ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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INVESTIGATION OF THE ELECTROMAGNETIC CALORIMETER BASED ON LIQUID KRYPTON

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НОВОСИБИРСК

Investigation of the Electromagnetic Calorimeter based on Liquid Krypton

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ABSTRACT

Effects determining the energy and spatial resolution of a calorimeter based on liquid krypton have been studied. By read-out from the cathode strips of 10 mm width the spatial resolution of 0.4 mm was obtained with cosmic rays. The energy resolution of the calorimeter (0.4 tons of krypton) has been measured with positrons. The energy resolution (rms) of 5.7% at $E=130$ MeV and 1.7% at $E=1200$ MeV was achieved. The measurements are compared to Monte-Carlo simulations.

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1. INTRODUCTION

An electromagnetic calorimeter based on 35 tons of liquid krypton [1] is developed for the KEDR detector [2] which will be used at the e^+e^--collider VEPP-4M with the maximum beam energy of 6 GeV. Use of LKr is attractive due to possibility to obtain a good energy resolution (the same, as with NaI and CsI calorimeters) and better spatial resolution for the photons. The possibility to obtain the better spatial resolution is due to fine granularity which can be simply realized in LKr calorimeter. In this case it is possibly to measure the photon conversion point in contrast to crystal calorimeters, where the photon position is determined by the shower center of gravity.

A longitudinal segmentation of LKr calorimeter provides important information for the particle identification.

Main effects, determining the energy and spatial resolution of the LKr calorimeter, have been studied by a Monte-Carlo simulation. A small prototype (7 kg of LKr) and prototype with 0.4 tons of LKr have been built to measure the spatial and energy resolution. The measurements are compared to Monte-Carlo simulation.

2. MAIN PROPERTIES OF LIQUID KRYPTON

Main parameters of liquid krypton as detector media for the calorimeters, compared to other materials, are presented in Tables 1 and 2.

Table 1

Properties of the materials for calorimeters

	NaI(Tl)	CsI(Tl)	BGO	BaF_2	LAr	LKr	LXe
Density, g/cm^3	3.67	4.53	7.13	4.88	1.40	2.45	3.06
Radiation length, cm	2.59	1.85	1.12	2.03	13.5	4.60	2.77
Moliere radius, cm	4.31	3.76	2.70	—	10.0	6.66	5.71
Nucl. interaction length, cm	41	84	22	30	84	60	55
$(dE/dX)_{min}$, MeV/cm	4.85	5.60	9.20	—	2.31	3.45	3.89
Radiation resistance	satis.	satis.	satis.	good	fine	fine	fine

Table 2

Physical properties of LAr, LKr and LXe

	LAr	LKr	LXe
Atomic number Z	18	36	54
Atomic mass A	40	84	131
T (boiling), K	87.1	119.6	164.9
T (melting), K	83.6	115.8	161.2
ρ_{liquid}/ρ_{gas}	784	641	519
V_e, mm/μs *) at 1(5) kV/cm	1.8(3.0)	2.4(4.0)	2.2(2.7)
W, eV pair	24.4	20.5	15.6

*) data from Ref. [3].

The radiation length of LKr is equal to 4.6 cm and required longitudinal size of a LKr electromagnetic calorimeter is about 70 cm for the energy $E_\gamma \leqslant 5$ GeV.

Krypton is radioactive due to the β-decay of Kr^{85} isotope. A maximum energy of electrons is 0.67 MeV, an average energy is

0.25 MeV and half decay time is 11 years. Our measurement of the radioactivity with several samples of industrial krypton showed, that 300 β-decays/sec occur in 1 cm^3 of LKr in agreement with measurements performed by P. Lebedev and A. Bolozdynya (privite communications).

Industrial krypton is sufficiently pure (contamination of the electronegative impurities is below 10^{-7}), so that no further purification is needed.

3. POSITION RESOLUTION FOR MINIMUM IONISING PARTICLES

3.1. Calculation of Spatial Resolution

In the ionization chambers the charge distribution at the cathode and anode has some peculiarities which depends on many parameters. For simplicity let's consider a case, when a particle moves perpendiculary to the plane of electrodes and produces uniform ionization. In this case the time dependence of the current is

$$I(t) = (Q_0/T_d)(1 - t/T_d)$$

where Q_0 is a produced charge, T_d is total drift time of electrons in the gap. To obtain the current distribution $i(x, t)$ over coordinate at the electrode, it is convinient to use the formula from Ref. [4] for the distribution of the linear density of charges induced at the electrode by a point charge. Signal distribution $Q(x)$ over coordinate at the elecrode can be obtained by integrating the current $i(x, T)$ over time. The shape of the signal distribution on the electrodes depends on the integrating time τ_i.

In the case of total charge collection ($\tau_i \gg T_d$) the distribution of the charge at the anode is strongly peaked with opposite sign «tails». The distribution at the cathode is less peaked with the «tails» of the same sign.

Charge distribution at the anode (A) and cathode (C) strips with a width (S) of 10 mm and with chamber gap (d) of 10 mm is shown in Fig. 1 as a function of the track distance from the strip centre.

In the simplest case, when a charge of one sign only is measured at the anode, the coordinate is determined by strip number and the position resolution is $\sigma_x = S/\sqrt{12}$.

