Z. Phys. C – Particles and Fields 9, 315–320 (1981)

Zeitschrift für Physik C Particles and Fields

Energy Carried by Gamma Rays and Neutral Particles in Multihadron Final States at Petra

JADE-Collaboration

W. Bartel, D. Cords, P. Dittmann, R. Eichler, R. Felst, D. Haidt, H. Krehbiel, B. Naroska, L. H. O'Neill, P. Steffen, H. Wenninger[1], Y. Zhang[2]

Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Federal Republic of Germany

E. Elsen, M. Helm[3], A. Petersen, P. Warming, G. Weber

II. Institut für Experimentalphysik der Universität, D-2000 Hamburg, Federal Republic of Germany

S. Bethke, H. Drumm, J. Heintze, G. Heinzelmann, K. H. Hellenbrand, R. D. Heuer, J. von Krogh, P. Lennert, S. Kawabata, H. Matsumura, T. Nozaki, J. Olsson, H. Rieseberg, A. Wagner

Physikalisches Institut der Universität, D-6900 Heidelberg, Federal Republic of Germany

A. Bell, F. Foster, G. Hughes, H. Wriedt

University of Lancaster, England

J. Allison, A. H. Ball, G. Bamford, R. Barlow, C. Bowdery, I. P. Duerdoth, J. F. Hassard, B. T. King, F. K. Loebinger, A. A. Macbeth, H. McCann, H. E. Mills, P. G. Murphy, H. B. Prosper, K. Stephens

University of Manchester, England

D. Clarke, M. C. Goddard, R. Marshall, G. F. Pearce

Rutherford Laboratory, Chilton, England

M. Imori, T. Kobayashi, S. Komamiya, M. Koshiba, M. Minowa, M. Nozaki, S. Orito, A. Sato, T. Suda[4], H. Takeda, Y. Totsuka, Y. Watanabe, S. Yamada, C. Yanagisawa

Lab. of Int. Coll. on Elementary Particle Physics and Department of Physics, University of Tokyo, Japan

Received 2 February 1981

Abstract. The fraction of the total available energy carried by photons and the fraction carried by neutral particles of all types in e^+e^- multihadron final states have been measured at three centre-of-mass energies between 12 and 35 GeV. These fractions are approximately 27% and 37% with no strong dependence on centre-of-mass energy and the event topology. The neutrino energy fraction is estimated to be less than 10% at the 95% confidence level.

In this paper we report on measurements of the fractional energy carried by gamma rays ϱ_γ, and by all neutral particles ϱ_N in the reaction $e^+e^- \rightarrow$ hadrons at centre of mass energies of 12 GeV, around 30 GeV and around 35 GeV. These energy fractions are relevant for the study of hadron production by e^+e^- annihilation because they provide information about the gross features of the final state and its production mechanism. A measurement of the difference $\varrho_N - \varrho_\gamma$ provides a sensitive upper limit on the energy fraction carried away by neutrinos, which is predicted to be about 2% for standard QCD models and which is estimated to lie between 18% and 28% for a model with liberated integrally charged quarks [1].

The gamma ray energy fraction ϱ_γ is essentially obtained from a measurement of the energy deposited in a photon detector about 125 cm away from the point where electrons and positrons annihilate, whereas the neutral energy fraction ϱ_N is given by the complement of the charged energy fraction $\varrho_N = 1 - \varrho_{\text{charged}}$. Charged particles are detected some

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[1] On leave from CERN, Geneva, Switzerland

[2] Visitor from Institute of High Energy Physics, Chinese Academy of Science, Peking, People's Republic of China

[3] *Present address:* Texaco AG, Hamburg, Germany

[4] *Present address:* Cosmic Ray Laboratory, University of Tokyo, Japan

0170-9739/81/0009/0315/$01.20

30 cm from the interaction point by a tracking chamber.

Through the decay of particles in the final state, the fractions ϱ_γ and ϱ_N depend on the distance from the interaction point at which the particles are detected. Thus they require careful definition. The procedure followed here will be first to attribute the energy of every observed charged particle to the charged particle energy and observed photon energies to the gamma ray energy of the final state. Then the energies of charged particles and of gamma rays from the decay of K_s^0 and... particles will be subtracted from the charged particle and gamma ray energies respectively. This approach arises from practical considerations: the K_s^0 and Λ multiplicities and energy spectra can be estimated from available data and the corresponding corrections are small enough that their uncertainty does not dominate the systematic error of the final results.

