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FIRST OPERATION OF THE PWO CRYSTAL CALORIMETER AS A MASS SPECTROMETER IN A HEAVY-LOAD HIGH ENERGY PHYSICS EXPERIMENT

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Abstract

Blick A.M. et al. First operation of the PWO crystal calorimeter as a mass spectrometer in a heavy-load high energy physics experiment: IHEP Preprint 96-57. – Protvino, 1996. – p. 8, figs. 3, refs.: 19.

The lead tungstate (PWO) heavy crystal calorimeter is tested in a GAMS-type experiment detecting 50,000 π^o-mesons produced in 32.5 GeV/c intensive π^- beam of the 70 GeV IHEP accelerator. In spite of a huge beam load of the calorimeter cells (up to 10^6 π^-/s), a clean $\pi^o \to 2\gamma$ signal is observed. The measured PWO spectrometer mass resolution is in a good accord with previous electron beam tests and GEANT calculations. A high precision of the real-time PWO spectrometer calibration, using the π^o signal during physics run, is achieved. The results of these very first spectrometric beam tests confirm a high performance of multicell PWO spectrometers in heavy-load high energy physics experiments of both fixed target and collider types (LHC, etc.).

Аннотация

Блик А.М. и др. Первое применение кристаллического PWO-калориметра как масс-спектрометра в эксперименте по физике высоких энергий с большой загрузкой: Препринт ИФВЭ 96-57. – Протвино, 1996. – 8 с., 3 рис., библиогр.: 19.

Калориметр из тяжелых кристаллов вольфрамата свинца (PWO) испытан в эксперименте на спектрометре ГАМС. Зарегистрировано 50 тыс. π^0-мезонов, образованных в интенсивном π^--пучке с импульсом 32,5 ГэВ/с, выведенном из 70-ГэВ ускорителя ИФВЭ. Несмотря на огромную загрузку ячеек калориметра пионным пучком (до 10^6 $\pi^-/$с), получен чистый сигнал распада $\pi^o \to 2\gamma$. Измеренное разрешение PWO-спектрометра по массе находится в хорошем согласии с предыдущими испытаниями на электронных пучках и расчетами по программе GEANT. Достигнута высокая точность калибровки PWO-спектрометра в реальном времени в течение физического сеанса с использованием сигнала от π^0-мезона. Результаты этих самых начальных спектрометрических испытаний в пучке подтверждают высокие качества многоячеистых PWO-спектрометров нестабильных частиц, распадающихся на фотоны, необходимые для проведения экспериментов по физике высоких энергий при большой светимости как на выведенных пучках, так и на коллайдерах (LHC и др.).

Introduction

The first beam studies of PWO calorimeter prototypes built of $PbWO_4$ heavy crystals [1-4] have introduced, since 1992, this novel photon detection technique to the high-energy physics community, proposing to use it at the future LHC of CERN. After the successful electron beam tests, the PWO calorimeters entered the LHC experimental program as basic photon/electron detectors in mighty CMS (ECAL) [5] and ALICE (PHOS) [6] projects.

Until recently, the beam tests of PWO matrices (IHEP, CERN, KEK) were limited to the study of their response to electrons [7-11]. In the present experiment the PWO calorimeter has been tested for the first time as a mass spectrometer capable to detect several high-energy photons, to select the events over photon multiplicity and reconstruct π^o mesons through their two-photon decay

$$\pi^o \to 2\gamma. \tag{1}$$

1. SAD-60 PWO calorimeter

The measurements were performed during March 1996 run of the IHEP 70 GeV proton synchrotron using 32.5 GeV/c negative pions and 9.3 GeV/c electrons, extracted from the internal accelerator target through the 4B beam channel. The PWO crystal calorimeter SAD-60 used in these studies is an initial phase (40%) of SAD, the small angle multiphoton detector being built to upgrade the present GAMS-4π spectrometer [12]. Part of the spectrometer apparatus [13] is used in the measurements.

