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ABSTRACT

Theoretical and experimental studies in the Institute (Novosibirsk) on the behavior of particle polarization in storage rings are reviewed. In theoretical works the motion of particle spins in arbitrary inhomogeneous fields was investigated. The methods for obtaining the beams with a required polarization direction in storage rings and accelerators are described. It is shown that direction-variable fields on some parts of the orbit may be used to avoid the resonance depolarization upon acceleration of polarized particles to high energies. The conditions for the existence of radiative polarization of electrons and positrons were revealed. The methods for measuring the polarization of the single and colliding beams are described. The results of measuring the time and degree of radiative polarization are presented. The action of spin resonances was studied. The use of polarized beams to find an absolute energy of particles in a storage ring and to compare precisely anomalous magnetic momenta of electrons and positrons is described.

RADIATIVE POLARIZATION: OBTAINING, CONTROL, USING

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1. REVIEW OF THEORETICAL RESULTS

1. The effect of radiative polarization of high-energy light charged particles (electrons and positrons) at their motion in a homogeneous magnetic field was theoretically found in 1963 by Sokolov and Ternov /1/. This effect can be interpreted in a classical way, considering a noncharged particle with a high spin $S \gg \hbar/2$ and a magnetic momentum $\mu = qS$, moving straightly across the magnetic field H , due to a precession magneto-dipole radiation, the . Then in its frame system with a magnetic field γH , due to a precession magneto-dipole radiation, the magnetic momentum will "damp" to the position "along the field" (minimum of energy) according to the equation

$$\frac{dS_{\parallel}}{d\tau}=\frac{2q}{3c^3}\left(\vec{S}\times\frac{d^3\vec{\mu}}{d\tau^3}\right)_{\parallel}=\frac{2q^5}{3c^3}(\gamma H)^3 S_{\perp}^2 , \qquad \left(S_{\parallel}=\vec{S}\vec{H}/H\ ,\ S_{\perp}^2=S^2-S_{\parallel}^2\right).$$

In a laboratory system

$$\dot{S}_{\parallel}=\frac{2q^5}{3c^3}\gamma^2 H^3 S_{\perp}^2 . \tag{1}$$

From this the characteristic time of damping (at small deviations of the magnetic momentum from the field direction) is

$$\tau_p = \left| \frac{4S}{3c^3} q^5 \gamma^2 H^3 \right|^{-1}.$$

When considering this case in a quantum-mechanical way the following equation is obtained

$$\dot{S}_\parallel = \frac{2q^5}{3c^3} \gamma^2 H^3 S_\perp^2 - \frac{2\hbar}{3c^3} \gamma^2 |q^5 H^3| S_\parallel . \tag{2}$$

This equation within the classical limits gors to (1). The equilibrium polarization degree remains equal to 100% for an arbitrary spin.

For a charged particle with the charge e and gyromagnetic factor g $(q = ge/2mc)$ the corresponding equation has the general for /2/

$$\dot{S}_\parallel = \alpha_- S_\perp^2/\hbar - \alpha_+ S_\parallel , \tag{3}$$

where the coefficients $\alpha_\pm$ do not depend on the spin value and in the ultra-relativistic case are proportional to $\gamma^2 H^3$. For the spin $1/2$ the equation takes the form $(S_\perp^2 = \hbar^2/2)$:

$$\dot{S}_\parallel = \alpha_- \hbar/2 - \alpha_+ S_\parallel .$$

The quantum-mechanical sense of the coefficients $\alpha_\pm$ become clear from the comparison of this equation with an elementary balance equation for the spin $1/2$ as a two-level system: α_+ and α_- are the sum and difference of spin-flip probabilities for the $1/2$ spin per a unit time: $\alpha_\pm = P_\uparrow \pm P_\downarrow$

Note, that for a particle with a high spin the polarization rate is determined by the difference of the spin-flip probabilities $(\tau_p^{-1} = |\frac{2S}{\hbar}\alpha_-|)$, while for the spin $1/2$ the rate $\tau_p^{-1} = \alpha_+$.

For the case of a particle with a high gyromagnetic factor $(g \gg 1)$ the spin-depended part of the charge radiation, as compared with the magnetic momentum radiation, can be neglected. In this case the particle non-inertion motion is negligible, the reverse transition probability disappears:

$$\alpha_+ = |\alpha_-| = \frac{2\hbar}{3c^3}\gamma^2|q^5H^3|$$

and equation (3) coincides with (2). For a charged particle with $g \sim 1$, the quantum fluctuations of radiation results in reverse transitions $(\alpha_+ > |\alpha_-|)$ and decreases the equilibrium polarization degree ζ . Thus, for an electron in a homogeneous magnetic field $\zeta = |\alpha_-|/\alpha_+ = 92\%$.

The evaluation of the polarization time examplified by an uncharged particle (neutron) was given by V.L.Lyuboshits /3/.

2. The result obtained by Sokolov and Ternov pointed to the presence of a polarizing mechanism. To clarify real possibilities to produce polarized light particles in storage rings, it was necessary to study radiative polarization in inhomogeneous fields.

In inhomogeneous fields the polarization state variation occurs due to both the direct radiation effect and as the result of the orbital motion perturbation due to radiation (mainly).

A study of the direct radiation effect on the polarization of ultra-relativistic light particles in arbitrary inhomogeneous fields (only slight field variations about the radiation formation length were assumed) was performed by V.N.Baier, V.M.Katkov and V.M.Strakhovenko /4-7/. It was found that the field inhomoheneity did not significantly change a polarizing mechanism, resulted from the direct interaction of a spin with radiation.

The importance of studying the effects of radiation influence on polarization via an orbital motion is associated with the fact that the time of orbital motion relaxation is many orders lower than that of polarization. The study of these effects was started by V.N.Baier and Yu.F.Orlov /7,8/. It was shown that the orbital diffusion caused by quantum radiation fluctuations in the presence of small vertical distortions of closed orbits in a storage ring, resulted in spin diffusion. This depolarizing influence of radiation is of a resonance nature, and at adequate closeness of the frequencies of precession and disturbance destructs radiative polarization.

3. For a complete answer to the question on the existance of radiative polarization a detailed analysis of the polarization behaviour with the account of all specific features of pa rticle motion in storage rings was necessary to do. Later on a study of the spin dynamics not restricted by an ordinary case of approximately axial magnetic fields /9-11/. Generalization on the case with arbitrary inhomogeneous fields is of practical interest for studying possibilities to obtain any required polarization direction. Methods and concepts were developed enabling

a unified description of the radiative polarization to be obtained in arbitrary electromagnetic fields with the account of all significant orbit-spin coupling effects. The analysis makes it possible to describe quantitatively the process of polarization both in usual cases and in those with direction-variable fields /2,12,13/.

It was stated that for any stationary magnetic (electromagnetic) fields providing the existance of closed (and stable) particle orbits $\vec{z}(\theta)$ (θ is the generalized asimuth) there exists closed (periodically repeated on the given asimuth) spin trajectories $\vec{n}(\theta)$ stable not less than in nearly unidirected fields (instability is possible only in the vicinity of spin resonances) /9,10/. A spin deviated from $\vec{n}$ precesses around $\vec{n}$ (similar to that precessing around $\vec{H}$ in a unidirected field).

This fact provides extensive possibilities, by introducing specific fields, to obtain any stable direction of the particle spin on the given asimuth in a storage ring (in particular, a longitudinal one).

As regards the procedure, it is reasonable to note that the possibility to realize, by choosing the magnetic field geometry, a stable spin motion with a given direction in the required orbit point is analogous to that for the achievement of stability in orbital motion of particles in a storage ring with a complicated form of the equilibrium trajectory. For example, the introduction of a longitudinal low-value magnetic field to a storage ring (with plane closed orbits) results only in a slight deviation in the equilibrium polarization stable direction from a vertical one (far from spin resonances). In addition, the introduction of the field rotating a spin by a unity-order angle at a single transit does not destruct the spin motion stability and results in a strong variation of the equilibrium polarization $\vec{n}$.

4. The well-known situation, in which polarized beams may exist is the motion in an accelerator or a storage ring with a constant (in direction) magnetic field. The natural direction of the stable polarization lies along the field transversal to the particle velocity.

Already in this case, the polarized beams substantially expand the possibilities for carrying out experiments in physics. In particular, one can determine the spin properties of final states by measuring the azimuthal distribution of the reaction products for the transversally-polarized colliding beams. It becomes also possible to carry out precise experiments /26, 27, 32, 34, 35/.

Of great interest is the problem of obtaining beams with any preassigned polarization direction. As an example, in experiments with the longitudinally-polarized (parallel to velocity) electron-positron colliding beams of the same helicity, the one-photon electro-dynamic channel is closed and therefore, all the rest of the annihilation processes, either non-one-photon or non-electrodynamic, are emphasized.