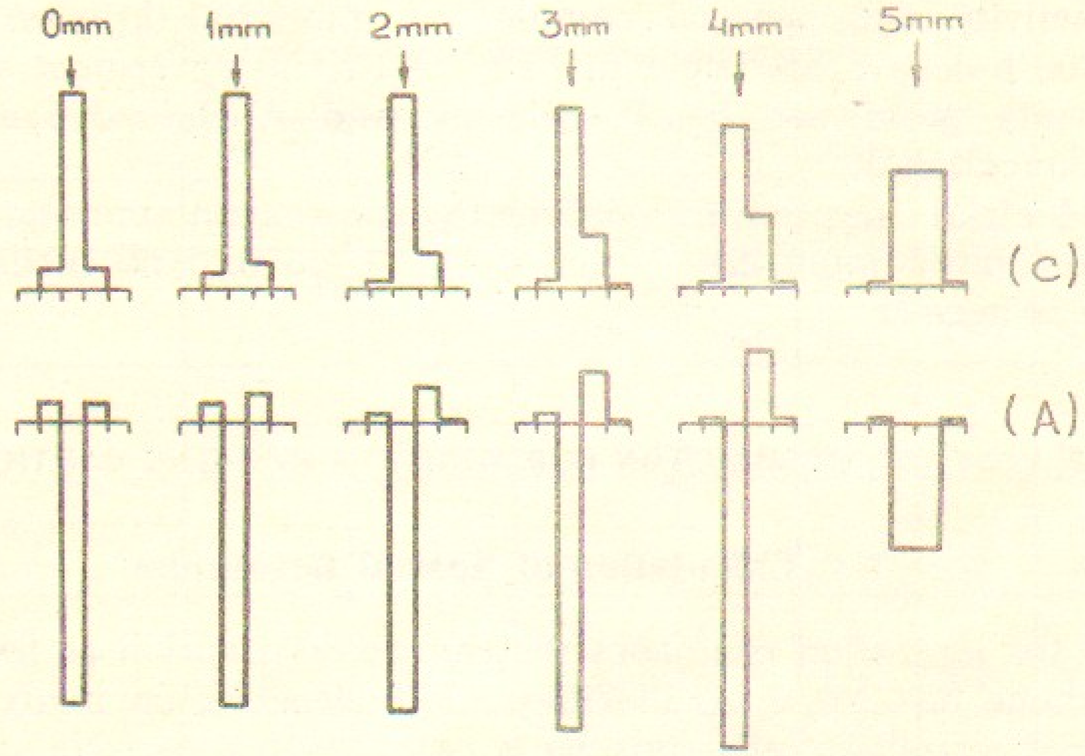

Fig. 1. The charge distribution at the cathode (*C*) and anode (*A*) for different track distance from the strip centre. The strip width is 10 mm and the gap is 10 mm.

Much better accuracy can be achieved if the strip charges at the cathode are measured. (In principle the same resolution one can obtain by anode read-out with bipolar ADC.) Since the distribution is narrow, main information is provided by 2-3 strips. In this case the track position can be determined by the charge centre of gravity. When the track is perpendicular to the plane of electrodes, the main contribution to the resolution comes from the electronics noise. One can show, that the accuracy of the centre of gravity determination is

$$\sigma^{(2)}_{x_c}=S\frac{\sigma_n}{A}\sqrt{1-2\frac{x_c}{d}\left(1-\frac{x_c}{d}\right)},\qquad \sigma^{(3)}_{x_c}=S\frac{\sigma_n}{A}\sqrt{2+3\left(\frac{x_c}{d}\right)^2}$$

for read-out from 2 and 3 strips respectively. Here x_c is the centre of gravity position, measured from the strip centre, d is the gap width, A is the total pulse height, σ_n is the electronics noise in each channel. If the signal to noise ratio $\sigma_n/A=50$ (what can be easily achieved in practice), one can obtain $\sigma_{x_c}\approx S/50=0.2$ mm.

The centre of gravity position sligtly differs from the particle coordinate due to discrete measurements. In Fig. 2 the centre of gravity coordinate measured by 2 and 3 strips is shown versus the

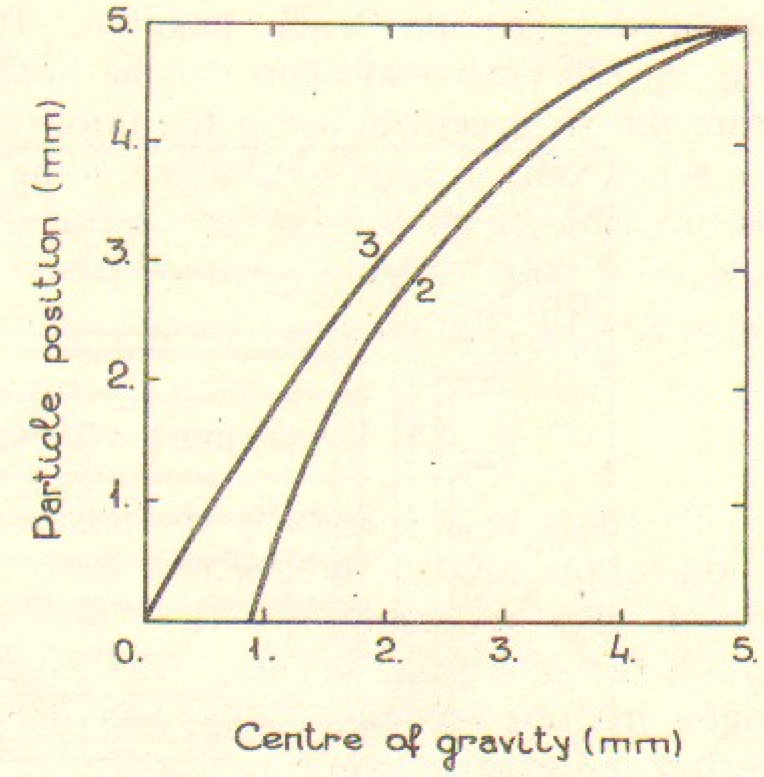

Fig. 2. The dependence of the coordinate of the centre of gravity on the real track position for read-out from 2 and 3 strips.