The SAD-60 detector is composed of PWO cells arranged in a 9 x 7 matrix, with one-cell hole in the matrix center to let the beam through. The cells have a shape of hexagonal prisms, $19X_o$ to $26X_o$ long ($X_o = 8.8\ mm$ in this crystal, which is heavier than iron). With the scintillation light attenuation length of our crystals $\lambda_{att} \approx 1\ m$, the above cell size is optimum for photons in our energy range [10]. Longer cells are positioned in the SAD-60 center. The cell width, the distance between two parallel lateral faces, is 24 mm.

Each crystal is wrapped into aluminized mylar and viewed by a FEU-147 PMT coupled to the crystal with the Dow Corning Q_2-3067 optical compound. The PMT signals are read out through 50 m cables with the standard GAMS-4π electronics (12 bit QDC [14] with 60 ns gate, CAMAC version).

For data taking an auxiliary GAMS DAQ system is used, which includes a VME based CETIA UNIX workstation and a VME crate equipped with FIC8232 single board computer and CBD8210 CAMAC branch driver. The FIC reads events ($\approx$ 1.5 Kbits/event) during 1.4 s accelerator beam spill and then optionally writes them with a speed up to 1000 events/s. The workstation is used for the set-up control and for data monitoring. Unlike the basic GAMS DAQ [13,14], the QDC pedestals are not automatically subtracted in our measurements. The pedestals are written on tape during the accelerator cycle, both outside and inside the beam spill (twice before the spill, then after each tenth detected event and finally ten times after the spill), providing the information necessary to evaluate pile-up effects in the SAD-60 cells.

To monitor each SAD-60 channel the optical fiberglass system with light-emitting diodes (similar to [13,15]) is used. Three LEDs (green, yellow and orange) produce signals in the calorimeter cells, equivalent to 5 GeV gamma showers. The monitoring system is triggered simultaneously with each pedestal, inside and outside the beam spill, allowing one to follow time variation of each SAD-60 channel inside the spill as well as a slow drift of channels, ensuring < 1% precision. A stable FEU-84-3 PMT is used in the monitoring system as a reference.

The PWO scintillation intensity is rather sensitive to temperature variations (1.9%/^oC [11]). Thermal stabilization is provided with an air flow through the SAD-60 box.

2. SAD-60 calibration

The beam calibration of SAD-60 is performed in several steps. First, the detector is irradiated by muons, and the high voltage of each PMT is installed so that the minimum-ionizing particle peak ($\approx$ 350 MeV gamma-shower equivalent) comes to the 30th QDC channel. This provides a sufficient dynamical range ensuring the calorimeter linearity better than 1% [13,14].

Then 9.3 GeV electrons are used to establish accurate calibration coefficients. The SAD-60 is continuously moved vertically and horizontally across a wide (5 cm spot) electron beam collecting necessary statistics in each PWO crystal. This automatic calibration procedure, standard for GAMS spectrometers operating at IHEP and CERN, is described in detail elsewhere [13]. The resulting electron energy peak, obtained during the SAD-60 calibration, is presented in fig. 1.

Finally, a fine SAD-60 tuning is performed off-line using the real multigamma events written on tape during the π^- beam run ("self-calibration"). With two-gamma combinations selected in the π^o peak region, using the π^o mass as a constraint, the calibration coefficients have been obtained after a few iterations [16]. The coefficients turned out to

