OBSERVATION OF BOUND STATES OF PARTICLES IN THE STORAGE RING

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Abstract

The deviation from the law τ_1/N, where τ_1 is a mean life-time of the one-particle state, of N-particle state life-time in the storage ring was experimentally observed. Authors relate this deviation to interaction between the particles, conditioned by the fields excited in passive resonant devices of vacuum chamber of the storage ring. According to experimental data the binding energy of particle pair for various cases is calculated.

INTRODUCTION

The operating modes of the charged particle storage rings can be conditionally divided into two types: high-current mode and low-current mode.

At high-current mode (the stored current is varied from several milliamperes and higher) the essential influence on parameters of circulating bunch is rendered by so-called collective effects: spatial charge of bunch, the electromagnetic fields exciting by a bunch in passive resonant elements of the vacuum chamber, intrabeam scattering etc.

At a low-current mode (the stored currents, as a rule, are no more than one-two milliamperes) it is usually considered, that the mentioned above factors can be neglected and dynamics of particles and the bunch characteristics are well described by so-called one-partial theory, without taking into account interaction of particles with each other and with vacuum chamber.

The natural question is: as far as such approximation is valid, whether is it basically possible to account particles in the storage ring free, i.e. not connected by interaction with each other, whether is it possible "to regulate" such interaction and whether is it observable?

In the present report the results of experimental research of the given question are submitted.

THE SCHEME OF EXPERIMENT

Observation and examination of bound states of electrons was carried out on the electron storage ring H-100 NSC KIPT [1]. The scheme of experiment is presented on Fig. 1. The electrons in the storage ring were injected from the linear accelerator, for compensation of particle energy losses the resonator (1) of RF-system was mounted in one of straight section of the storage ring.

The energy of circulating electrons was 70 MeV; the losses on synchrotron radiation (SR) were about $\Delta E \approx 4.6$ eV per turn, the orbit length $\Pi \approx 5.741$ m. In view of experiment geometry, it provided intensity of photon stream from one electron in spectral interval 400 - 700 nm $\sim 4 * 10^5$ ph./el. s, that allowed to indicate reliably the single electron with help of PM, operating in direct current (dc) mode.

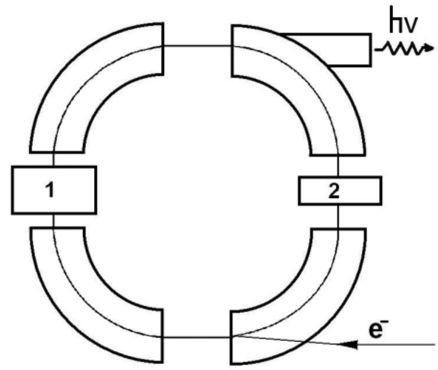

Figure 1: The scheme of experiment. 1 - resonator of RF-system for energy losses by electrons on synchrotron radiation compensation, 2 - the demountable passive resonant element which was identical to one used in [2], 3 - PM for electron counting, 4 - PM high-voltage power supply, 5 – direct current amplifier, 6 - strip-chart recorder for the time intervals measurement.

In Fig. 2 is shown an example of PM current change. The number of circulating electrons varied from 8 up to 0. These results demonstrate an opportunity of reliable registration of single electron and measurement of corresponding time intervals.

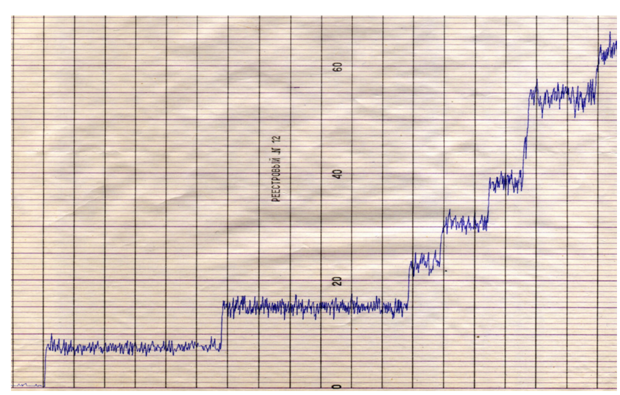

Figure 2: An example of PM current change.

For particle bound states observation it was necessary to choose such technique, which, first, excludes any influence on dynamics of particles and, second, is the most responsive to bonding existence between particles. As such technique it was chosen the measurement of time intervals during which there was numerable amount of electrons in the storage ring. Such technique excludes any influence on dynamics of circulating particles and allows know their quantity at any moment absolutely precisely.

