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L.M.Kurdadze, S.I.Serednyakov, V.A.Sidorov, A.N.Skrinsky, G.M.Tumaikin, Yu.M.Shatunov

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A B S T R A C T

The radiative polarization of the beams has been studied experimentally with the electron-positron storage ring VEPP-2M. The polarization of one beam was measured by the variation in the counting rate of particles scattered inside a bunch (Touschek effect) during the resonance depolarization by an external electromagnetic field. The obtained experimental values of the time and degree of polarization are in good agreement with theoretical predictions. Depolarizing factors are considered. The possibility is shown to pass the energy range of the beam 500-650 Mev without polarization destruction. Measurement of the muon azimuthal anisotropy in the reaction $e^+e^- \to \mu^+\mu^-$ proves the conservation of polarization in the interaction of colliding electron-positron beams.

It is known /1,2/ that during the prolonged motion in the magnetic field electrons and positrons can be polarized due to radiation of photons if no depolarization factors are present. In simple cases the polarization degree tends to the limiting value

$$\zeta_0 = \frac{8}{5\sqrt{3}} = 0.924$$

according to the law

$$\zeta = \zeta_0 (1 - e^{-\frac{t}{\tau_p}}) \qquad (1)$$

with a characteristic time

$$\tau_p = \left[\frac{5\sqrt{3}}{8} \frac{me^2c}{\hbar^2} \gamma^2 \left(\frac{H}{H_0} \right)^3 \right]^{-1} \qquad (2)$$

where γ - relativistic factor, H - magnetic field value, $H_0 = 4.41 \times 10^{13}$ oersted.

For the majority of the electron-positron storage rings the polarization time can be less than the lifetime of circulating beams. Thus a possibility appears to obtain intensive beams of electrons and positrons with a high polarization degree allowing to expand considerably the range of experiments studying electromagnetic interactions with the colliding beams.

First measurements of the polarization of an electron beam in a storage ring have been performed in Novosibirsk in 1970 with the storage ring VEPP-2 /3/. This experiment gave evidence for the effect of radiative polarization. However because of the reconstruction of the VEPP-2 complex these experiments were stopped with the idea of their continuation in the new storage ring VEPP-2M /4/. Similar measurements have been carried out in 1972 in Orsay /5/.

I Depolarizing resonances

The problem of spin motion in a magnetic field has been considered by different authors (see, for instance, /6-7/). In the homogeneous field spin processes with a frequency

$$-\vec{W} = \left(\frac{q_0}{\gamma} + q' \right) \left(\vec{H}_x + \vec{H}_z \right) + \frac{q}{\gamma} \vec{H}_v \qquad (3)$$

where $\vec{H}_x, \vec{H}_z, \vec{H}_v$ - transverse and longitudinal components of the magnetic field $\vec{H}$ with respect to the velocity, q', q_0 - anomalous and normal parts of the magnetic moment q.

In the approximation of plane orbits ($H_v = H_x = 0$) all the particles in a polarized beam have constant in time spin projections on the direction H_z.

Under real conditions of the accelerators and storage rings small inhomogeneities of the field lead to a depolarization due to spread of particle trajectories. The depolarization is small unless the spin precession frequency is an integer multiple of some perturbation harmonics. If the resonance condition is fulfilled

$$\nu = n + m\nu_z + k\nu_x + \ell\nu_s \qquad (4)$$

where $\nu = \gamma \frac{q'}{q_0}$; ν_z, ν_x, ν_s - frequencies of vertical and radial betatron and synchrotron oscillations in units of the revolution frequency ω_s, the coherent rotation of spins occurs generally around the direction of the perturbative field H_n with a frequency $\omega_n = \omega_s \frac{H_n}{H_z}$.