5. The first suggestions (1970) for producing the required polarization direction, in particular, longitudinal, were given in /10/ (see also Review /7/ p. 477 (p.714)). Longitudinally

polarized beams can be obtained in various ways. Consider simple examples /10/. Introduce a radial magnetic field H_x into a straight section of the storage ring. To change the spin direction in respect of velocity on the angle $\pi/2$ it is necessary to use for electrons $H_x l = 23$ kgauss×meter , where l is the length of a section with the introduced field (for protons $H_x l = 27$ kgauss×meter; the proximity of the required field values is explained by the fact that the anomalous magnetic moments of an electron and a proton have almost the same absolute value). By varying the value H_x along the section, any required polarization direction can be obtained at the collision point. To restore the polarization direction along the field and the particle velocity upon its initial direction, the condition $\int_S H_x(\theta)d\theta = 0$ should be imposed. No special problems are presented in restoration of the orbit on the section output. Such methods provide a high degree of the radiative polarization.

When rotating at the present plane by the transverse (in respect of velocity) fields, a relation exists between the velocity angle φ relative to the main orbit plane and the spin angle ψ in respect of velocity:

$$\varphi/\psi = 2/\gamma(g-2) \equiv 1/\nu .$$

When the radial fields are used, at the point of longitudinal polarization the velocity inclination angle is $\pi/2\nu$. The amplitude of the orbit vertical distortions within the section with introduced radial fields will depend on energy. The choice of a method is determined by specific experimental conditions.

For example, the particle trajectory within the section may be of the form shown in Fig. 1a. The raidal magnetic field is transverse to the figure plane and introduced to regions I, II, III. The opposite-direction longitudinal polarization is produced between regions I, II and II, III (arrows point to the polarization direction). As another example, the method suggested in /14/ can be taken (see Fig.1b). Here longitudinal polarization is produced between regions II and III. (The opposite-direction longitudinal polarization may take place between regions I, II and III, IV). The characteristic property of this method consists in the fact that the collision of longitudinally-polarized particles occurs at the point O, which position along the vertical does not depend on energy.

At a motion along one orbit in any magnetic field electrons and positrons are polarized in opposite directions due to radiation (in particular, it is also valid at the point of longitudinal polarization, that gives equal helicities). Colliding electron-positron beams with the same polarization direction can be obtained. For this purpose it suffies to separate the polarized beams energies by a radial electric field and to invert one beam polarization direction by making it to pass adiabatically through the induced spin resonance /11/. The state of the reverse-direction polarization is dynamically as stable as "natural", and due to radiative processes it will only relax slowly to the latter.

When beams move along different trajectories, as, e.g., in storage rings DORIS (BRD) or DCI (France), the states of beams with any relative signs of longitudinal polarizations can be stable in respect of radiative processes. Thus, at concentric trajectories (similar to those in the above storage rings) the equal helicity states take place, provided that at the collision point the trajectory inclination angles to the main orbit planes (the orbit planes are parallel) are equal (a head-on collision) $\varphi = \pi/2\nu$.

The state with opposite helicities takes place provided that the inclination angles, e.g., are $\pm\varphi$ (the beam collision angle is 2φ , Fig. 2)

Then, polarization of both beams proves to be longitudinal (with accuracy $\sim \varphi/\gamma$) in their centre of mass system.

Other examples of longitudinal polarization in a straight section (with the spin and orbital motion restoration) can be given by the methods utilizing (instead radial fields)combinations of longitudinal and vertical fields /15/ and those of radial and vertical fields /16/.

6. To produce longitudinal polarization a longitudinal magnetic field can be used, not distorting the equilibrium particle orbit. Consider an interesting example /10, 33/. Let two opposite straight sections be present in a storage ring. Introduce to one of them on the length ℓ a longitudinal field H_v rotating a spin vector by a half turn around the rate. The required field value $H_v = 2\pi E/ge\ell$, where E is the particle

energy. In this case the stable equilibrium polarization n in the opposite section is directed along (against) velocity independently of energy, and in the main part of the orbit it is transverse to a guiding field, its orientation in the orbit plane on the asimuth given being depeddent on energy. The spin oriented in the main region along the field proves to be inverted via a particle revolution. This means that the fractional part of the spin precession rate around n is always equal to half the particle revolution frequency independently of energy[x]. It is interesting, that in this case the spin motion is even more stable than in a usual case of a unidirected magnetic field: all spin resonances, including those with betatron harmonics, become actually impossible, since the resonance would also denote simultaneous instability of the orbital motion.

In principle, possible for electrons (positrons) methods of polarization control can also be applied to heavy particles. Due to the absence of the effect of radiative polarization these particle beams should be either injected already polarized, or somehow be polarized in the storage ring. For example, one may expect to obtain polarized proton (antiproton) beams in storage ring by using the spin dependence of the nuclear interaction of particles with polarized targets, applying electron cooling to maintain sufficiently small beam sizes.

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[x] In storage rings with direction-variable fields the frequency of spin precession around n is defined not only by the energy of a particle but by all structure of the field over the closed orbit /9, 10/. In the case considered the angle of spin rotation around n during the period of the particle's revolution in the storage ring does not depend on energy $(H_v \sim E)$ and is equal to π .

7. The preparation for a practical operation with polarized particles in storage rings (including those with complicated field and trajectory configurations) demanded the development of a more extensive and detailed analysis of polarization behaviour in the region of spin resonances. The complete solutions have been obtained for all the cases of single crossings of resonances at any rate which generalize the results given in /17/. A problem has been solved on the spin motion at multiple periodic and "noise" crossings of any resonances (both machine's and those induced by the external high-frequency fields) /11/.

One of the important problems where the results of studying the spin dynamics can be applied is the depolarization suppression when passing the spin resonances (due to energy change, for ex.) particularly actual for heavy particles (see, e.g.Review /18/). The compensation of dangerous harmonics of the disturbing fields or the increase of the resonance crossing rate can obviously be recommended. For example, the depolarizing influence of resonances with betatron frequencies can be eliminated by a system providing rapid crossing due to betatron frequency jumps /19/. To supress depolarization on resonances with revolution frequency effective is a method based on not the compensation of dangerous harmonics but on their increase by introducing to the sections of additional fields to the value when the resonance crossings become adiabatic /20/.

The introduction of fields greatly disturbing the spin motion enables simultaneous suppression of the effects of resonances with betatron frequencies as well. The limiting case may be the above example with the introduction into the straight section of longitudinal field rotating a spin by a half-turn (distortions in the magnetic system focusing properties, if necessary, can be compensated by the introduction of additional lenses). In this case it is of advantage to inject longitudinally polarized particles directly to the opposite section where the equilibrium polarization direction is parallel to velocity.

When accelerating up to high energies $(\nu \gg 1)$ it is easier to invert a spin in the section by transverse to the orbit magnetic fields, since the required value of these fields is approximately   times lower than the required value of a longitudinal field. The condition of orbit restoration can simultaneously be fulfilled, too. For example, introduce the transverse fields forming an angle 120° to three successive regions I, II and III, as is shown in Fig.3 (The figure plane is transverse to velocity, magnetic field II is horisontal). In each region the spin is revolved around the field by the angle π . It can readily be seen, that the vertically-oriented spin upon its transit of these three regions proves to be inverted.   In this case the particle velocity direction is restored with the accuracy up to ν^{-3} . (Without further complication of this system an accurate velocity restoration can also be provided). The resulting spatial orbit displacement can readily be compensated on the subsequent region by a unidirected field with a zero average value not distorting the direction of the spin and velocity.

Here again likewise in the method with a longitudinal field, the fractional part of the frequency of the spin precession around $\vec{n}$ is equal to half that of the particle revolution.

Since in these cases spin resonances are impossible at any energy, in the process of acceleration the beam polarization degree will be kept constant.

The switching on of rotating fields during acceleration can be performed adiabatically with the spin and orbital motions kept stable.

The problem of keeping polarization at acceleration and deceleration may be actual for light particles as well. For example, electrons can be quickly polarized at high energy and then decelerated up to that, required for the experiment. An advantageous approach may be fast polarization in a special storage ring with a high field at a low energy, then followed by the transition of polarized particles to the main storage ring.

During dynamically slow (adiabatic) passing of a spin resonance in electron and positron storage rings the depolarizing action of quantum fluctuations should be taken into account which is maximum in the resonance region. Introducing sufficiently large coherent perturbations (additional fields in straight sections) the resonance can be shifted to such an extent that the depolarization is suppressed due to radiation fluctuations /20/.