The experiment was carried out with the JADE detector at the e^+e^- colliding beam facility PETRA at DESY. Descriptions of the JADE detector have appeared in previous publications [2]. Charged particle trajectories are reconstructed in the central drift chamber (jet chamber), which covers 97% of the full sphere. This drift chamber is in a solenoidal magnetic field of 4.8 kG. The momentum resolution is $\Delta p/p = \pm 2.2\%$ p(GeV/c). Photons are detected by an array of lead glass counters surrounding the coil of the magnet and mounted on the two end caps of the iron yoke. The lead glass counters cover 90% of the full solid angle. All counters were calibrated in a test beam, and the energy resolution of the individual counters was measured to be $\Delta E/E = \pm 6\%/\sqrt{E(\mathrm{GeV})}$ up to $E = 6$ GeV. Particles emitted at a polar angle (θ) of 90° from the beam axis penetrate a total of 11 mm of aluminium and 10 mm of plastic material before they reach the first sense wire of the drift chamber. The gas and the support structures of the jet chamber itself represent a total thickness of material corresponding to 0.04 radiation length. Particles reaching the lead glass penetrate the aluminium magnet coil, which is 8 cm thick. Measured gamma ray energies are corrected for losses in this material.

The data for the present analysis were taken at centre-of-mass energies of $\sqrt{s} = 12$ GeV, around 30 GeV and around 35 GeV. The 30 and 35 GeV samples were not accumulated at fixed energies, but rather by collecting all events at a range of energies between 27.40 and 31.56 GeV and between 33.0 and 36.72 GeV. The trigger conditions and the criteria for the selection of events were the same as those previously used by JADE in measuring the total cross section for single-photon annihilation to multihadronic final states. [2] The resulting sample is essentially free of two-photon process and τ lepton background. In order to minimize the loss of energy due to particles which escape down the beam pipe an additional acceptance cut is made for this analysis: $|\cos(\theta_{\mathrm{jet}})| < 0.7$. The sphericity axis [3] is taken to give the jet direction.

The JADE detector is in principle capable of measuring directly the energy fraction $\varrho_\gamma = \sum_i E_i^\gamma/\sqrt{s}$. However in deriving this number from the raw measurements several corrections have to be applied. The most important is due to the fact that the energy clusters in the lead glass detector from photons and charged tracks, particularly in jet events, often overlap. Thus in general clusters cannot uniquely be attributed to charged particles or to photons. Therefore we have adopted the following procedure to determine ϱ_γ: for each event an expectation value is computed for the total amount of Cerenkov light generated in the lead glass by all of the charged particles belonging to that event. The Cerenkov light due to charged particles, converted to an equivalent shower energy, is subtracted from the total energy measured in the lead glass arrays to obtain ϱ_γ.

The Cerenkov light generated by hadrons at momenta of about 1.5 GeV/c and lower can be measured by the JADE detector itself, using multihadronic final states from one photon annihilation and two photon processes. Charged particle tracks are selected which are well separated from any other charged track or cluster in the lead glass. In these favourable cases the lead glass energy can confidently be associated with this single charged particle. If this energy, corrected for losses in the magnet coil and pressure vessel, is more than 80% of the particle momentum, the particle is regard as an electron or positron and not considered further. In addition suitable cuts are made to reject particles with poorly measured momenta or directions and particles which are ejected from the beam pipe or inner wall of the pressure vessel. Many of the latter are protons too slow to give rise to Cerenkov light.

Above approximately 1.5 GeV/c particles tend to be near the axis of a jet and we no longer find a statistically useful sample of tracks and clusters which meet the criteria defined in the previous paragraph. At high momenta the data of Barber et al. [4] are used to obtain an expected pulse height for each track. These data are for pions of 1.8 to 3.9 GeV/c momentum incident normally upon 40 cm thick lead glass counters. The main uncertainties in our treatment of high energy hadron interactions in the lead glass arise in scaling from 40 cm to other thicknesses of lead glass, from the assumption that non-pions make the same average pulse heights as pions of the same momenta, and from detailed differences between the light guide configurations of JADE and that of [4]*.

Averaging over all events, the Cerenkov light associated with charged particles is equivalent to between 13% and 16% of the centre-of-mass energy, decreasing slowly as this energy increases. This is between 1/2 and 3/4 of the light due to gamma rays.

Figure 1 shows the distributions of the gamma ray energy fraction, corrected for charged particle contributions as described above, for the three centre-of-mass energies. The gamma ray energy so computed can become negative for individual events because the charged particle contribution subtracted is only an expectation value, not the actual energy loss by charged particles for each event.