be very close to those measured during the electron beam calibration. Nevertheless, when using them we achieved a noticeable improvement in two-gamma mass resolution.
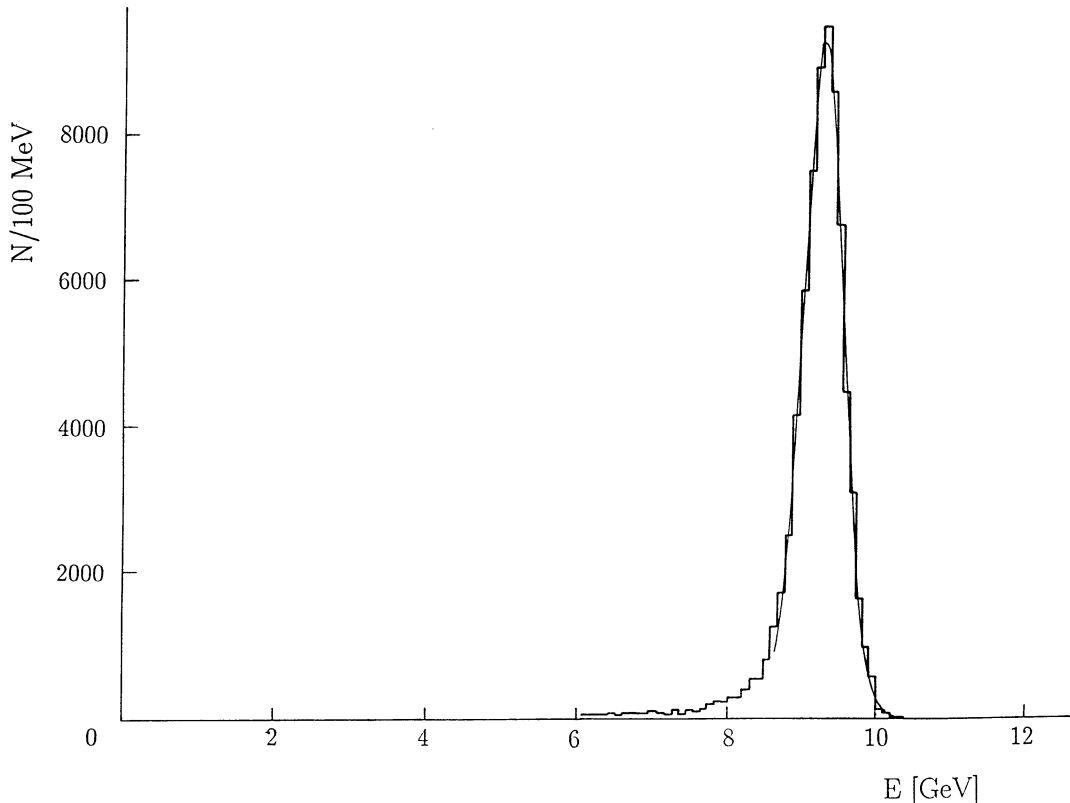

Fig. 1. Measured spectrum of the SAD-60 PWO matrix signals in 9.3 GeV wide electron beam. Curve is a Gaussian with $\sigma_E/E = 2.9\%$.

A number of electrons emitted from the PMT photocathodes per 1 MeV of shower energy, N_{phe}, is the main parameter which defines the energy resolution of a PWO calorimeter [10]. In the SAD-60 case, $N_{phe} \approx 1$ photoelectron/MeV as measured in the electron beam. With a geometrical efficiency of scintillation light collection (ratio of the PMT photocathode area to that of the crystal rear face), which is $\approx 25\%$ in the SAD-60 case, this corresponds well to the values obtained in previous PWO measurements [8,9]. According to the GEANT calculations [10] (cf. formulae (3), (5) in this ref.) the energy resolution of SAD-60 for electrons (photons) equals, in an ideal case,

$$\sigma_E/E = 3.6\%/\sqrt{E} + 0.5\%. \tag{2}$$

With E = 9.3 GeV this gives 1.7%. One should add the e^- beam momentum dispersion ($\approx 1.5\%$) and the spread caused by some materials along the beam line (resulting in a low energy "tail", visible in fig. 1), as well as the PWO matrix calibration precision ($\approx 1.5\%$), the PMT time drift (the same order), etc. So, finally one arrives at a value of

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$\approx 3.1\%$. This is not far from 2.9% obtained during the SAD calibration in a wide electron beam (fig. 1)[1].

3. Measurements of multi-gamma events

After the electron calibration, during the principal part of the measurements, the beam line was switched to 32.5 GeV/c π^- mode. A part of the GAMS guard system [17] surrounding 5 cm long CH target was used in a DAQ trigger selecting neutral meson states, produced in the charge exchange reaction

$$\pi^- p \to M^o n. \qquad (3)$$
$$\hookrightarrow k\gamma$$

The sandwich counters [18] are used to veto reaction (3) events except those with gammas emitted from the target in a forward cone (15 $mrad$) viewed by the SAD-60.

The π^- beam spot ($\approx 4\ cm$) was made much larger than the SAD-60 central hole, so a large fraction of the beam hit the PWO cells around the hole. This helped to reproduce experimental conditions typical for the future high luminosity experiments (CMS at LHC, COMPASS at SPS, CERN) and to test the PWO calorimeter under such conditions.