8. On the basis of the results of the spin dynamics analy-

It is interesting to note that with the account of this effect the maximum polarization degree is achieved in a storage ring with an inhomogeneous specific-form field /2/ and equals to 95% (in a homogeneous field - 92%).

For a quantitative description of the radiative polarization kinetics at any point an investigation was carried out without limitations imposed by the closeness of spin resonances. Since polarizing processes proceed slowly, it proved necessary to take into consideration the higher-orders resonances as well. As a result, formulas were obtained determining the region of radiative polarization existance and enabling us under the conditions given to find the direction and degree of the equilibrium polarization and its damping time.

A very important practical problem has been considered on the colliding beams polarization behaviour /21/. It has been shown that the conditions of polarization stability of the colliding beams about those of the orbital motion at collision*.

9. Advantageous for the faster polarization proves to be the introduction of magnetic "snakes", i.e. regions with a strong sign-variable vertical magnetic field $H(\theta)$ /22/**. The

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* A special study is necessary to do for finding optimal conditions to have good enough luminosity and good enough equillibrium degree of radiative polarization simultaneously. By preliminary estimates, these requirements can be satisfied. They can be relaxed additionally if one uses many bunches regime in two-ring colliding beams facility.

** A similar method was independently suggested by A.Hutton in his work "Control of the low energy characteristics of the ISR electron ring using wiggler magnets"(Part.Accel. v.7, No 3, 1976). Note that, in our opinion, the basic formula for relaxation time of polarization used in this work is not quite correct and, therefore, the quantitative results are wrong.

minimal number of field oscillations is determined by the admittable amplitude of spatial orbit pulsations in the section. According to /2, 5-7/, the inverse polarization time is

$$\tau_p^{-1} = A\gamma^2 \oint |H|^3 d\theta \qquad (4)$$

where A is the constant parameter. From this it is seen that by increasing the field on a relatively small length, the polarization time can significantly be decreased. In this case the equilibrium polarization degree is equal to

$$\zeta = \frac{8}{5\sqrt{3}} \oint H^3 d\theta \Big/ \oint |H|^3 d\theta .$$

It is evident that by introducing a "snake", a high polarization degree can be provided without orbit distortions on the main sections. For this purpose the condition

$$\int_S |H|^3 d\theta - \left|\int_S H^3 d\theta\right| \ll \int_S |H|^3 d\theta$$

should be fulfilled, providing that various-sign fields are greatly different in their value. At the same time the conditions $\int_S H d\theta = 0$ and $\int \theta H d\theta = 0$, can be fulfilled, too. It is reasonable that by this method the sign of equilibrium polarization can also be changed by varying the field signs in a "snake". In particular, one may reversibly change the particle helicity in the region of longitudinal polarization. Of particular advantage for independent control of the colliding beams polarization is the two-rings case.

II. Methods of Polarization Measurements

1. Polarization of electrons and positrons which results from their prolonged motion in a magnetic field can be measured by various methods. The processes useful for measuring the transverse polarization of high energy particles in a storage ring were proposed and considered in /7, 23-25/.

At energies of the order 1 GeV polarization of one beam can be measured by the dependence of elastic scattering of the particles in a bunch on their polarization. Due to energy exchange $\pm \Delta E$ in scattering, the particles leave a beam and can somehow be detected. This method becomes low-efficient for higher energies since, owing to a growth in the particle transverse momenta, both the cross-section of the process and the polarization contribution decrease.

The cross-section of Compton scattering of circularly polarized photons is also dependent on the electron polarization. The asymmetry of secondary γ -quanta with energy $\sim \gamma^2 \hbar \omega_{ph}$ is maximum for the energy $\hbar \omega_{ph} \approx mc^2/\gamma$. For electron energies in the order of several GeV the maximum asymmetry can be achieved using the ultraviolet (500-100 Å) part in the synchrotron radiation spectrum of an electron beam characterized by a considerable degree of the different sign circular polarization above and below the equilibrium orbit plane. The following scheme for an experiment can be suggested.

The beam is "prepared" as two consequent bunches so that the "light" of the first one is reflected and focused by a spherical mirror at a distance of its radius equal to half the distance between the bunches. The detection of recoil electrons deflected by a guiding magnetic field in coincidence with a secondary γ -quantum makes it possible to choose the required part of the spectrum. The reflection of either of the upper or lower part of the synchrotron radiation (with respect to the electron orbit plane) allows easy alternation of an asymmetry sign. For the number of electrons 10^{10} in each bunch the number of "useful" events is about 10^3 per second. The same counting rate may be achieved using a continuously operating laser with several Wt in power. Lasers are efficient for electron energies of the order 10 GeV where the asymmetry is maximum in the optical part of the spectrum. The main disadvantage of the Compton scattering application for polarization measurements apparently consists in the necessity of sharp focussing of photons and precise adjustment of the electron orbit.

Another method of polarization measurements exists, free of this disadvantage, which uses scattering by a jet of atomic polarized hydrogen. For the already achieved densities of polarized hydrogen ($\rho \sim 10^{12}$ cm^{-3}, $\zeta = 1$) at $E = 1$ GeV and jet diameter 0.5 cm the number of events per second is numerically equal to the electron beam current in mA. The azimuthal anisotropy for the transverse polarization of electrons is ± 10%. In the case of longitudinal polarization the counting rate of useful events varies by a factor of 8 for parallel and antiparallel orientation of the electron spins in the beam and in the target. The possibility of simultaneous scattering of electrons and positrons as well as weak dependence of the scattering cross-section on the particle energy $(\sigma \sim \gamma^{-1})$ mak, the polarized gas target application to be a convenient means for measuring the polarization of both one beam and colliding beams.

The product of the polarization degrees of colliding beams can directly be measured in the experiments on high energy particles interactions. The cross-sections of two-particle reactions depend on the mutual orientation of electron and positron spins /7/. The cross-section of the μ -meson pair creation is strongly polarization dependent:

$$\sigma_{\mu\mu}\left(\theta=\frac{\pi}{2}, \varphi=\frac{\pi}{2}\right)=0 \;, \quad \sigma_{\mu\mu}\left(\theta=\frac{\pi}{2}, \varphi=0\right)=2\sigma^{0}_{\mu\mu} .$$

The reactions in which pseudoscalar mesons are produced are less convenient for polarization measurements, since their cross-sections are as a rule smaller than $\sigma_{\mu\mu}$. However, in the region of resonances where the corresponding cross-section greatly increases, the observation of the azimuthal anisotropy of final particles appears a convenient method for measuring the transverse polarization. The longitudinal polarization of colliding beams can easily be observed from the elastic scattering of electrons on positrons. The cross-section of this process at $\theta=\frac{\pi}{2}$ varies by a factor of 8 for parallel and antiparallel particle spins.

2. When operating with polarized beams, it is advisible to be able to depolarize a beam. For this purpose one can use a "machine" resonance of sufficient power. In many cases, however, it is not of advantage since either beam energy or fre-

quency of betatron oscillations should be changed. More promising method is provided by using the external high-frequency electromagnetic field resonant with the spin precession frequency.

Such exitation should not result in variations of the beam sizes; so the RF-field frequency should not coincide with one of the combinations of orbital oscillation frequencies. That is why for the transverse in the pont of the excited electron polarization it is more safely to switch on the longitudinal magnetic field. At higher energies, however, when $\nu \gg 1$, the transverse H_x - field is more convenient for beam depolarization since the required longitudinal fields are considerably larger for the same depolarization time:

$$\left| \int H_{v} d\theta / \int H_{x} d\theta \right| \approx \nu$$

The application of a running wave with $|H_x| = |E_z|$ provides additional possibilities in two-beam experiments. In the absence of reflection each of the colliding beams can be depolarized separately by choosing the direction of wave propagation. In addition, it seems possible to depolarize selectively bunches of one beam if short-time pulses in phase with the revolution frequency are used. This method will allow experiments with the colliding beams containing simultaneously polarized and unpolarized particles, other parameters being equal.

III. Experiments with Polarized Beams

1. Experiments on measuring the electron polarization were started in Novosibirsk in 1970 with a storage ring VEPP-2 /7/. The first result gave evidence for radiative polarization. However, because of the reconstruction of the VEPP-2 complex the experiments were stopped and continued in 1974-1975 using a new storage ring VEPP-2M /26-27/. Measurements of the transverse polarization degree were performed by detecting elastic scattering of the particles in a bunch. Two systems of scintillation counters have been used in VEPP-2M, one detected electrons with an energy transfer $\Delta E/E \geqslant 20\%$, while the second-electrons and positrons with $\Delta E/E \simeq 5\%$. When the beam was quickly depolarized using the noise-modulated high frequency longitudinal magnetic field (resonant with the spin precession frequency) a jump in the counting rate $\dot{n}$ of such events was observed (Fig.4). The dependence of this jump value $\Delta = (\dot{n}_0 - \dot{n}_p)/\dot{n}_0$ on the time passed from the beginning of a polarization cycle until switching the depolarizing RF-field allowed determination of the limiting polarization degree $\zeta = 0.90 \pm 0.15$ and the time of radiative polarization $\tau_p = 68 \pm 10$ min at the energy 625 MeV.