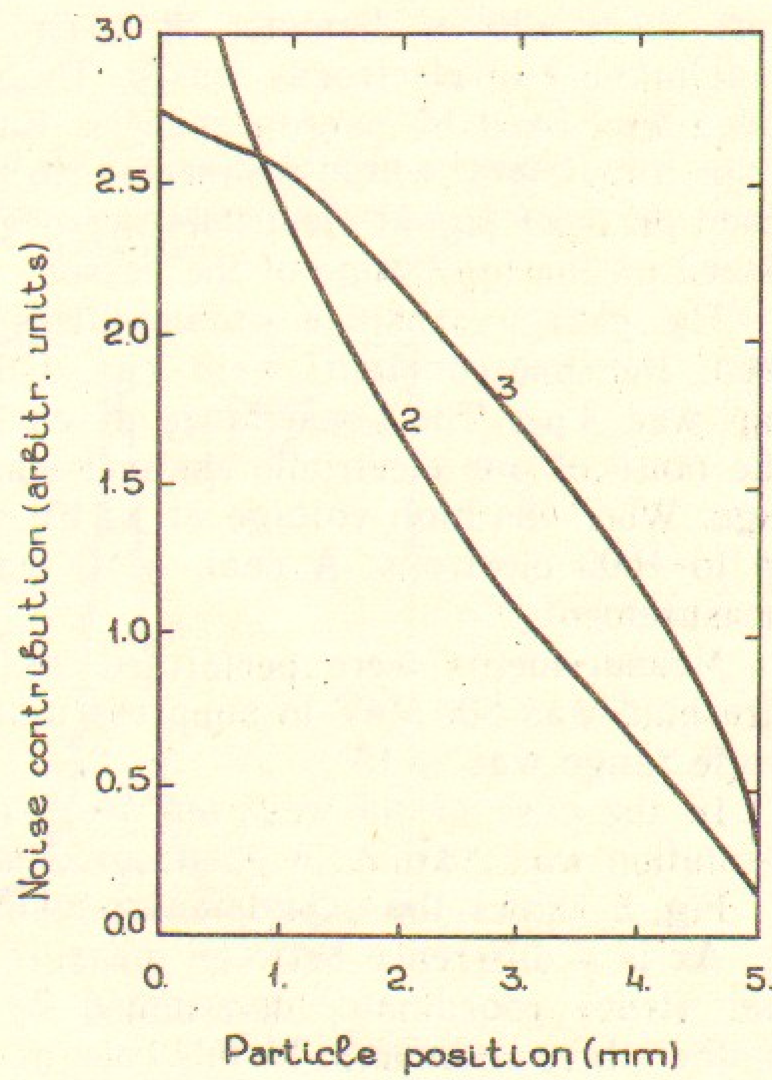

Fig. 3. The contribution of the noise to the spatial resolution versus track position for read-out from 2 and 3 strips.

real particle coordinate. The noise contribution to the position resolution depends on track position. This dependence is shown in Fig. 3. The best resolution can be obtained in the region 0.8—5 mm from the strip centre, using the information from two strips.

When only a small fraction of the charge is collected, ($\tau_i \ll T_d$) the distribution of the charge on the cathode and anode is very narrow and the spatial resolution is determined by strip width ($\sigma_x = S/\sqrt{12}$) for read-out from anode or cathode.

3.2. Experiment with Cosmic Muons

To study experimentally the position resolution, a prototype with 4 ionization LKr chambers has been built. Its lay-out is shown in Fig. 4. The total amount of LKr was about 7 kg. For thermostabilization the operating krypton was loaded in LKr bath. A liquid nitrogen in heat-exchange tube was used for cool down and cooling during the experiment.

Chamber electrodes, fabricated from foiled fiberglass plates, were discs with a diameter of 15 cm and a 1 mm thickness. The total number of electrodes was 9. The gap of 10 mm between electrodes was fixed by capron spacers. Each signal electrode had five strips of 10 mm width, connected to individual preamplifier. The other parts of signal electrodes were grounded. Preamplifiers were placed on the top flange of the vessel.

The charge sensitive preamplifiers with RC-CR shaping were used. The time constants were 3 μs, a drift time of electrons in LKr gap was 4 μs. The capacitance of each channel was about 50 pF. The noise of one electronic channel was 1000 electrons on the average. When the high voltage of 1.8 kV was supplied, the noise grew up to 1600 electrons. A peak ADC was used for the pulse height measurement.

Measurements were performed with cosmic muons. An energy threshold was 600 MeV to suppress multiple scattering. The covered angle range was ±15°.

In the case of the read-out from anode the measured position resolution was 2.8 mm, in good agreement with expected one. .

Fig. 5 shows the experimental result with read-out from cathode: Δx is a difference between measured coordinate in any chamber and «true» coordinate, determined by least-square method using another three chambers. In this case $\sigma_x = \mathrm{FWHM}/2.36 = 0.4$ mm.