Beyond the resonances the diffusion of an average spin value is possible due to stochastic jumps of energy and transverse momentum of the particle (scattering on the residual gas, quantum fluctuations of radiation etc.) /8-9/. The diffusion velocity is determined by the frequency shift from the nearest resonance as well as by the value of the corresponding perturbation harmonic, its influence being characterized by the ratio of the polarization and depolarization time τ_p / τ_d. The calculation of this quantity requires generally the knowledge of all the perturbations. However to estimate the power of depolarizing resonances it is sufficient to use a model where a short skew quadrupole giving the gradient $\frac{\partial H_x}{\partial x}$ is introduced into the magnetic structure of the storage ring. The results of the calculation for such a model are shown in Fig.1. The values of all perturbation harmonics $\left(\frac{\partial H_x}{\partial x}\right)_n$ are assumed to be identical and equal to the experimentally measured value of a zero harmonic $\left(\frac{\partial H_x}{\partial x}\right)_0 \approx 0.01 \frac{H_z}{R_0}$. Fig.1 shows that polarized beams can be obtained everywhere in the energy range from 500 up to 670 Mev excluding narrow resonance bands which can be shifted easily by choice of operating frequencies of betatron oscillations.

II Experiments with one beam. Depolarizer

Similarly to the first experiments with VEPP-2 to measure the degree of electron polarization a method was chosen using the polarization dependence of the cross section of particle elastic scattering inside a bunch (Touschek effect) /10/. In the bunch frame of reference particles undergo scattering in the collisions caused by transverse oscillations, so that a part of the transverse momentum transforms into the longitudinal one. In the laboratory frame the relativistic transformation increases the longitudinal momentum by a factor of γ. Thus after scattering two particles have momenta differing by $\pm \Delta P$ from the equilibrium one and can be separated by the magnetic field of the storage ring to the different sides from the equilibrium orbit and somehow be detected.

The polarization contribution to the counting rate of such events is characterized by the ratio

$$\Delta = \Delta_{max} \zeta^2 = \frac{N_0 - N_p}{N_0}$$

where N_0, N_p - counting rates for the nonpolarized and polarized beam normalized to the square of a circulating current.

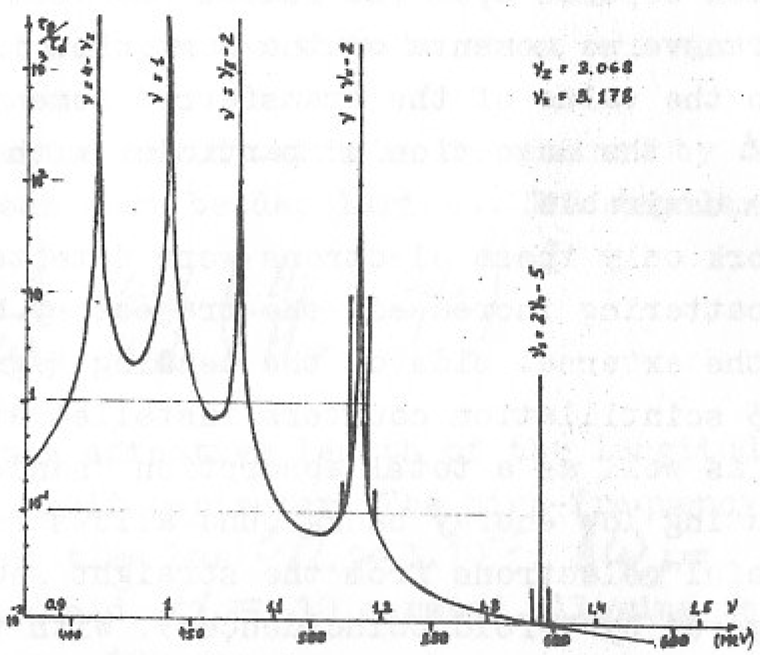

Fig.1 Estimate of depolarizing resonance power in terms of the ratio of polarization and depolarization time.