2. Good agreement of the measured quantities with those calculated provided evidence for a small value of the depolarizing factors at the experiment energy ($E = 625$ MeV) that was just expected after numerical estimations of the depolarization time. In the estimation a model was used in which the perturbation in the form of a squew quadrupole was introduced

into the ideal structure of a storage ring (the quadrupole strength was obtained by measuring the coupling of vertical and radial particle oscillations). The results of the numerical calculations of "machine" depolarizing resonances whose power is characterized by the ratio of polarization and depolarization and depolarization times τ_p / τ_d are given in Fig.6. In VEPP-2M the radiative polarization is possible in the energy range above 490 MeV excluding narrow resonance bands which can easily be "shifted" by choosing the operation frequencies of betatron oscillations ν_x, ν_z. The calculations also showed that resonances can be passed without polarization destruction, that was later examined experimentally. At the rate of energy variation 10 MeV/sec no pronounced decrease in the beam polarization degree has been observed upon passing the resonances with betatron oscillations of both the first and the second orders.

The linear resonance $\nu = \nu_z - 2$ has been studied in more detail. Fig. 7 shows the behaviour of the counting rate of elastic scattering events in a polarized beam near this resonance. At the frequency of vertical betatron oscillations $\nu_z = 3.152$ (exact resonance at $\nu_z = 3.1565$) polarization is maintained for a ling time. Switching of noise pulsations of the guiding magnetic field $\Delta H/H \approx 2 \cdot 10^{-3}$ (resulting in the modulation of the spin precession frequency of the same order) at $\nu_z = 3.152$ did not change the polarization degree, while at $\nu_z = 3.156$ for $t = 400$ sec resulted in complete beam depolarization confirmed by the absence of variations in the counting rate when a depolarizing RF-field was switched on for control.

The calculation for a resonance $\nu = 1$ (the frequency of anomalous spin precession equals to the revolution frequency at $E = 440.65$ MeV) showed that at a given rate of the energy variation a resonance cannot be passed without complete depolarization unless special care is taken. To confirm this postulation several experiments were performed, in which the polarization degree was measured upon decreasing the polarized beam energy to the region of an integer resonance and returning it to the initial value with the same rate. Up to 448 MeV the polarization was maintained, at 443 MeV and below complete depolarization occured.

The depolarizing action of the quantum fluctuations of radiation while passing an integer resonance can be prevented increasing the perturbation resonance harmonic by introducing the constant field into a straight section /20/. To verify experimentally the possibilities of passing an integer resonance without beam depolarization, a solenoid with a longitudinal magnetic field was placed in one of the VEPP-2M straight sections $\overline{H}_v/\overline{H} = 0.03$. The calculation shows that this field value is sufficient for secure passing of the resonance with the energy variation rate 10 MeV/sec. In this case the central resonance is being passed dynamically slowly, while the first of the possible side resonances associated with phase oscillations - rapidly.

This experiment was performed in the following way. To a bunch of the polarized at E = 625 MeV positrons an unpolarized bunch of equal current was added shifted in phase on $\frac{\pi}{4}$. The comparison of the counting rates of elastic scattering in each bunch provides a continuous and fast measurement of the polarization degree. At an energy 510 MeV by varying in turm ν_z and ν_x the betatron resonances $\nu = \nu_z - 2$ and $\nu = \nu_x - 2$ were "removed", then a longitudinal field was switched on, and when the particle energy was decreased to 400 MeV this field was switched off. A subsequent measurement showed polarization conservation. In a control cycle, repeating all the procedures except the introduction of the longitudinal magnetic field, complete disappearance of the positron polarization was observed. Thus, a possibility has been shown experimentally to pass integer resonances without beam depolarization.

3. As mentioned above, the condition for the colliding beams polarization conservation is close to that for the orbit stability at collision. Polarization of the colliding beams was measured by a system of counters simulyaneously detecting electrons and positrons lost from the beams due to elastic scattering inside the bunches. It was shown that up to the currents 10 x 10 mA at E = 650 MeV radiative polarization occured in a usual way. Polarization did not vanish after decreasing energy to 510 MeV where it was maintained for a long time. The maximum luminosity of polarized colliding beams was achieved in the φ -meson region $2 \cdot 10^{29}$ $cm^{-2} sec^{-1}$ /26/. Two experiments using polarized colliding beams were performed by studying the azimuthal anisotropy of created particles. At

the energy 2·650 MeV the anisotropy in production of muon pairs was observed which supported polarization of the colliding beams. The investigation of anisotropy in charged kaons production was carried out at the ϕ -meson energy after e^+ and e^- beam polarization at 650 MeV for the time $t = 2\tau_p$ (Fig. 8). The measured value of the product of polarization degrees was $\zeta_+\zeta_- = 0.63 \pm 0.14$.

4. Radiative polarization was also studied on other electron-positron storage rings. In 1971 the positron beam polarization was measured on ACO (France) using the inside-bunch scattering. For depolarization passing of an integer machine resonance at 440 MeV was used. It was shown that positron polarization was maintained (in good operation points) in the presence of an electron beam up to the currents close to the simiting ones (by beam-beam effects), and the action of some machine depolarizing resonances was demonstrated /28/.

In 1975 polarization measurements were performed on the storage ring SPEAR. At first the polarization of one electron beam was observed according to the inside-bunch scattering and depolarization at an integer resonance /29/. Then the polarization of colliding beams was demonstrated by measuring the anisotropy of muon pair creation at an energy 3.7 GeV /30/.

The experience gained on these three storage rings shows that radiative polarization can be obtained over the wide range of experimental conditions, and the luminosity of polarized colliding beams is already sufficient to perform various high-

A good example of such an experiment was that carried out by the SPEAR group on the determination of the primary jet spins in multihadronic events /31/. It was shown that polarization greatly facilitated such experiments.

5. On VEPP-2M the radiative polarization was used for another type of experiments. The detection of a jump in the variation of the counting rate of elastic scattering events inside a bunch at a definite frequency of the depolarizing field also measures the average spin precession frequency Ω. The measuring of value of $\Omega = \gamma \frac{\mu'}{\mu_0} \omega_s$ allows determination of the energy for a relativistic electron, since $\frac{\mu'}{\mu_0} \cong \frac{g-2}{2}$ is known with high accuracy from the $g-2$ experiments.

Energy spread in the beam to a first approximation does not restrict this method accuracy /32/. The particle energy deviation by $\Delta\gamma$ from the average value γ_0 in the presence of the accelerating RF-field results in synchrotron oscillations of frequency $\omega_\gamma \ll \Omega$, which modulate the spin precession frequency. The averaged over phase oscillations spectrum of spin motion has a central line and side band frequencies at a distance $n\omega_\gamma$. The phase modulation parameters are usually chosen so that the depolarization time τ_d is much lower at the central frequency as compared with the side band ones. The width of the spectrum central line is determined by the difference between the particle energy γ_0 averaged over phase oscillations and the equilibrium one γ_S associated, e.g., with quadratic nonlinearity of the storage ring. When compensating this and other non-linearities, the spin frequencies spread can be minimized to the value determined by the squared energy spread, that enables determination of the average absolute energy of particles with a limiting accuracy given by the known value of the electron anomalous magnetic moment. In practice, however, this accuracy is restricted by slow irregular pulsations of the storage ring magnetic field "smearing" the average precession frequency. At present the system stabilizing the magnetic field of VEPP-2M provides one measurement accuracy ± 2×10^{-5}.

The first application of this method of energy calibration consisted in the ϕ -meson mass measurement /27/. Before the experiment an absolute calibration of the storage ring energy scale was performed using resonance depolarization.

Each measurement cycle was started and ended with a control calibration of the beam energy at $E = 509.6$ MeV. Three cycles measuring the ϕ -meson excitation curve were performed over the energy range 1014-1026 MeV. The luminosity integral was $L = 4 \times 10^{34}$ cm^{-2}.