The noise contribution, averaged over the pulse height spectrum,

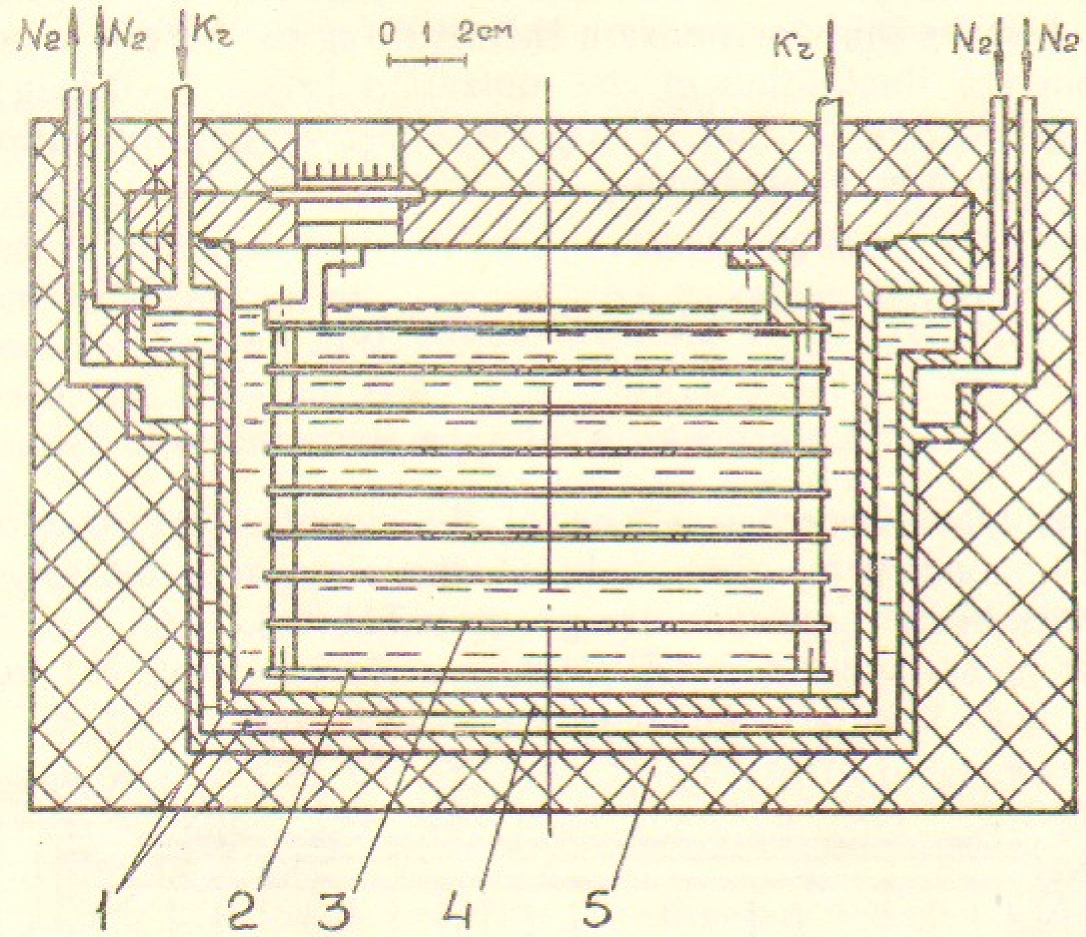

Fig. 4. A cross-section of the 7 kg liquid krypton prototype:
1 — liquid krypton; *2* — high voltage electrodes; *3* — Read-out electrodes; *4* — Stainless steel vessel; *5* — Plastic foam.

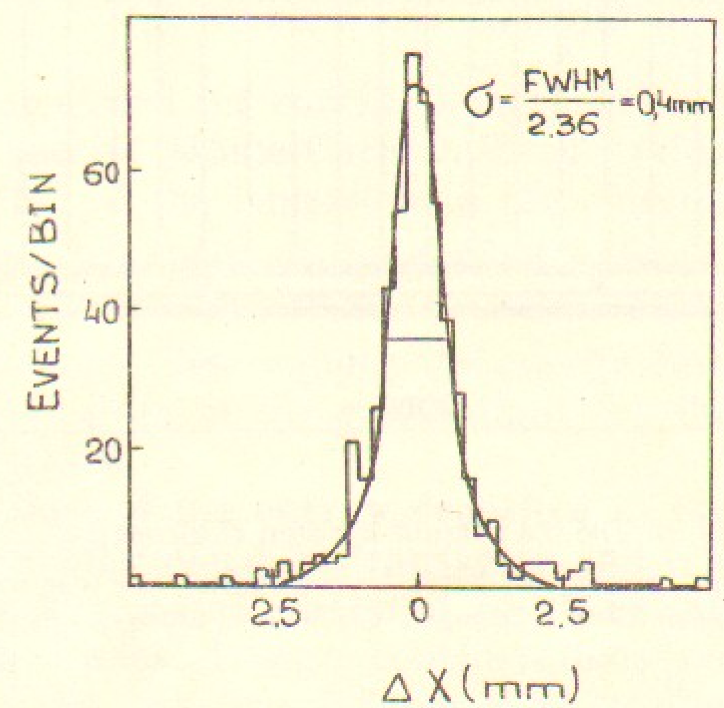

Fig. 5. The position resolution of LKr chamber measured with cosmic rays.

is equal to 0.3 mm, the contribution of the multiple scattering is 0.1 mm, besides that for nonzero incident angles there is a contribution from the fluctuation of the ionization losses ($\sim 0.7 \cdot \mathrm{tg}\,\theta$, mm) giving in average 0.1 mm. Thus, the experimental resolution is in agreement with estimated one.

4. ENERGY RESOLUTION

4.1. Calorimeter Prototype Construction

Fig. 6 shows a cross-section of the liquid krypton calorimeter prototype, constructed for study of the energy resolution. Disign parameters of the prototype are given in Table 3.