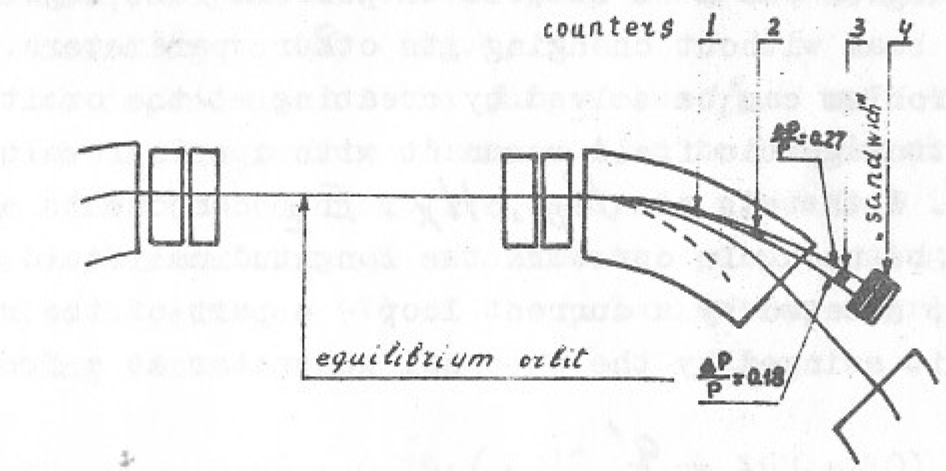

Fig.2 Layout of counters for detection of electrons scattered inside a bunch (Touschek effect).

This contribution depends upon the radial and vertical components of the transverse momenta of the particles in the bunch as well as upon the value of the transferred momentum Δp. To increase Δ the detection of particles with high momentum transfer is desirable.

In this work only those electrons were detected whose energy after scattering increased, the trajectory being correspondingly in the external side of the bending magnet (Fig.2). The system of 3 scintillation counters installed at the computed trajectory as well as a total absorption "sandwich" counter for eliminating low energy background allows reliable detection of "useful" electrons from the straight section (the system is triggered by 4-fold coincidences). With the account of the Gaussian distribution of radial and vertical transverse momenta for the particles with an energy in the range 1.18-1.27 of an equilibrium value E = 625 Mev the following computing values have been obtained:

$$\Delta_{max} = 0.30 \qquad N_0 = 0.05$$

Experimental counting rate is N_0 = 0.04. This value depends strongly on the orbit position and beam sizes which can change during the experiment. Thus for reliable measurement of the polarization degree one must be able to perform fast depolarization of the beam without changing its other parameters.

Such a problem can be solved by creating at the orbit the variable electromagnetic field resonant with a spin revolution frequency /4/. With this aim H_v, H_x, E_z components of the field can be used. In our work the longitudinal field has been employed, created by a current loop - a part of the resonance circuit swinged by the external generator at a frequency

$$\omega_d = \omega_0 \left(\gamma \frac{q'}{q_0} - 1 \right) \qquad (5)$$

The absolute value of the energy of beam particles is known with insufficient accuracy, thus use of frequency modulated high-frequency field is reasonable. The modulation

depth $\Delta\omega_d$ is chosen so that to cover all the range of energy inaccuracy.

The magnetic field value is determined by the time during which the beam must be depolarized. The depolarization time

$$\tau_d = \frac{1}{\omega_s} \frac{\Delta\omega_d}{\omega_d} \left(\frac{H_z}{H_v} \frac{2L}{\ell} \right)^{-2}$$

where ℓ - the effective length of the longitudinal magnetic field, L - orbit perimeter. The high-frequency system used at the present time has $\ell/L \simeq 3.10^{-3}$, $\Delta\omega_d = 2$ x 100 kc and the magnetic field H = 10 oersted allowing to depolarize the beam for $\sim$ 100 sec.

The polarization degree was measured in the following manner. In each measurement cycle the electron current $I \approx$ 30 mA was retained at definite energy for some time. The counting rate N_p normalized to I^2 was measured, then the depolarizer was switched on for 100 sec, the counting rate being measured once more after its switching off. Fig.3 presents velocity dependence upon the depolarizer frequency. One can see that after the depolarizer work the counting rate jumps up at a definite frequency. At other values of the beam energy the depolarizer frequency at which the jump in counting rate occurs varies according to (5) (Fig.4).

