It is also not very clear how we solve such a QED problem because of the nonperturbative nature of physics. In these circumstances, we shall use an equivalent boson description of electron fields for such problems, which is quite useful for the analysis of collective phenomena.

In order to study such a complicated problem, we assume a simple nuclear charge distribution: spherical and uniform distribution with radius R. This simple model may not be a very accurate picture of the low-energy heavy-ion collision experiments in the sense that the colliding nuclei may form a nuclear molecular state. However, this simplification is a first step in studying the collective excitations. The "nuclear" charge radius R is considered to be a parameter, but it must be within a physically meaningful radius of the order of 10–30 fm. In the vacuum around such a large-Z nucleus, spontaneous pair creation of $e^{\pm}$ may occur. The electron of the pair may partially screen the nucleus and positron runs away from it. Then the nucleus is surrounded by an electron cloud which is tightly bounded. It is shown that the cloud itself may oscillate, and these oscillation modes decay into e^-e^+ through electromagnetic interactions. These positrons would be identified with the observed narrow positron peaks.

The QED action with a nuclear charge density $Ze\rho(x)$ can be reduced to the 2-dimensional one by assuming a spherical charge distribution. It is difficult to describe the collective motion in terms of the fermion theory in the case of strong electromagnetic fields. However, the problem could be treated rather easily by the equivalent boson theory. This bosonization technique was first invented by Coleman and Mandelstam[5]. They proved that the massive Thirring model is equivalent to the sine-Gordon model. After that, it became a widely accepted idea that the two-dimensional fermion theory could be described in terms of an equivalent two-dimensional boson theory. Our two-dimensional QED problem could also be described by the equivalent boson theory. This bosonization has been done by Hirata and Minakata[6]. We use their two-dimensional QED Hamiltonian to investigate the excitations of electron clouds around a nucleus. In their studies, they have taken only lowest-order partial waves for the electron ($j = 1/2$) and the Coulomb field[6],[3]:

$$H = \int_0^\infty dr \Big[\frac{1}{2}\sum_m [\Pi_m^2 + P_m^2 + (\partial_r\Phi_m)^2 + (\partial_r Q_m)^2] + \sum_{m,\delta}\frac{1}{4r^2}[1-\cos(\sqrt{\pi}(\Phi_m + Q_m - \delta T))]$$
$$+ \sum_m \frac{M^2}{\pi}(2-\cos(2\sqrt{\pi}\Phi_m)-\cos(2\sqrt{\pi}Q_m)) + \frac{e^2}{8\pi r^2}[(\Lambda - \frac{1}{\sqrt{\pi}}\sum_m(\Phi_m + Q_m))^2 - \Lambda^2] \Big] \quad , (1)$$

where $\Pi_m(P_m)$ is the canonical conjugate of $\Phi_m(Q_m)$, m is the eigenvalue of J_z, and δ indicates the chirality. T and $\Lambda(r)$ are defined by: $T = \int_r^\infty ds\, (\Pi_m - P_m)$, $\Lambda(r) = 4\pi Z \int_0^r s^2\rho(s)ds$. The first term in Eq.(1) corresponds to the kinetic energies of the fermions (electrons and positrons), the second term to the centrifugal barrier for the fermions, the third term proportional to $M^2 (M = \pi m_e/2^{(3)})$ to the fermion mass term, and the fourth term to the Coulomb interactions among fermions and between fermions and the nuclear charge. Correspondence between the fermion description and the boson one is understood by noting the electromagnetic charge: $Q_{EM} = -e/\sqrt{\pi} \sum_m [\Phi_m(r=\infty) + Q_m(r=\infty)]$, and the z-component of the total angular momentum: $J_z = 1/\sqrt{\pi} \sum_m m [\Phi_m(r=\infty) + Q_m(r=\infty)]$. where the boundary condition is taken as $\Phi_m(r=0,t) + Q_m(r=0,t) = 0$. From these quantum numbers, we find that the electron or the positron appears as a soliton in the boson theory. For example, a solution in the sine-Gordon-like Hamiltonian: Φ_m or Q_m = $[\tan^{-1}(e^{\pm 2M(r-r_0)})]/\sqrt{\pi}$ is a spherically symmetric wall located at r_0, and it corresponds to the electron or the positron.

Solving the equations of motion (e.g. $\partial\Phi_m/\partial t = \partial H/\partial\Pi_m$ and $\partial\Pi_m/\partial t = -\partial H/\partial\Phi_m$) with an ansatz: $\Phi_m = Q_m = \phi(r)$, we obtain the differential equation:

$$\frac{d^2\phi}{d\rho^2} - \frac{1}{\sqrt{\pi}}(\frac{\pi}{2\rho^2}+2)\sin(2\sqrt{\pi}\phi) + \frac{\alpha}{\sqrt{\pi}\rho^2}[\Lambda(\rho) - \frac{4}{\sqrt{\pi}}\phi] = 0 \quad . \qquad (2)$$

where ρ is defined by $\rho = Mr$.