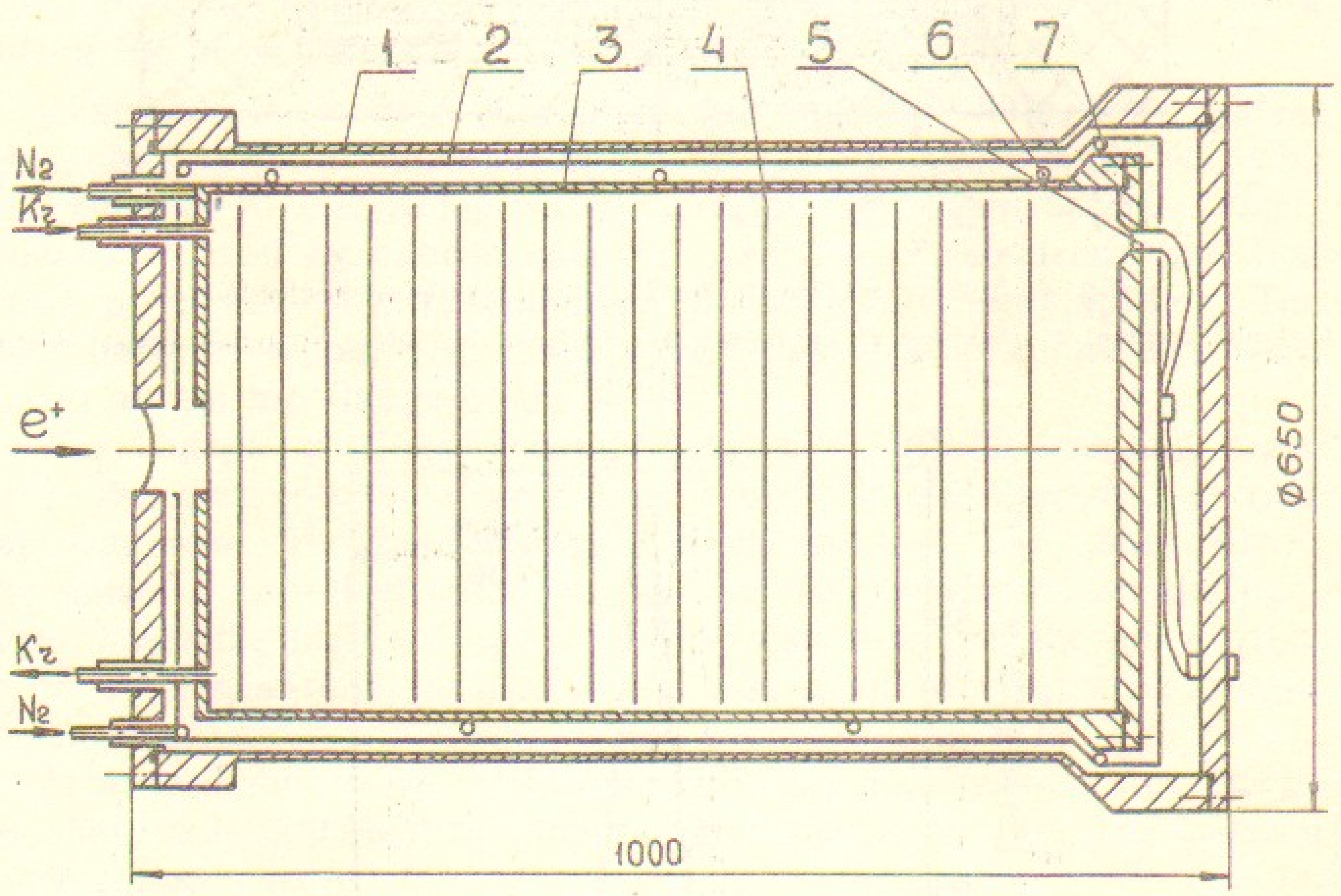

Fig. 6. The 0.4 t liquid krypton calorimeter:
1 — vacuum tank; *2* — copper screen; *3* — liquid krypton vessel; *4* — read-out and high voltage electrodes; *5* — feed-throughs; *6, 7* — liquid nitrogen tubes.

Table 3

Main parameters of the 0.4 t liquid krypton calorimeter

Gap width of liquid krypton	20 mm
Thickness of read-out and high voltage electrodes	0.5 mm G10+2·35 μm Cu
Lengh of calorimeter	16.4 X_0 (76 cm of LKr)
Diameter of calorimeter	9.5 X_0 (42 cm of LKr)
Number of read-out cells	19
Capacitance of an unit cell	240 pF (with LKr)
Thickness of entrance window	0.13 X_0 (2 mm Fe)

The cryogenic tank consists of inner and outer vacuum vessels. In the gap between vessels the copper screen of 2 mm and superinsulator (10 layers of aluminized mylar) were placed. After cool down by LN_2 up to 120 K a gaseous Kr was liquefied in the inner vessel. The filling time was about 34 hours. The heat flow into LKr during operation was 25 W and temperature raise was 2 K/12 hours. For cooling a LN_2 was used (twice a day), total LN_2 consumption was 50 l/day.

Processing of signals from the calorimeter consists of amplification by charge-sensitive amplifier and digitizing by peak ADC. The preamplifiers and shapers were located on the flange of cryostat and signals are transported to ADC by coaxial cables.

4.2. Monte-Carlo Calculation

We have calculated the contribution of different effects in energy resolution. A special Monte-Carlo method taking into account the space distribution of the ionization in the calorimeter gap has been developed to get the shape of the current pulse. Then the processing of the current pulse by electronics was simulated.

The main effects, determining the energy resolution, are discussed below and results of the calculations for the 0.4 t of LKr prototype are presented.

1. **Fluctuations of the energy deposited in liquid krypton.** These fluctuations are determined by transverse and rear leakage from the calorimeter, energy loss in material of an entrance window and in material of electrodes. Design considerations require the electrode thickness to be not less than 0.5 mm of G-10. Fig. 7 shows the contribution of these effects to energy resolution (curve *1*).

2. **The geometrical factor.** The integrated charge on the input of

the preamplifier depends on space distribution of the ionization in the gap. This dependence is decreased with the charge collection time however, the signal is also decreased and contribution of the electronics noise grows. The calculation shows that collection of 0.05—0.1 from the total charge is close to optimal. The contribution of this effect to the energy resolution is shown in Fig. 7 (curve *2*).