The dependence of the jump value Δ upon the time passed from the beginning of the run up to the depolarizer switching on at the resonant frequency is presented in Fig.5. The curve was drawn through experimental points using the analytical time dependence (1) of the polarization degree with the following parameters

$$\zeta_{max} = 0.92 \pm 0.15; \qquad \tau_p = (68 \pm 10)$$

The error of ζ_{max} is determined primarily by the accuracy of measurement of rms transverse momenta in the beam σ_{p_x}, σ_{p_z} as well as by the value of the momentum transfer $\Delta p/p$ which are used in the calculation of the coefficient Δ_{max}. Both experimentally measured quantities are consistent with theore-

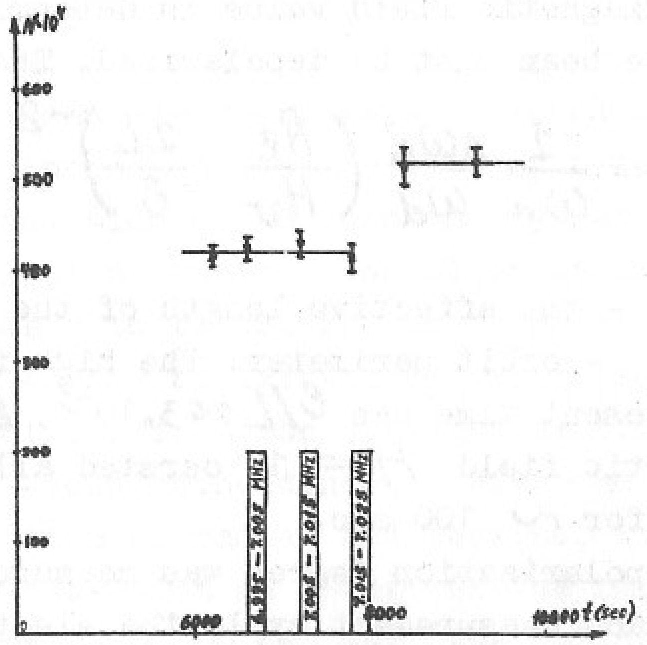

Fig.3 Relative variation of the counting rate versus depolarizer frequency.

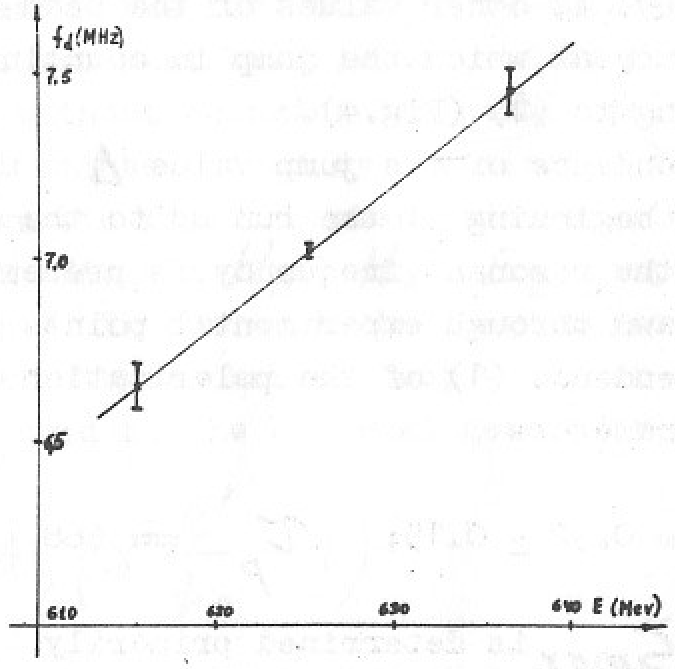

Fig.4 Resonant depolarization frequency versus beam energy.

tical values $\zeta_0 = 0.924$, τ_p = 72 min, providing evidence against considerable depolarizing factors at the energy E = 625 Mev.

Besides that it was shown that polarization was not violated during the energy variation from 650 to 500 Mev and back for the time $\sim$ 100 sec. Crossing spin resonances $\nu = \nu_x - 2$ and $\nu = \nu_z - 2$ doesn't lead to notable depolarization not contradicting to the estimates (Fig.1).