Further corrections are applied to the data of Fig. 1 for several effects which are estimated only in the mean over all events, not event by event. 1) Approximately 14% of the photons in the events selected for this analysis convert before reaching the jet chamber. The resulting electrons and positrons are treated as hadrons since they make tracks, and some fraction of their energy is subtracted from the total energy registered in the lead glass. The size of this effect has been estimated with Monte-Carlo simulations of multihadronic final states [5] including bremsstrahlung from the initial e^+ and e^-. 2) Losses due to small gaps in the lead glass system were also calculated with the same Monte-Carlo program. 3) A correction was made for photons generated by nuclear interactions in the material before the jet chamber. 4) Protons ejected from the same material with momenta below the Cerenkov threshold require a further correction. They were initially treated as pions, so their energy was incorrectly subtracted from the total energy recorded in the lead glass. 5) Estimates of the energy deposited by interactions in the lead glass of the neutral hadrons K_L^0 [6], n and $\bar{n}$ [7] are also subtracted. 6) The extra energy released by the annihilation of $\bar{p}$'s is accounted for [7]*. A visual scan of a small sample of the data at each energy has been made to search for and to estimate the size of all effects not simulated by the Monte-Carlo calculations or otherwise taken into account. Each of the individual corrections 3)–7) changes the final result for the mean energy carried by gamma rays by at most 2% of the centre-of-mass energy. Adding these together, with appropriate signs and estimated uncertainties, we obtain net corrections to the gamma ray energy of $-2.3\% \pm 2.4\%$, $-1.6\% \pm 1.5\%$, and $-0.7\% \pm 1.5\%$ of the centre-of-mass energy at 12, 30, and 35 GeV respectively.

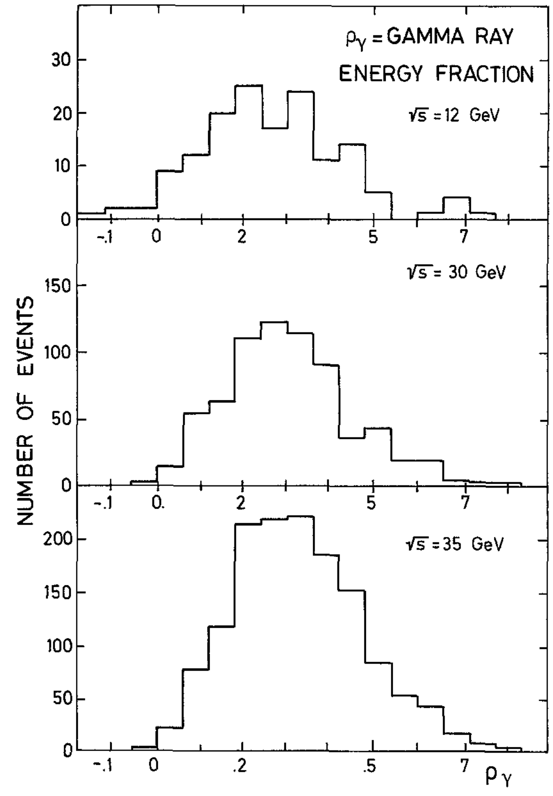

Fig. 1. The distribution of gamma ray energy fraction event by event for three centre-of-mass energies, computed under the approximations described in the text

Finally the mean energy per event of gamma rays from π^0's originating in the strange particle decays $K_s^0 \to \pi^0\pi^0$ [6] and $\Lambda(\bar{\Lambda}) \to n(\bar{n})\pi^0$ [8] is subtracted from the mean total energy of all photons. The K_s^0 correction is estimated at $-1.1\% \pm 0.6\%$ of the centre-of-mass energy at 12 GeV and $-1.2\% \pm 0.6\%$ at the

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[*] In order to account for the difference between 40 cm and the actual thickness the JADE lead glass system presents to particles – about 34 cm on average for the tracks involved in this analysis – we assume that, for each given energy, the average quantity of Cerenkov light created by pions is proportional to the thickness of lead glass lying in their path. We use the same assumption at lower energies for which JADE data are available on hadron interactions in the lead glass. For each of the well-isolated clusters defined in the text the energy loss by the incident particle is normalized to the total thickness of lead glass in the particle's path. The effective "dE/dx" so obtained is fitted as a function of particle momentum and used in the ϱ_γ analysis to obtain an expectation value for the quantity of Cerenkov light generated by each charged particle track. The systematic errors for these approximations are large. They are estimated as follows: the path lengths in the lead glass barrel of high momentum particles coming from the interaction region vary from 30 cm to 42 cm, with an average of 34 cm. We take the half width of this range divided by the mean, 6/34, to be a reasonable estimate of the (1σ) relative systematic error on the computed amounts of Cerenkov light generated by hadrons for all momenta