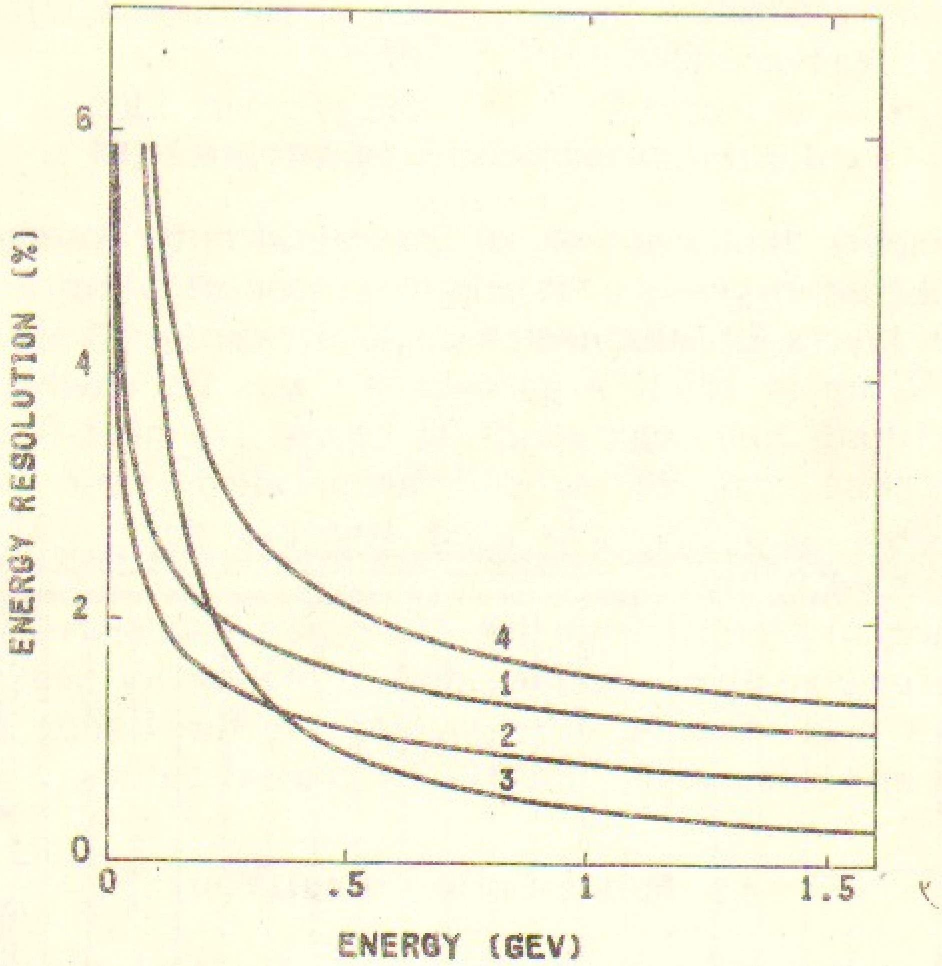

Fig. 7. Calculated contributions of different effects to energy resolution of the 0.4 t liquid krypton calorimeter:

1—fluctuations of the energy deposited in liquid krypton; *2*—the geometrical factor; *3*—radioactive and electronic noise; *4*—quadratic sum of all effects.

3. **Electronics and radioactive noise.** Krypton radioactivity is a noise source. To reduce this noise, a short shaping time is necessary, but in this case electronics noise raises. The calculation taking into account the krypton radioactivity, electronics noise and geometrical factor shows that if we use the preamplifier based on the FET SNJ-903L, the RC-2CR shaping with time constants of 0.8 μs is close to optimal. In this case we collect 5% of the total charge. The unloaded noise of an electronics channel is about 750 electrons (rms) and the noise slope is 3.2 electrons/pF. The capacitance of one LKr read-out cell is 240 pF and noise from one electronics

channel is 1300 electrons. The calculated energy equivalent of the electronics noise (from 19 channels) is 1.9 MeV. The calculated contribution of the radioactive noise to the energy resolution is 2.5 MeV. Total calculated energy equivalent of the noise (radioactive and electronics) is 3 MeV. The measured noise of one channel in the calorimeter was about 1 MeV and noise contribution from all 19 channels was 4.5 MeV. The difference between calculated noise and measured one is probably due to pickup noise. Curve *3* in Fig. 7 shows the experimental noise contribution to the energy resolution.

4. **Variations of the gaps.** We have calculated the contribution of the gap variations to the energy resolution in the assumption, that the fluctuations of the electrode positions are random. In this case at $E=100$ MeV the energy resolution is 1.2% at $\sigma_d=1$ mm (rms). In constructed calorimeter the measured gap variation was 0.23 mm (rms) and contribution of this effect to energy resolution is equal 0.4% at $E=100$ MeV (energy dependence is $1/\sqrt{E}$), i. e. it is negligible comparing to other effects.

Curve *4* in Fig. 7 shows the energy dependence of the calculated energy resolution (quadratic sum of the above-mentioned effects). Energy resolution is 1.5% at $E=1$ GeV and 4.6% at $E=100$ MeV. At low energy the resolution is mainly determined by electronics noise and radioactivity of krypton. The accuracy of the performed calculation is estimated to be 5—10%.

4.3. Experimental Results

In August 1988 the LKr calorimeter was tested in the positron test beam at VEPP-3 storage ring. The range of positron momentum was 130—1200 MeV/c. The momentum resolution of the test beam was:

$$\frac{\sigma_p}{p}=\sqrt{(0.17)^2+\left(\frac{0.36}{p,\,\mathrm{GeV}/c}\right)^2},\ \%$$

Fig. 8 shows dependence of the pulse height on the applied high voltage. The pulse height depends on the drift velocity, attenuation length (due to electronegative impurities) and on recombination of electrons. We have not yet exact analysis of these effects. All below presented results were obtained at high voltage of 1.08 kV.

The response of the calorimeter is linear in the energy region of 130—1200 MeV: nonlinearity is below 0.5%.