In the experiment the decay mode $\phi \to K_L + K_S$ was detected by 2 charged pions produced in the decay $K_S \to \pi^+ \pi^-$. The experimental data and optimized curve are shown in Fig. 9. The corresponding value of the ϕ -meson mass 1019.48 ± 0.13 MeV with the data of other experiments is shown in Fig. 10; the accuracy was 2 times better than the world-average. The same method of beam energy calibration was used to measure the sum of K^+ and K^- masses /34/. In this experiment positrons were polarized at 650 MeV, then the energy was decreased to 509 MeV and at constant parameters the beam was kept for an hour (for complete stabilization of all thermal regimes). Then the depolarizer RF-field of small height was switched on, its frequency was slowly changed, and by the jump in the counting rate of positrons scattered inside a bunch the spin precession frequency was determined, and respectively, the absolute positron energy was obtained with an accuracy of the order 2 x 10^{-5}. After the injection of an electron bunch a nuclear-emulsion chamber was exposed. The resulting accuracy of the $K^{+}+K^{-}$ mass determination was about 80 KeV (2 times better than the world-average). The decay mode $\phi \rightarrow K^{+}+K^{-}$ was detected in the nuclear emulsion precalibrated by monochromatic protons which enabled determination of the kaon kinetic energy with an accuracy 40 KeV.

The identity of the particle and antiparticle properties was checked with high accuracy by the comparison of the anomalous magnetic moments of electrons and positrons and simultaneous measurement of their precession frequencies (both particles being moved along the same equilibrium orbit in the storage ring magnetic field) /35/.

The experiment was carried out at E = 625 MeV at the same time using electron and positron beams. After the doubled period of the polarization time a small height depolarizer field was switched on and its frequency was slowly varied. The jump in the counting rate of the scattered e^{+} and e^{-} (inside the bunch) gave their precession frequencies. The comparison of these frequencies provides that of the electron and positron anomalous magnetic moments. These moments were shown to be equal an accuracy not worse than 1.10^{-5}, two orders better than the accuracy of other experiments on measuring the anomalous magnetic moment of a positron.

To demonstrate an actual resolution of the method, the electron and positron energies were slightly separated by a radial electric field. From the measurements it can easily be seen that the precession frequencies were also separated by an expected value.

In conclusion, it can be said that the extent field of applications known, designing new storage rings, to take into account the necessity to have good conditions for the generation, control and using of radiative polarization.

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Captions to Figures

Fig. 1a. Production of longitudinal polarization. Variant 1.

Fig. 1b. Production of longitudinal polarization. Variant 2.

Fig. 2. Production of longitudinal polarizated colliding beams of opposite helicity.

Fig. 3. The scheme of spin flip by 180° in a straight section around the radial direction with particle velocity restoration.

Fig. 4. The counting rate of elastic scattering events in a bunch versus the depolarizer frequency.

Fig. 5. The jump in the counting rate during depolarization versus time from the beginning of a polarization cycle.

Fig. 6. Calculation of depolarizing resonances.

Fig. 7. Depolarization at the resonance $\nu = \nu_2 - 2$

Fig. 8. Azimuthal anisotropy of $K^{\pm}$-mesons produced with polarized beams.

Fig. 9. Excitation curve of the ϕ -meson.

Fig. 10. World values of the ϕ -meson mass.

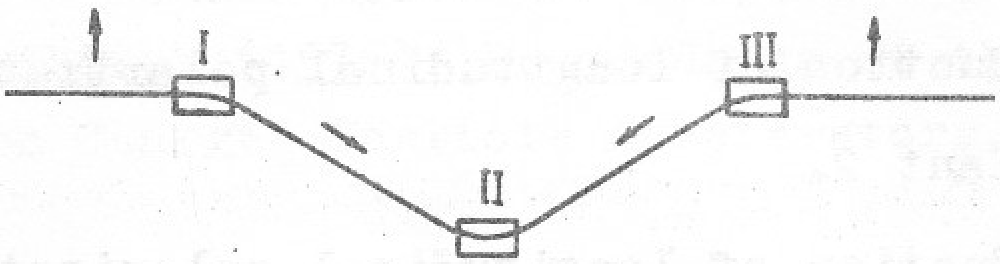


Fig. 1a

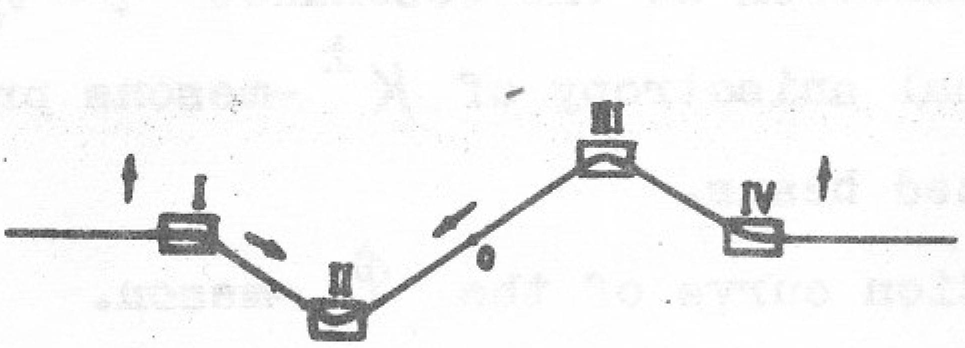


Fig.1b

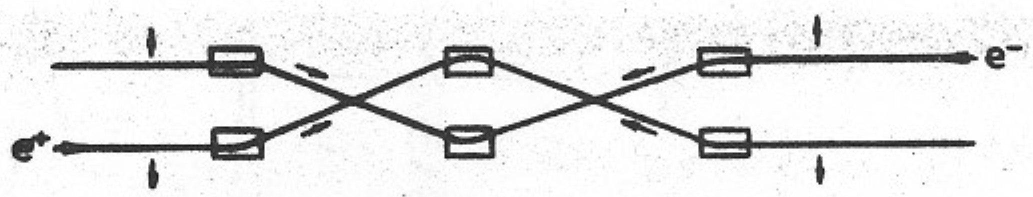
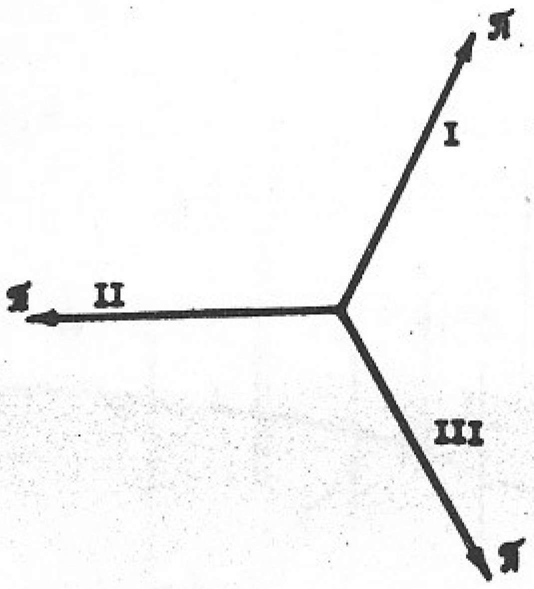