During the π^- beam data taking, $1.5 \cdot 10^6$ neutral trigger events were written on tape with a total flux of 10^{10} π^- through the target. These events were further processed with the gamma shower reconstruction programs analogous to those used in the GAMS experiments [13,19]. The main contributions to the M^o in (3), detected by the SAD-60, are given by the π^o, $2\pi^o$, η and $\eta\pi^o$ neutral states.

The events with two or more gamma showers and with a total gamma energy release in the SAD-60 being within 3 GeV interval around the beam energy, were retained for further analysis. $5 \cdot 10^4$ of them contain π^os produced mainly in the $\pi^- p \to \pi^o n$ reaction with some contribution from $\pi^- p \to \pi^o \pi^o n$.

4. Two-gamma mass resolution

The two-gamma effective mass resolution of SAD is defined both by the energy and space resolutions of gammas:

$$\sigma_M/M \approx (\sigma_{E_{\gamma 1}}/E_{\gamma 1} \oplus \sigma_{E_{\gamma 2}}/E_{\gamma 2})/\sqrt{2} \oplus \sigma_{r_{\gamma\gamma}}/r_{\gamma\gamma}, \qquad (4)$$

where $r_{\gamma\gamma}$ is the space separation of two showers produced by photons in the SAD.

The two-gamma mass spectra were first measured with an event sample, in which the pile-up effects are not essential. Such events are selected by the distance of gammas from the PWO matrix center: events with gammas in the border cells, i.e., those around the central hole or at the edge of the SAD-60 (the impact points of gammas being of $< 45\ mm$ or $> 70\ mm$ distance from the SAD-60 center), are excluded. The π^o mass resolution

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[1]The energy resolution spread over the PWO matrix surface (cell-to-cell variation) is 0.3%.

is obtained to be $\sigma_M = 5.0$ MeV, $\sigma_M/M = 3.7\%$ (fig. 2). Similar resolution is observed without event selection, when lowering the beam intensity to $1.4 \cdot 10^6$ π^-/s. In this case the pile-up contribution is also small.
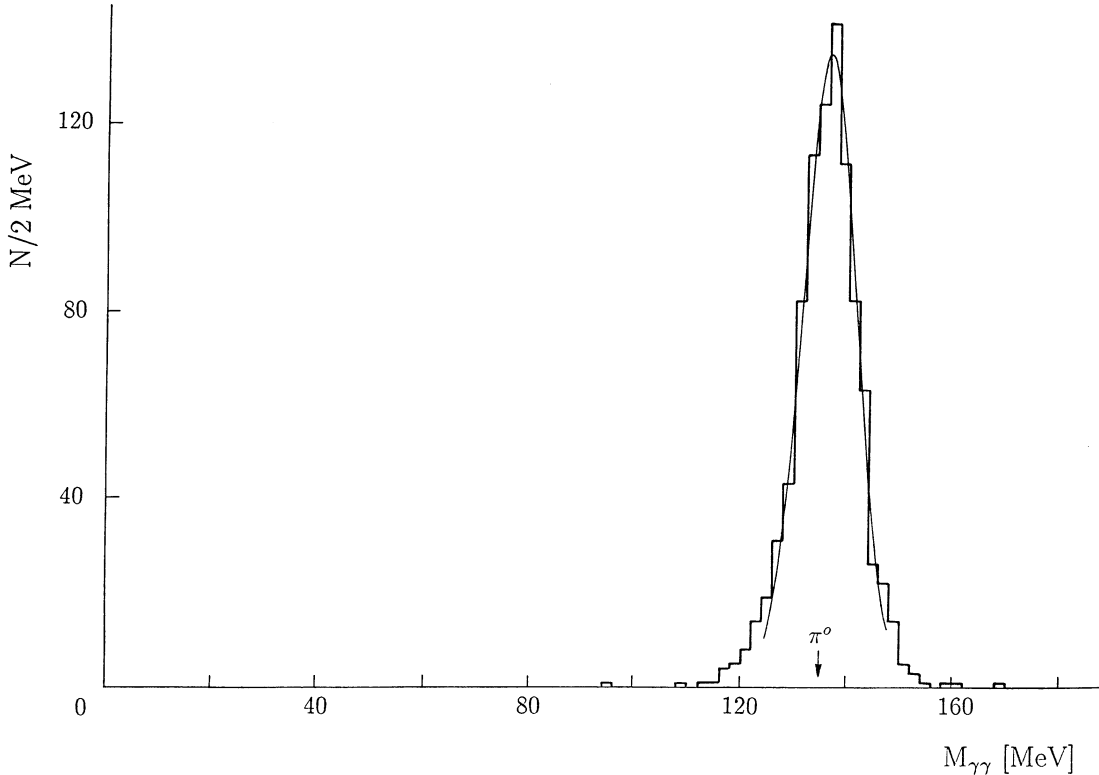