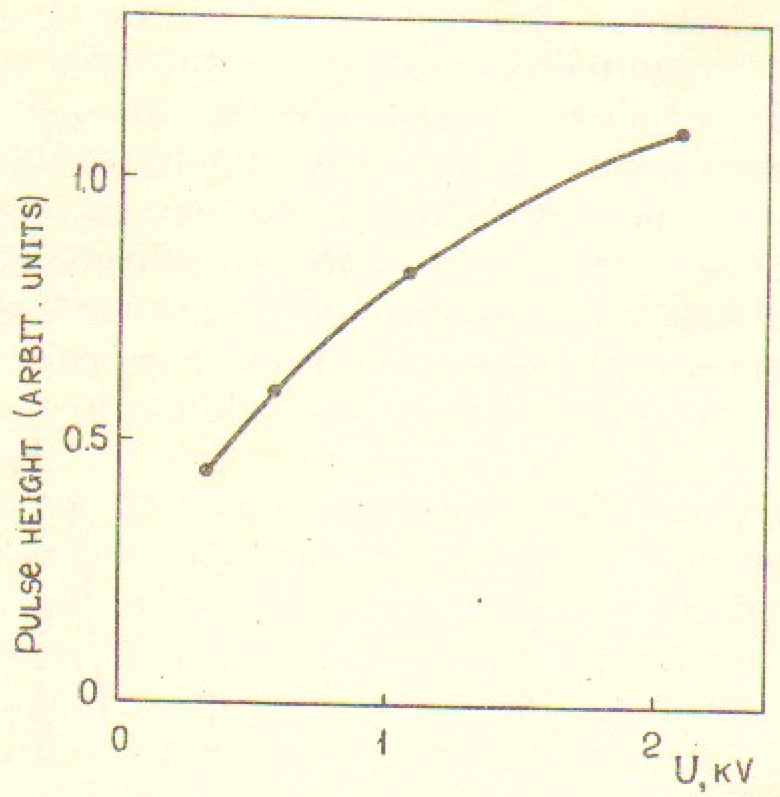

Fig. 8. The dependence of the pulse height on the applied high voltage. The curve is drawn to guide the eye.

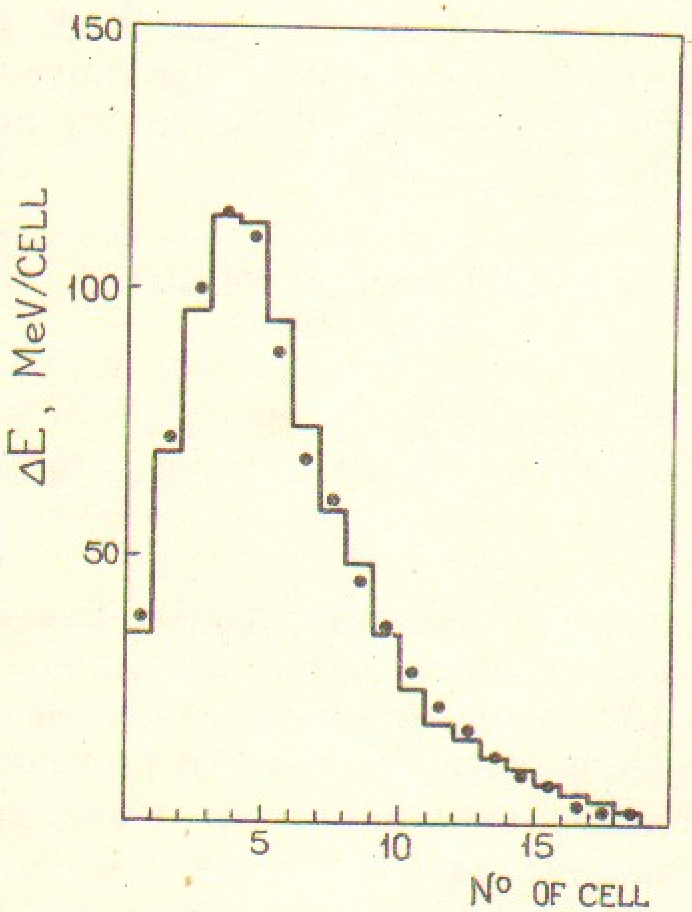

Fig. 9. The longitudinal distribution of the shower energy in the calorimeter: points are data and histogram is Monte-Carlo. $E=840$ MeV.

Fig. 9 shows the longitudinal distribution of shower energy in the calorimeter. Experiment is in a good agreement with Monte-Carlo simulation. The accuracy of the Monte-Carlo simulation is about 5%.

A typical distribution of the difference between energy obtained from calorimeter and beam energy is shown in Fig. 10. The solid line is a fit by the Legendre polinomials. From this fit the FWHM was obtained and an energy resolution is defined as

$$\frac{\sigma_E}{E} \approx \frac{FWHM}{2.36\,E}.$$

In order to reduce the influence of the relative uncertainty of the calibration of the electronics channels we have optimized the calibration constants. They were varied to minimize FWHM. The improvment of the resolution due to this optimization is about 10—15%. Maximum variation of the calibration constants is 10%. The results are given in Table 4 and are shown in Fig. 11.

Table 4

Energy resolution of the 0.4 tons LKr calorimeter: σ_E/E, %

Energy, MeV	Experiment		Calculation
	no optimization	optimization	
132	6.12±.61	5.73±.40	4.82±.39
217	4.35±.05	3.95±.12	3.42±.24
430	3.25±.08	2.74±.13	2.32±.12
640	2.61±.04	2.34±.14	1.91±.09
840	2.50±.04	2.15±.04	1.70±.09
1190	2.01±.15	1.66±.15	1.47±.08

After experiments with 0.4 tons prototype calorimeter during one month we performed the measurement of the drift velocity and attenuation length of electrons with three samples of krypton in special small device. One sample was used in 0.4 t calorimeter during 1 month, another two were not used. The results of the measurement are given in Table 5. The accuracy of the performed measurement is estimated to be 10%. One can see no visible degradation of krypton during a long time in the calorimeter with construction materials (several types of G10, teflon cables and nonmachined stainless steel).