Fig. 2



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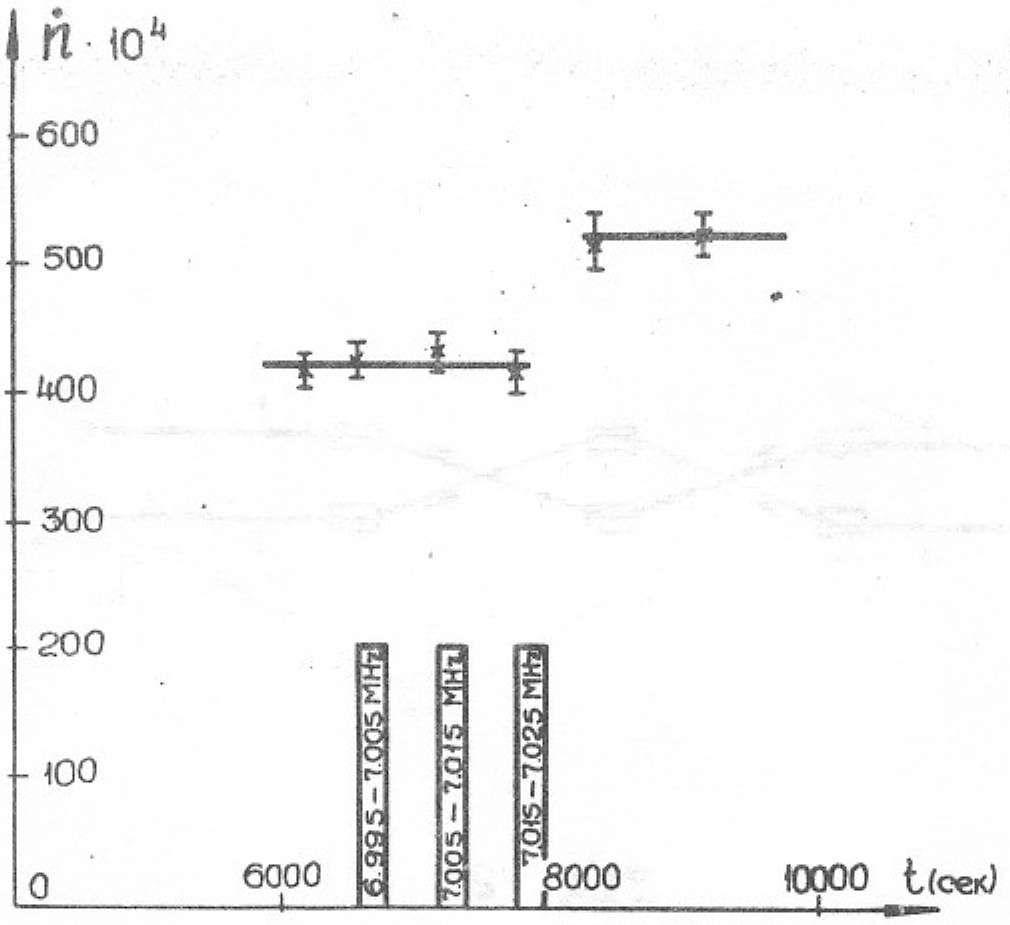
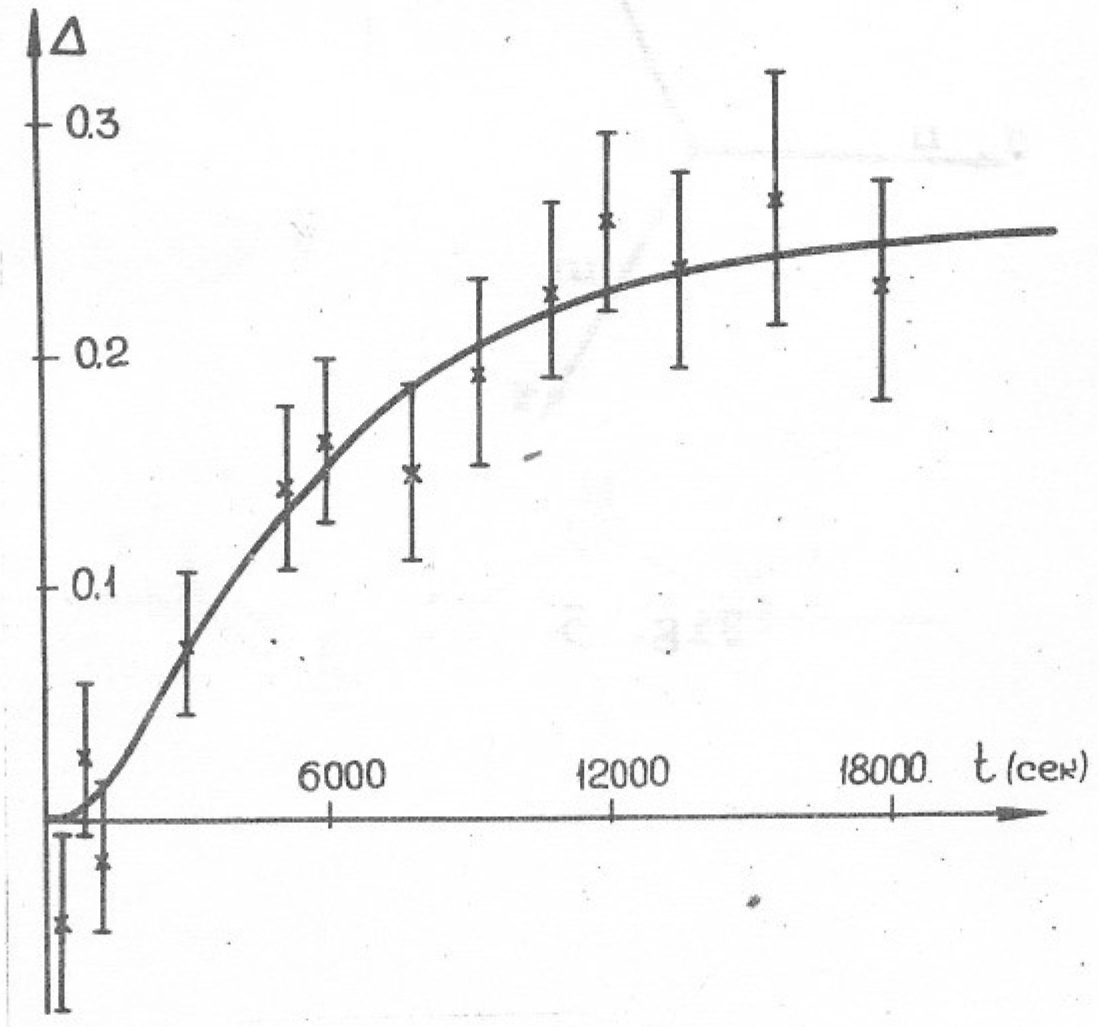

ṅ · 10⁴
600
500
400
300
200
100
0
6000
8000
10000
t (сек)
6.995 – 7.005 MHz
7.005 – 7.015 MHz
7.015 – 7.025 MHz

Fig. 4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0.1
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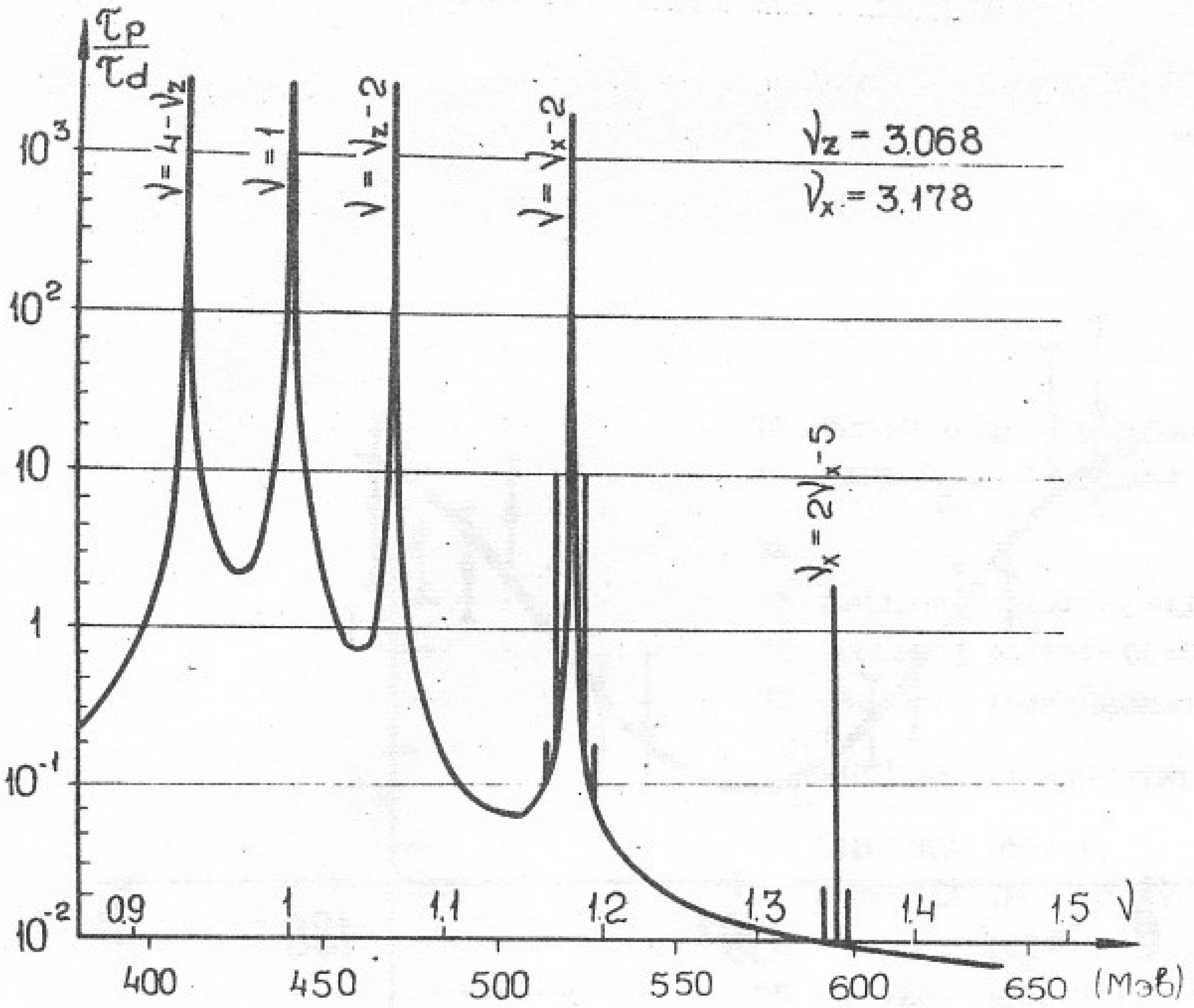
12000
18000
t (сек)