Fig. 2.   Effective mass spectra of γ-pairs measured with SAD-60 *PWO* calorimeter in high intensity 32.5 GeV/c π^- beam. Events are selected by the distance of gammas from the *PWO* matrix center (see the text). Curve is a Gaussian with $\sigma_M/M = 3.7\%$.

With no event selection and full intensity ($4 \cdot 10^6$ π^-/sec), when several SAD-60 *PWO* cells around the hole are loaded by more than 10^6 beam pions per second, the π^o peak becomes 10% wider (fig. 3) due to a contribution from the pile-up[2]: $\sigma_M = 5.5$ MeV, $\sigma_M/M = 4.1\%$.

The essential feature of all measured two-gamma spectra is that the background under π^o peak is always very low.

The ideal energy resolution (2) contributes to the SAD-60 π^o mass resolution (4) as 1.5%. The shower coordinate precision, scaled from previous data [3,4,8], equals 0.9 mm.

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[2]The *PWO* crystals used in the SAD-60 were produced at the Bogorodisk factory (Russia) during 1995 with a technology different from that used for the first set of crystals ($1993 - 1994$) [3, 4, 7-9]. The result of this technology change turned out to be negative: unlike the first fast crystals [8], a sample produced in 1995 shows the sizable slow component, the scintillation signal has a long "tail". This tecnology is not used any more, the *PWO* crystals produced at present are as fast as in 1994 [8], with 90% of the signal within 100 ns gate.

Then $\sigma_{r_{\gamma\gamma}} = 1.3\ mm$, and with the man gamma separation $r_{\gamma\gamma} = 7\ cm$ in π^o decay (1) in reaction (3)[3], one obtains $\sigma_{r_{\gamma\gamma}}/r_{\gamma\gamma} = 1.9\%$. So, the π^o mass resolution is expected to be 2.4% in an ideal case (no pile-up, and the showers are fully spatially separated in the SAD). In our experiment $r_{\gamma\gamma} \approx 2.4\ PWO$ cells only, two showers produced in decay (1) overlap essentially. This increases the errors both in gamma energies and in their coordinates thus increasing σ_M/M.
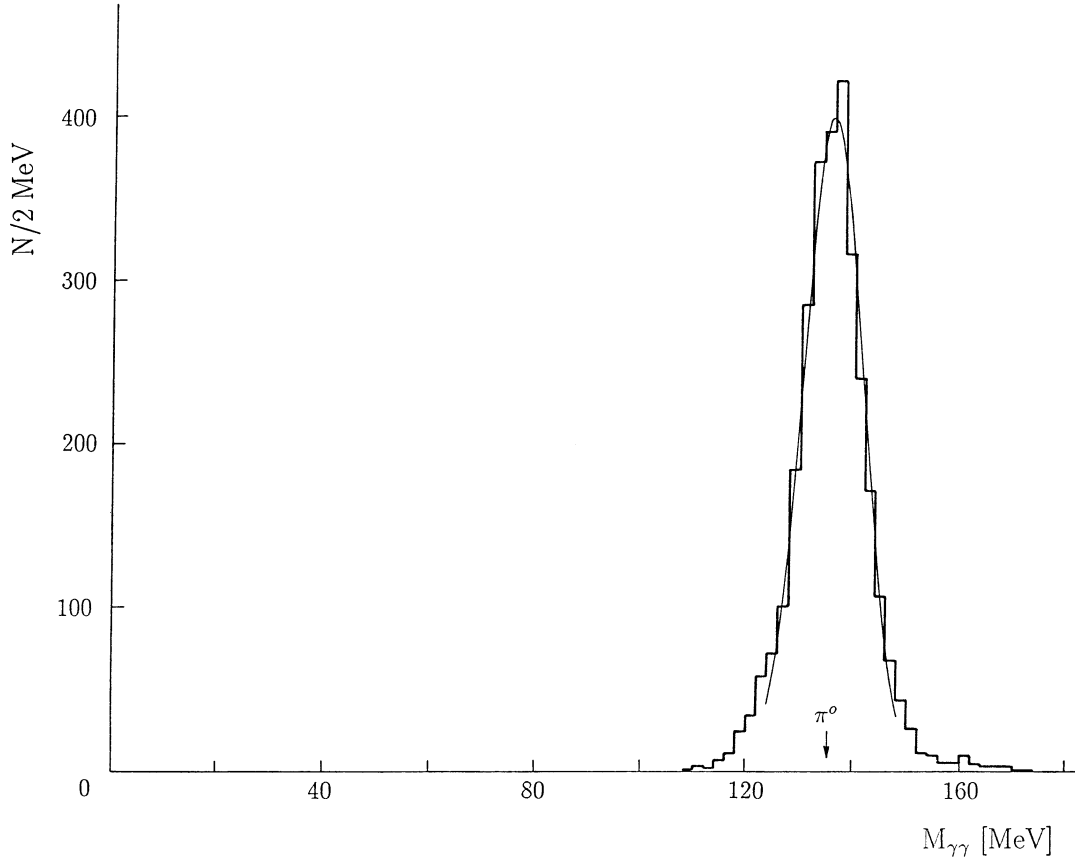