III Polarization of colliding beams

Depolarizing influence of a colliding beam has been analyzed in /11/. It is shown that beyond depolarizing resonances (4) the radiative polarization is conserved if interaction of the colliding beams (beam-beam effects) is small, i.e. if the condition of their existence is fulfilled.

To observe polarization of electron-positron colliding beams an experiment has been performed to measure azimuthal anisotropy of muons in the reaction $e^+e^- \to \mu^+\mu^-$.

The differential cross-section for the reaction $e^+e^- \to \mu^+\mu^-$ with the account of polarization has the following form

$$\frac{d\sigma_{\mu\mu}}{d\Omega} = \frac{r_0^2}{16\gamma^2}\beta\left\{2 - \beta_\mu^2 \sin^2\theta\left[1 + \zeta^+\zeta^-(2\sin^2\varphi - 1)\right]\right\}$$

where θ - a polar angle with a polar axis along the direction of the beam, φ - an azimuthal angle measured from the median plane, ζ^- and ζ^+ - polarization degrees of the electron and positron beam respectively. The azimuthal anisotropy of this distribution is quite considerable, for instance for complete polarization $\zeta^+ = \zeta^- = 1$:

$$\frac{d\sigma_{\mu\mu}}{d\Omega}\left(\theta = \frac{\pi}{2}, \varphi = \frac{\pi}{2}\right) = 0 \qquad \frac{d\sigma_{\mu\mu}}{d\Omega}\left(\theta = \frac{\pi}{2}, \varphi = 0\right) = 2\frac{d\sigma_{\mu\mu}}{d\Omega}$$

The experiment was performed at the beam energy 2E = 1300 Mev. Measurements began when the currents $I^{\pm} \simeq 15$ mA

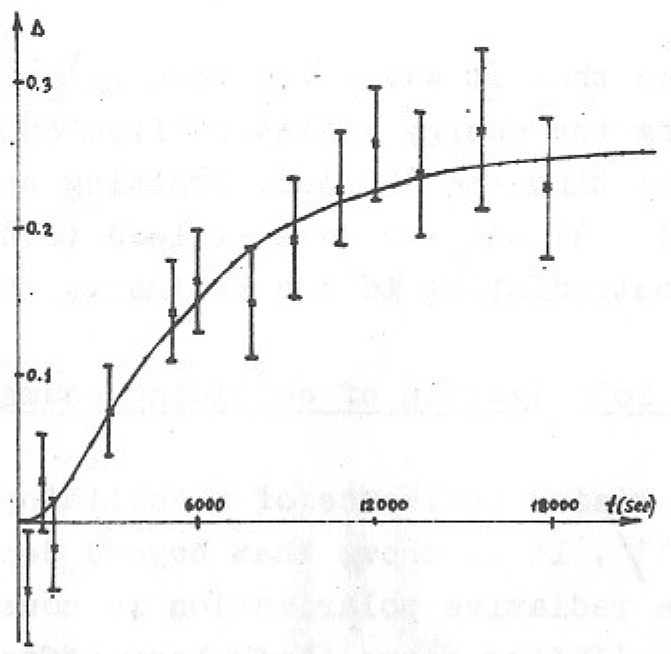

Fig.5 Time dependence of the jump value Δ.