From all processes, which effect on the particles lifetime in the storage ring, the most responsive to magnitude of potential barrier and, hence, to presence of bonding between the particles, are 1) inelastic scattering on electrons of atoms of residual gas (so-called δ-electron knocking-out) and 2) excitation of synchrotron oscillations by quantum fluctuations of radiation. The particles lifetimes, which were stipulated by these processes, in the given experiment conditions are accordingly equal:

$$\tau_\delta = \frac{1.35*10^{-4}}{P}\gamma\left(\frac{\Delta E}{E}\right)_{\max} \quad (1)$$

$$\tau_{quant.} = \frac{\tau_s}{2}*\frac{e^\alpha}{\alpha}\text{ , where } \alpha = 4.7(tg\varphi_s - \varphi_s) \quad (2)$$

Here γ=140 – relativistic factor, P – pressure in vacuum chamber mm Hg,

$$\left(\frac{\Delta E}{E}\right)_{\max} \cong \left[0.85\frac{eV_0}{E}(\sin\varphi_s - \varphi_s\cos\varphi_s)\right]^{1/2} \quad (3)$$

$\cos\varphi_s = \Delta W / eV_0$, ΔW – the particle energy losses on radiation by one turn, V_0 – amplitude of an external RF-field, $\tau_s = \frac{6.176*10^5}{\gamma^3}$ [s] – the time of synchrotron oscillation damping.

From two processes said the preference should be rendered to that, which "gradient" and, hence, sensitivity, is higher.

Under these conditions ($P=5*10^{-8}$ mm Hg and V_0=20 V) the lifetime stipulated by single-valued elastic scattering on atoms of residual gas (Z=7), is τ_{el}~320 s, and a lifetime stipulated by a bremsstrahlung in a field of atom nucleus of residual gas is $\tau_{brst.}$~96. s.

The results of calculations show, that the most responsive to existence of binding between the particles is the lifetime stipulated by excitation of synchrotron oscillations by quantum fluctuations of radiation. At $P\approx 5*10^{-8}$ mm Hg and V_0 ≈12 V, as it took place in experiment, the lifetime of particles in the storage ring was defined by excitation of synchrotron oscillations by quantum fluctuations of radiation and was ~5…20 s. It is ten times less, than lifetimes, stipulated by all other processes.

THE RESULTS OF EXPERIMENT

In experiment, in conditions when the lifetime of particles in the storage ring was defined by excitation of synchrotron oscillations by quantum fluctuations of radiation, the time intervals, during which in the storage ring circulated constant (from four up to one) amount of electrons, were measured. Obtained at identical conditions (amplitude of external RF-field, pressure in the vacuum chamber of the storage ring, amount of circulating particles) data have been incorporated into corresponding files and processed with the help of program Origin 7. For received distributions as the fitting function the function of a kind:

$$y = y_0 + A_1 e^{-\frac{x}{t_1}}$$

which describes radioactive decay, was used.

Parameters y_0, A_1, t_1 were defined from condition of magnitude χ^2 minimization for approximating function. For all cases of fitting the relation $0.001 \le \chi^2 \le 0.43$ was carried out at quantity of degrees of freedom 1…2 and at coefficient of determination $R^2 \ge 0.9998$.

From the law of radioactive decay of noninteracting particles follows $\tau_N/\tau_1 = 1/N$, where τ_N - the mean lifetime of N particles. As criterion of "coherence" of particles the magnitude

$$k = \left(\tau_N / \tau_1\right)_{ex} - \frac{1}{N}$$

has been chosen. For noninteracting particles $k=0$.

The binding energy of pair of particles was defined as $e(V_{2\tau 2} - V_{\tau 1})$, where amplitudes $V_{2\tau 2}$ and $V_{\tau 1}$ were calculated accordingly with expression (2). The values τ1 and 2τ2 were measured experimentally.

Dependences $\tau_N(N)$ have been measured in experiments for cases, when: I) on the storage ring the passive resonator [2] has been mounted and the amplitude of external RF-field V_0 was accordingly ~12 V, ~12.6 V, ~13.6 V, and II) when the passive resonator has been demounted, and V_0~13 V.

On Fig. 3 is represented the dependence of magnitude k on number of particles N for case when the passive resonator on the storage ring was mounted, V_0≈12 V and τ_1≈5.7 s. The obtained dependence convincingly enough shows a deviation of lifetimes of particles τ_N (N>1) from the law of radioactive decay of noninteracting particles *(k=0)*.