Fig. 3. The same as in fig. 2, but for all events. Curve is a Gaussian with $\sigma_M/M = 4.1\%$.

One should take into account some other factors contributing to the mass resolution:
$-$ PWO matrix calibration precision ($\approx 1.5\%$),
$-$ PWO scintillation signal variations with temperature ($\approx 1\%$),
$-$ PMT time drift, both long term and during the beam spill ($\approx 1\%$),
$-$ partial overlapping of two gamma showers ($\approx 1\%$),
$-$ pile-up of the SAD-60 central cells ($\approx 1\%$).

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[3]The $\eta \to 2\gamma$ decay, that provides a better mass resolution [13,15] (due to a four times larger gamma shower separation), is not measured with SAD-60 in the present experiment geometry, the minimum value of $r_{\gamma\gamma}$ exceeds in the η case the detector size.

This results in extra $\approx 2.5\%$, thus increasing the expected mass resolution from the above ideal value (2.4%) to $\approx 3.5\%$. The last value is in a good agreement with the measured resolution, $\sigma_M/M = 3.7\%$.

In a high intensity π^- beam, the pile-up effect increases to $\approx 3\%$ (estimated by using the pedestal events written during the beam spill, see above) resulting in a rise of the expected SAD-60 mass resolution up to $\approx 4.5\%$, not far from the measured value of 4.1%.

Conclusions

The lead tungstate (PWO) heavy crystal calorimeter is tested in a GAMS-type experiment detecting $5 \cdot 10^4$ π^o mesons. In spite of heavy π^- beam load of the calorimeter cells, low production cross section (10^{-6} of the beam flux) and limited gamma shower separation, a very clean π^o signal is observed. The measured PWO spectrometer mass resolution is in a good accord with previous electron beam test results and GEANT calculations. A high precision is achieved in the real-time PWO spectrometer calibration using the $\pi^o \to 2\gamma$ signal ("self-calibration"), which corrects all PWO crystal, PMT and electronic channel drifts during the physics run. Both the detector quality and the measurement precision were not optimized in the described beam studies and will be further improved. Nevertheless, the results of these very first beam tests of the PWO calorimeter as a precision mass spectrometer of particles decaying into photons, performed under conditions of a real physics experiment at the high energy accelerator, are very encouraging. They confirm the expected high performance of multicell PWO spectrometers in coming high luminosity experiments at colliders (CMS, etc.), as well as in those of the fixed target type (COMPASS, etc.).

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