We assume that the nuclear charge is screened by 4 units of the electron charge. This could be justified if the $S_{1/2}$ and $P_{1/2}$ levels dive into the negative energy continuum[7]. This screening is shown to happen by solving Eq.(2) with a boundary condition $\phi(r=\infty) = 2\sqrt{\pi}$. Actually the energies of these solutions have been shown to be lower than that of a nonscreening solution ($\phi(r=\infty) = 0$) in the case of $Z > Z_c$(a critical atomic number). There is a discrepancy in Z_c between the boson description[6] ($Z_c = 150$) and the one-particle theory[7] (Z_c= 173), and this difference must be investigated further. In the Z= 180 case, we choose R= 25 fm so that one of the resonance energies we obtain is 1.8 MeV, which is one of the e^+e^- energies in the coincidence experiments.

Next, we study small oscillations of these polarized clouds by expanding Φ_m and Q_m around the screening solution ϕ: $\Phi_m(r,t)= Q_m(r,t)= \phi(r)+ \delta_m(r,t)$. Choosing the variables $\xi_\pm$ as $\xi_\pm(r,t)= [\delta_+(r,t)\pm \delta_-(r,t)]/\sqrt{2}$, we obtain equations to describe two independent oscillation modes:

$$\frac{E_+^2}{2M^2}\xi_+ = [-\frac{1}{2}\frac{d^2}{d\rho^2} + (2+\frac{\pi}{2\rho^2})cos(2\sqrt{\pi}\phi) + \frac{2\alpha}{\pi\rho^2}]\xi_+ \quad , \tag{3a}$$

$$\frac{E_-^2}{2M^2}\xi_- = [-\frac{1}{2}\frac{d^2}{d\rho^2} + (2+\frac{\pi}{2\rho^2})cos(2\sqrt{\pi}\phi)]\xi_- \quad . \tag{3b}$$

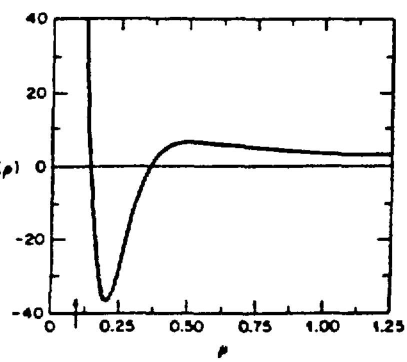

Fig.(1) Potential $V_-(\rho)$.

These equations are the "Schrödinger" equation: $\varepsilon_\pm\xi_\pm = [-d^2/(2d\rho^2)+V_\pm(\rho)]\xi_\pm$. The potential $V_-(\rho) = (2+\pi/(2\rho^2))\cos(2\sqrt{\pi}\phi)$ is shown in Fig.(1). The term $2\alpha/(\pi\rho^2)$ in Eq.(3a) is very small compared with other terms, so that $V_+(\rho)$ is almost the same shape as $V_-(\rho)$. The arrow in Fig.(1) is the position of the nuclear surface, therefore, the potential is strongly repulsive within the radius of the nuclear surface. This is due to the centrifugal barrier for the electrons. At $2\sqrt{\pi}\phi=\pi/2$ the potential becomes 0; it becomes minimum at $2\sqrt{\pi}\phi=\pi$, and it becomes small at large distances.

Resonance energies of these oscillation modes are calculated by solving the differential equations, and we get: E_+ = 1.8 MeV and E_- = 1.5 MeV for $Z=180$, $R=25$ fm. Dependence on Z and the radius has been examined, and we obtain E_+= 1.4 MeV for Z= 165 and R= 25 fm, and E_+= 3.6 MeV for Z= 180 and R= 10 fm. This indicates that there is a dependence on the atomic number, and the resonance energy is strongly affected by the choice of the radius.

We have found that a highly polarized vacuum around a large Z "nucleus" has at least two neutral oscillation modes, whose energies are in the few-MeV region, depending on the "nuclear" charge radius. These excited states would decay into an electron-positron pair through electromagnetic interactions. There is still a major problem to identify these excited states to the observed positron peaks because of strong final state interaction. In this decaying process, the positron and the "nucleus" is expected to interact strongly, so that the observed positron peaks may be broadened[8]. However, ambiguities of such a theoretical approach must be further investigated in the supercritical field case.

Acknowledgement

S.K. is supported by the Division of Nuclear Physics, U.S. Department of Energy under Contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems Inc., and by the State of Tennessee Science Alliance Center of Excellence Program under Contract No. R01-1061-68.

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