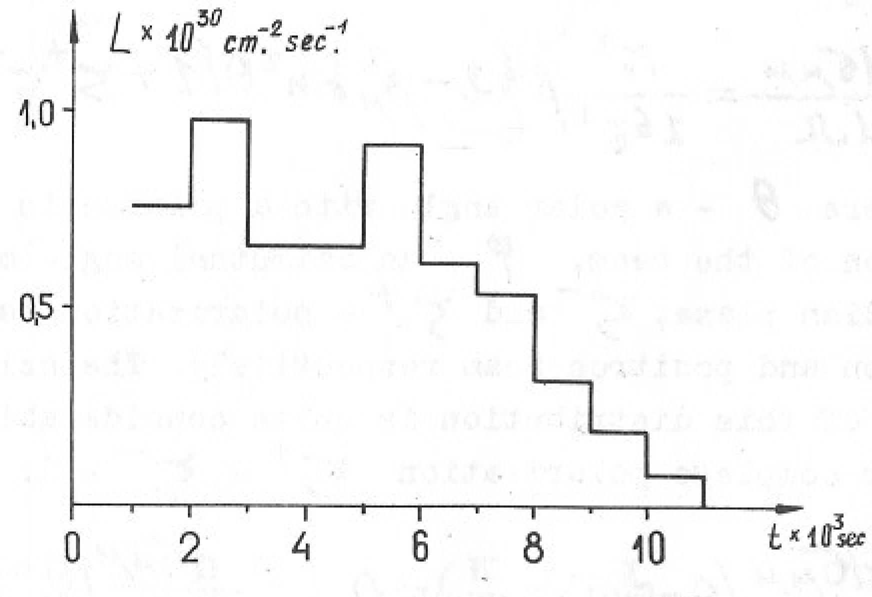

Fig.6 Distribution of total luminosity (over 8 runs) with time of beam circulation.

and $I \simeq$ 18 mA have been stored. To increase the beam lifetime the storage ring regime was chosen so that the operating betatron frequencies corresponded to the coupling resonance $\nu_z = \nu_x$ (round beams). Under these conditions maximal luminosity was equal to 2.10^{29} $cm^{-2}sec^{-1}$. When the luminosity decreased to $0.5 \cdot 10^{29}$ $cm^{-2}sec^{-1}$ the regime was returned to the operating point with small beam cross section, the luminosity increased and measurements were continued.

8 measurement runs were performed. Fig.6 presents the distribution of the total luminosity (over 8 runs) with the time of beam circulation in the storage ring.

For detection of muon pairs the "Olya" detector has been used /12/. Detector "Olya" contains 16 coordinate wire spark chambers with core memory ($\simeq$ 10.000 ferrites), 16 triggering scintillation counters composing 8 sandwiches for identification of the particle type.

To suppress the cosmic ray background time-of-flight and phase synchronization circuits were used for detector triggering. The total solid angle covered by the detector was $0.65 \times 4\pi$ steradian.

Control of the detector working regime, data accumulation and primary data processing were performed by a minicomputer M-6000 in the detector control room. The minicomputer was in turn connected with a universal computer "Minsk-32" whose magnetic tapes accumulated the data.

Quantitative characteristics of the experiment are given in the Table.

	Effect	Background
Time of the experiment, 10^3 sec	69	240
Number of detection system triggerings, 10^3	58	2.3
Luminosity integral, 10^{33} cm^{-2}	6.7	-
Number of elastic scattering events	3049	-
Computed number of the events $e^+e^- \to \mu^+\mu^-$	168 ± 3.0	-
Detected number of the events $e^+e^- \to \mu^+\mu^-$	178 ± 15	2

At the first stage of the analysis collinear tracks ($|\Delta\varphi| < 3^\circ$, $|\Delta\theta| < 4^\circ$) intersecting the collision point have been selected corresponding to two-particle processes of elastic scattering and meson pair production.

Further division of events into electrons and mesons was carried out using the amplitudes of sandwich counters. Fig.7 shows the spectrum of amplitude sums in sandwiches for collinear events. The vertical line corresponds to the boundary of electron-meson division. Elastic scattering events were used for normalization of the reaction under investigation.

Small admixture of pions was separated by nuclear absorption in the material of sandwiches (the total thickness for two particles of the pair was 104 g/cm^2). The additional error to the number of muons due to inaccurate knowledge of pion nuclear absorption was about 10%, i.e. less than a statistical error. The Table presents the experimental and computed (by QED) number of muons.

For the investigated process background consisted of cosmic particles triggering the detector. Background measurements were performed without the beams. Due to switching off the phase synchronization circuit the effective time of background measurements was by a factor of 40 greater than the real time.