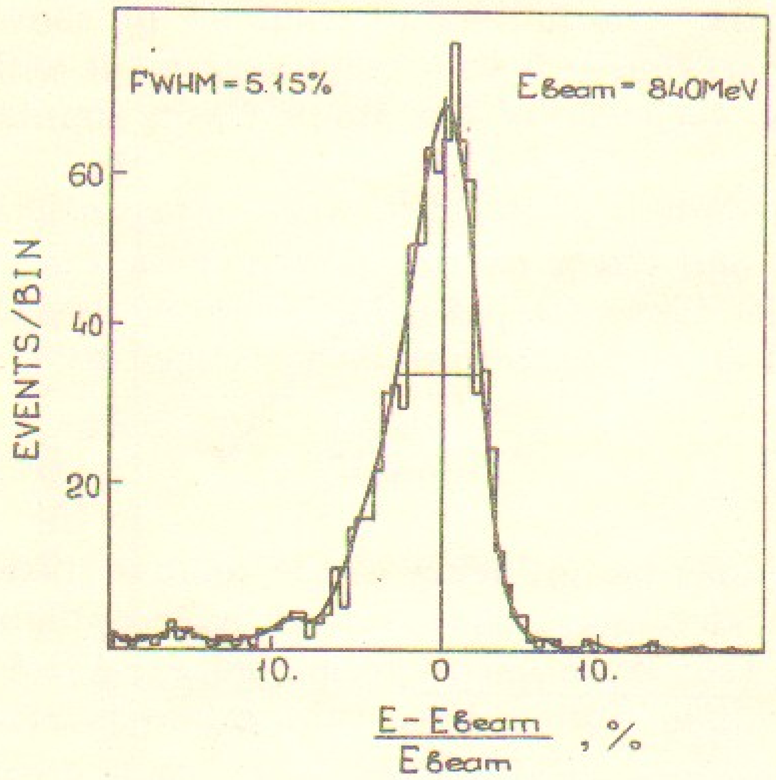

Fig. 10. A typical distribution of the difference between energy measured by the calorimeter and beam energy. The solid line is a Legendre polinomial fit.

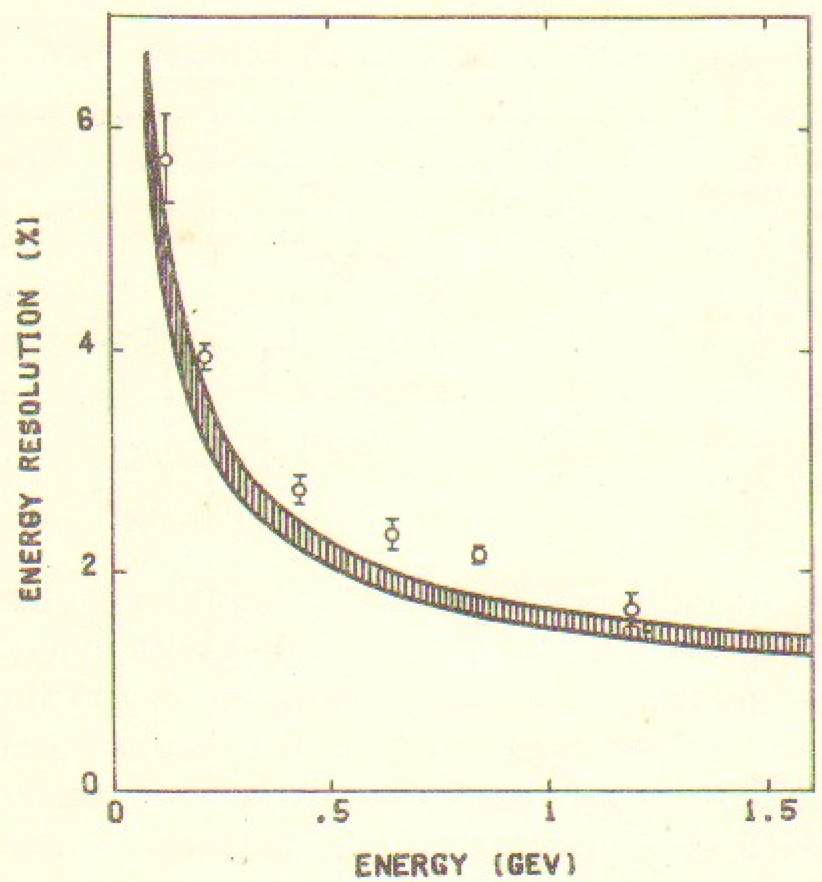

Fig. 11. Energy resolution (rms) of 0.4 T liquid krypton calorimeter (points), the band ($\pm\sigma$) shows the result of calculation including statistical errors of simulation and possible uncertainty of the electronics and radioactive noise.

Table 5

Drift velocity and attenuation length of electrons in LKr

gas sample	λ_{e^-}, mm			V_{e^-}, mm/μs		
	electric field , kV/cm			electric field , kV/cm		
	.416	.833	2.08	.416	.833	2.08
N1	11.4	18.6	41.7	1.59	2.08	2.40
N2	9.6	18.5	37.3	1.60	1.93	2.43
N3	11.1	26.6	41.7	1.56	1.83	2.26

N1 — was used in 0.4 t LKr calorimeter N2, N3 — were not used

5. CONCLUSION

Effects determining the energy and spatial resolution of homogeneous LKr calorimeter have been studied. At small LKr prototype by read-out from cathode strips the spatial resolution of 0.4 mm was obtained with minimum ionization particles.

A LKr calorimeter (0.4 t of LKr) was constructed to investigate the energy resolution and its performance was measured with positron beam of 130—1200 MeV. The energy resolution of 1.7% (rms) was achieved for 1200 MeV positrons. This value is comparable with an energy resolution of the best crystal calorimeters for Crystal-Ball and CLEO-2 detectors.

The results and experience obtained with the LKr prototypes are used in the construction of the 35 tons LKr calorimeter for KEDR detector at VEPP-4 in Novosibirsk.

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Изучение электромагнитного калориметра, основанного на жидком криптоне

Ответственный за выпуск С.Г.Попов

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