Fig. 5


$\frac{\tau_p}{\tau_d}$
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10^2
10
1
10^{-1}
10^{-2}
$\nu = 4-\nu_z$
$\nu = 1$
$\nu = \nu_z - 2$
$\nu = \nu_x - 2$
$\nu_z = 3.068$
$\nu_x = 3.178$
$\nu_x = 2\nu_x - 5$
0.9
1
1.1
1.2
1.3
1.4
1.5
ν
400
450
500
550
600
650
(Мэв)

Fig. 6

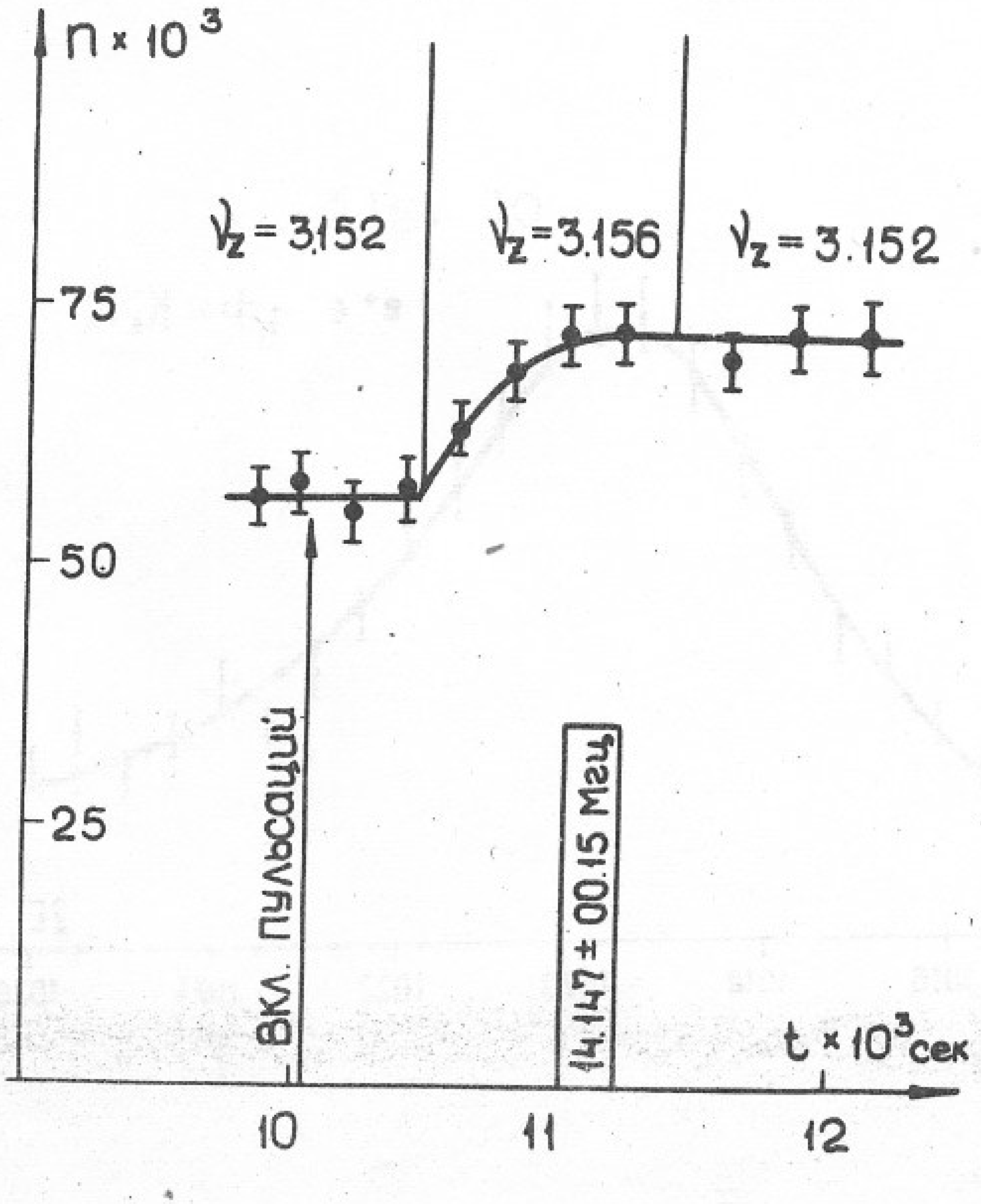

$n \times 10^3$
$\nu_z = 3.152$
$\nu_z = 3.156$
$\nu_z = 3.152$
75
50
25
ВКЛ. ПУЛЬСАЦИЙ
14.147 ± 00.15 Мгц
$t \times 10^3$ сек
10
11
12