The azimuthal anisotropy was quantitatively characterized by a parameter

$$\lambda = \frac{N_v - N_h}{N_v + N_h}$$

where N_v - the number of "vertical" muons ($45^\circ < \varphi < 135^\circ$), N_h - the number of "horizontal" muons ($-45^\circ < \varphi < +45^\circ$).

Fig.8 shows experimental and computed values of λ versus measurement time. Effect of beam polarization is seen clearly.

An additional proof of polarization conservation in the presence of the colliding beam was provided by measurement of electron beam polarization (by Touschek effect) in the presence of the positron beam at the end of one experimental run.

Thus, the possibility is proved to perform experiments with polarized colliding beams of electrons and positrons.

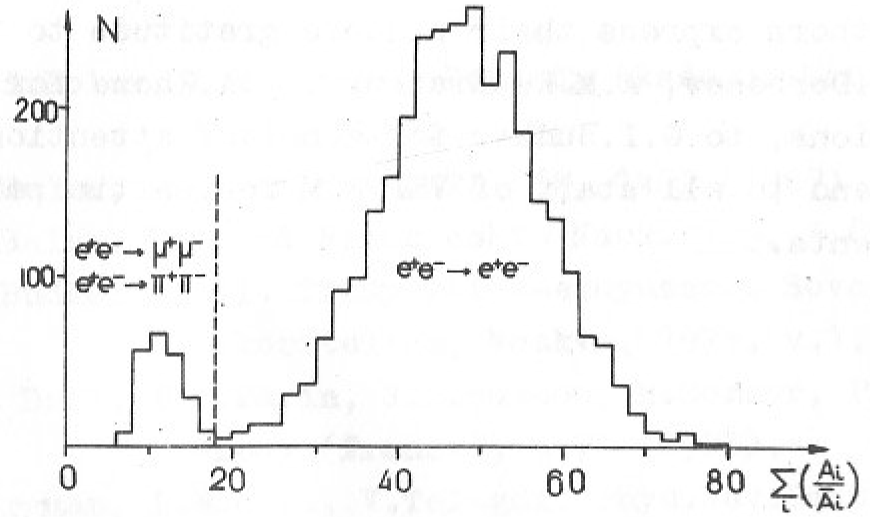

Fig.7 Spectrum of amplitude sums of sandwiches for collinear events.

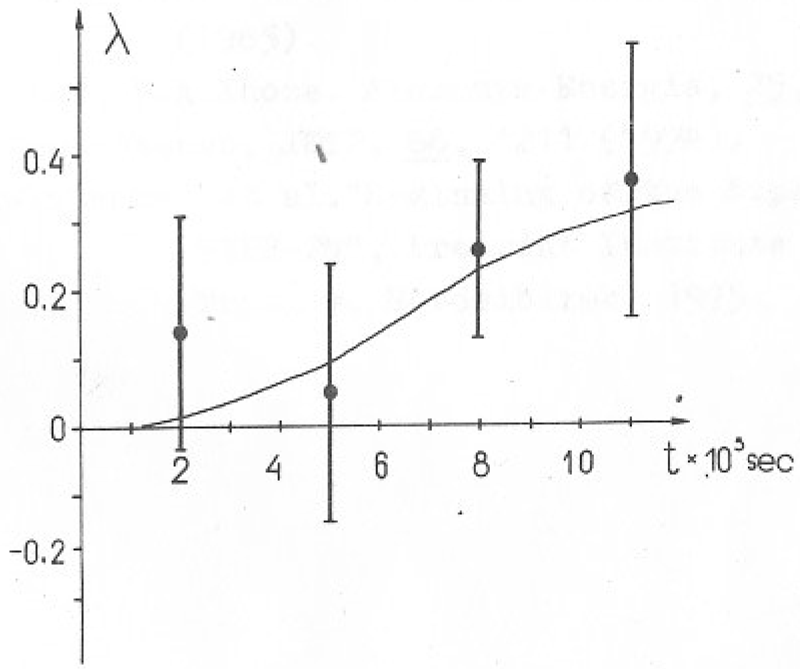

Fig.8 Experimental and computed values of λ.

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