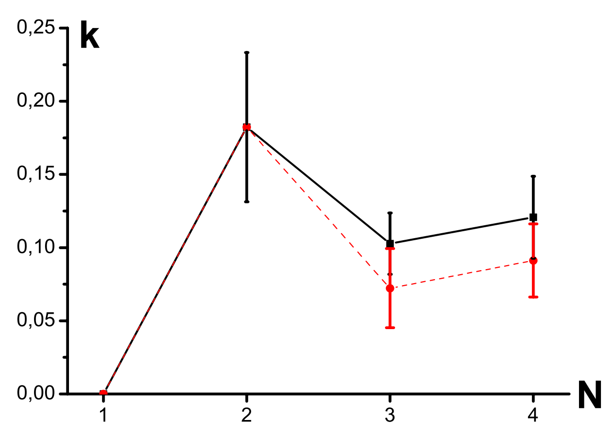

Figure 3: The dependence of magnitude k on number of particles N.

The solid line and the points on it correspond to experiment. The dashed line and points on it correspond to designed values *k* for case, when τ_1 and τ_2 are taken from experiment.

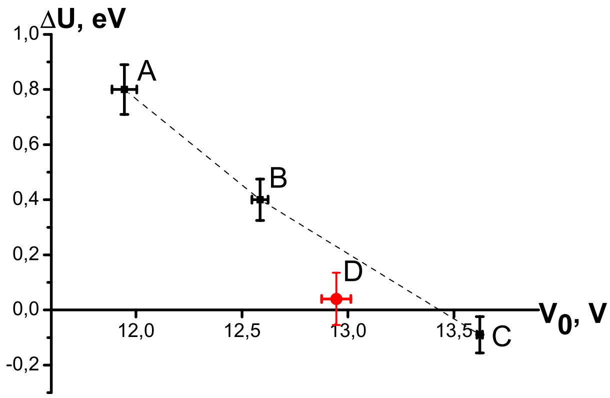

Figure 4: The dependence of binding energy of a pair of particles on RF-field amplitude.

On Fig. 4 is represented the dependence of binding energy of pair of particles on RF-field amplitude. Points A, B, C correspond to a case when on the storage ring the passive resonator was mounted, point D - when this resonator has been demounted.

Dependence *U* on V_0, apparently, is connected with dependence of a root-mean-square size of a bunch and, hence, the distance between particles on amplitude of exterior RF-field. It specifies also monotonicity of obtained dependence $U(V_0)$.

CONCLUSION AND DISCUSSION

Thus, for the first time in experiment the bound states of accounting amount of particles (electrons) in the storage ring were observed. It was observed both effective attraction and effective repulsion. A reason of such phenomenon is, in our opinion, interaction between the particles, stipulated by the electromagnetic fields excited by them in passive resonant devices of the vacuum chamber.

Quantum consideration of influence of such interaction on the particle state, in neglect of the radiation (in case of relativistic electrons), can be made in the frame connected with synchronous particle. In this frame the particle movement is nonrelativistic because the synchrotron oscillation frequency, as a rule, is much less than the revolution frequency. For protons it is obviously valid, as they in majority of known storage rings are nonrelativistic. Thus, for exposition of the interacting particles in the storage ring it is possible to use BCS theory of superconductivity and its deductions. According to this theory, anyone, somehow a weak interaction, which is characterized by attraction, leads to formation of the bound pairs of particles with certain aggregate orbital moment L and spin S. The state with L=0 (s-pairing) and S=0 is typical for superconductivity. However the formation of pairs with L≠0 is possible. When L=1, so-called p-pairing takes place. This kind of pairing characterizes superfluid state of ^{3}He whose atoms are fermions, as well as electrons or protons. The model of superfluid ^{3}He, in our opinion, in the best way approaches for exposition of bound states of particles in the storage ring because it does not suppose Meissner effect and vanishing of electrical resistance. Under certain conditions (pressure, exterior magnetic field) superfluid ^{3}He can transfer in A_1-phase. In this phase the state of a pair is characterized by the following quantum numbers: L=1, S=1, i.e. there is a polarization of particles. By taking into account the interest, which exhibits to sources of polarized particles for needs of physical experiments, it would be rather interesting to prolong researches on generation of so called "A_1-phase" in charged particle storage rings.

Besides, one more useful display of particles connection in the storage ring may be appreciable decrease of intrabeam scattering effect.

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