Fig. 7

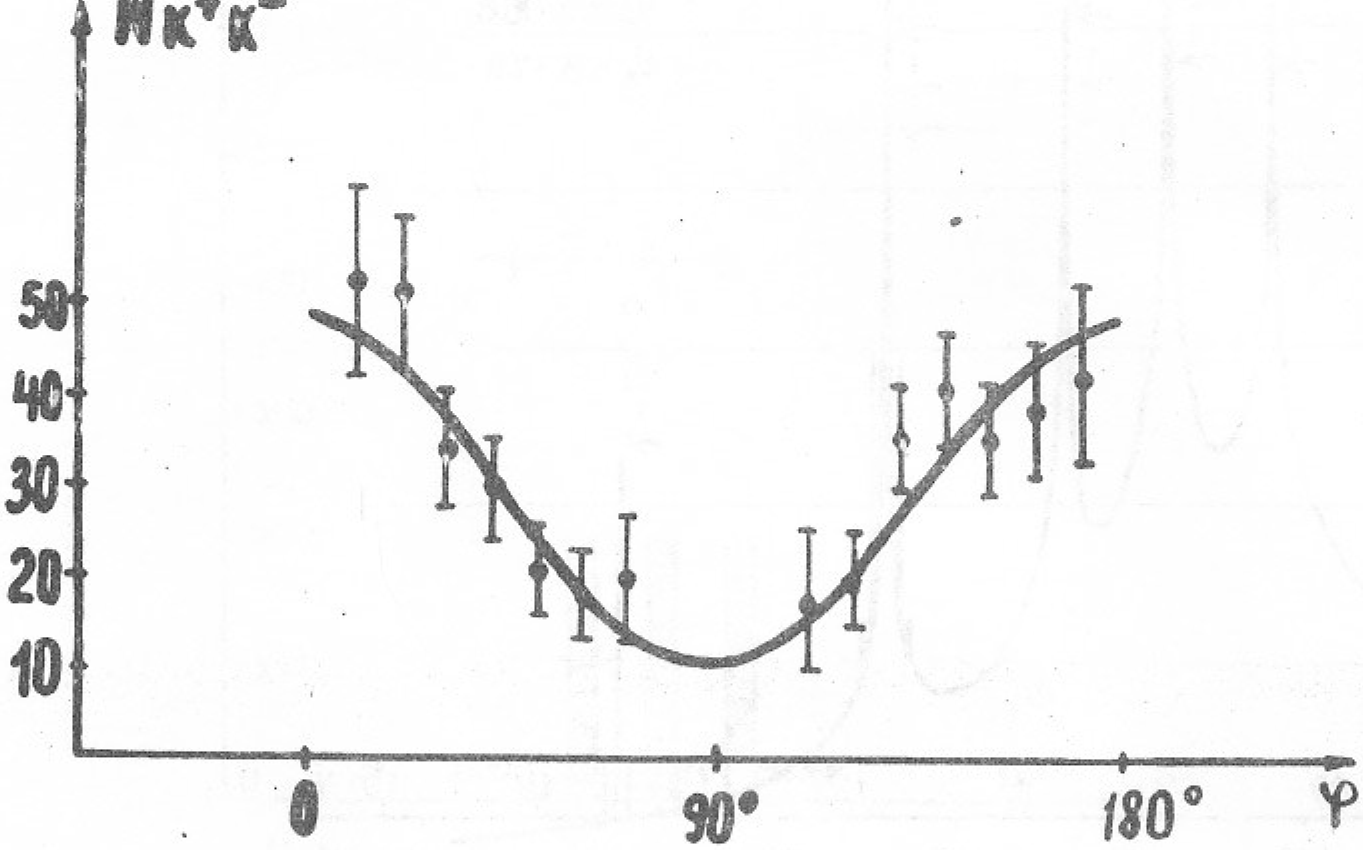
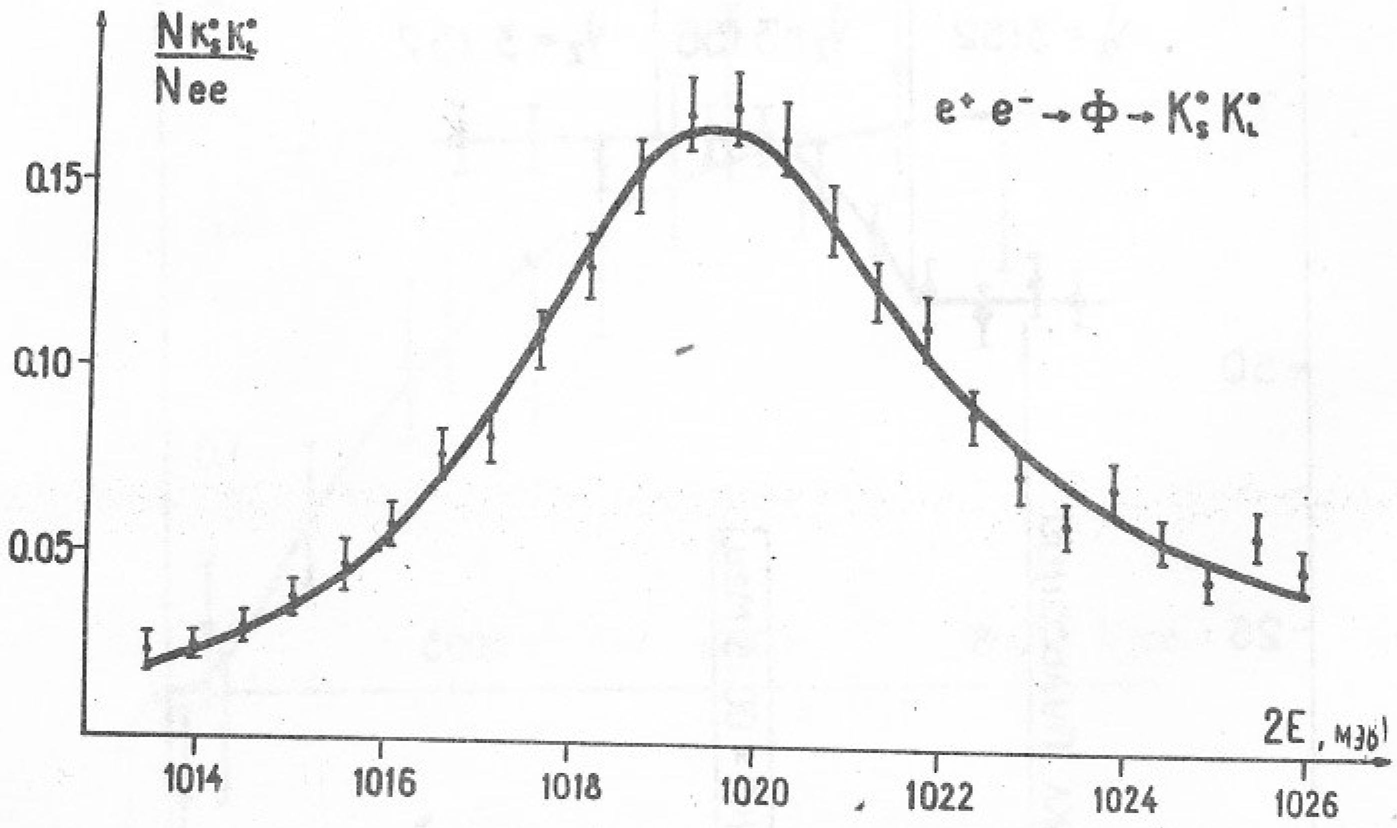

N K+K-
50
40
30
20
10
0
90°
180°
φ

Fig. 8


NK°sK°L / Nee
e+ e- → Φ → K°s K°L
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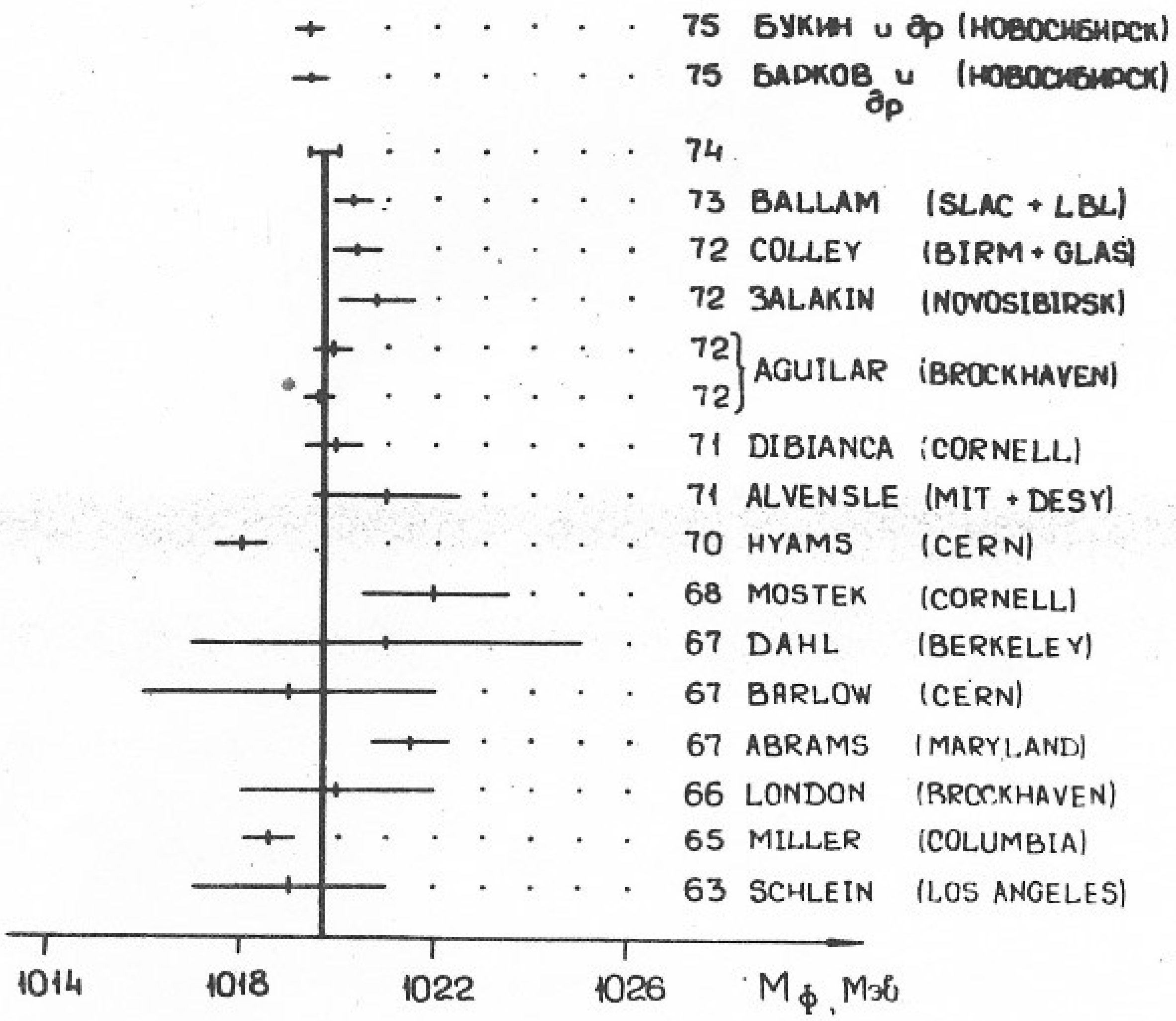
0.10
0.05
2E, мэв
1014
1016
1018
1020
1022
1024
1026

Fig. 9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75 БАРКОВ и др (НОВОСИБИРСК)
74
73 BALLAM (SLAC + LBL)
72 COLLEY (BIRM + GLAS)
72 3ALAKIN (NOVOSIBIRSK)
72
72
AGUILAR (BROCKHAVEN)
71 DIBIANCA (CORNELL)
71 ALVENSLE (MIT + DESY)
70 HYAMS (CERN)
68 MOSTEK (CORNELL)
67 DAHL (BERKELEY)
67 BARLOW (CERN)
67 ABRAMS (MARYLAND)
66 LONDON (BROCKHAVEN)
65 MILLER (COLUMBIA)
63 SCHLEIN (LOS ANGELES)
1014
1018
1022
1026
M_ϕ, Мэв

Fig. 10

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