[*] The effect of neutron interactions in the lead glass is estimated from the data of [4]. For antinucleon annihilation we assume that the total available energy is divided equally among π^+, π^- and π^0. All the energy of the π^0's and one half the energy of the charged pions is estimated to be seen, with the charged pion contribution given a 100% relative uncertainty

Table 1. The corrected gamma ray, neutral particle and neutrino energy fractions

$\sqrt{s}$ (GeV)		ϱ_γ	ϱ_N	Neutrino
12.00	All events	0.25 ± 0.04	0.37 ± 0.04	0.00 ± 0.06
	Planar	0.21 ± 0.05	0.32 ± 0.05	-0.01 ± 0.07
30.30	All events	0.28 ± 0.03	0.36 ± 0.04	-0.03 ± 0.05
	Planar	0.28 ± 0.03	0.36 ± 0.04	-0.03 ± 0.06
34.89	All events	0.30 ± 0.03	0.38 ± 0.04	-0.02 ± 0.05
	Planar	0.32 ± 0.03	0.41 ± 0.04	-0.02 ± 0.06

higher energies. The Λ correction is negligible ($<0.1\%$) everywhere.

The corrected mean fractional photon energies ϱ_γ are listed in Table 1. The indicated uncertainties are predominantly systematic and are mainly due to uncertainties in the treatment of nuclear interactions by pions in the lead glass.

The neutral energy fraction ϱ_N, i.e. the fractional energy carried away by photons, K_s^0's and Λ's long-lived neutral hadrons and neutrinos, has been obtained by calculating the complement to the charged energy fraction:

$$\varrho_N = 1 - \frac{\sum_i E_i^{\mathrm{ch}}}{\sqrt{s}}.$$

The charged energy is calculated from the measured momenta by assuming as a first approximation that all particles have the pion mass. Figure 2 shows the distributions, for the three different centre-of-mass energies, of the neutral energy fraction computed in this approximation. There are no negative entries in Fig. 2. (In a small number of cases ϱ_N is initially computed to be negative due to errors in the measured momenta of charged particles. These negative values are set to zero. Not doing so changes ϱ_N by only 0.8% of the centre-of-mass energy.)

As with the gamma ray fraction several corrections are applied to ϱ_N only in the mean rather than event by event. The Monte Carlo simulation mentioned above has been used to correct for geometrical acceptance losses, for losses due to the finite two-track resolution of the jet chamber and for e^+e^- pairs from photon conversion, which should not be introduced in the charged particle energy. Because the Monte Carlo meson jets include a realistic number of kaons, the effect of attributing the pion mass to kaons is also corrected for. Proton and antiproton mass effects are estimated from the available data [7] on p and $\bar{p}$ production. They require a correction of $-1.4\% \pm 0.7\%$ to the final neutral energy fraction at 12 GeV in the centre-of-mass, and $-0.5\% \pm 0.3\%$ at higher energies. Nuclear interactions of charged particles in the material before the jet chamber release π^0's and neutrons and cause an overestimate of ϱ_N. At the same time these interactions give rise to an effect in the opposite direction when low energy protons are ejected. The kinetic energy of such protons belongs to the charged particle energy, since it originally comes from charged hadrons. However the protons were counted as having the total energy of pions with the same momenta. This significant and uncertain effect requires correction of ϱ_N by $+2.3\% \pm 2.3\%$ at 12 GeV in the centre-of-mass and by $+1.5\% \pm 1.5\%$ at higher energies. A visual scan of a small sample of the events at each energy has been made in search of effects not otherwise accounted for. This scan leads to a correction to ϱ_N of $+2.3\% \pm 1.2\%$ at 35 GeV centre-of-mass energy and to smaller changes at the lower energies. The scan corrections are mainly due to charged particles ejected backwards into the jet chamber by nuclear interactions in the lead glass. Finally the computed neutral energy fraction is increased by $3.1\% \pm 1.2\%$ at 12 GeV and by $3.3\% \pm 1.3\%$ at the higher centre-of-mass energies in order to account for the charged decays of the neutral strange particles K_s^0 and Λ [6, 8].

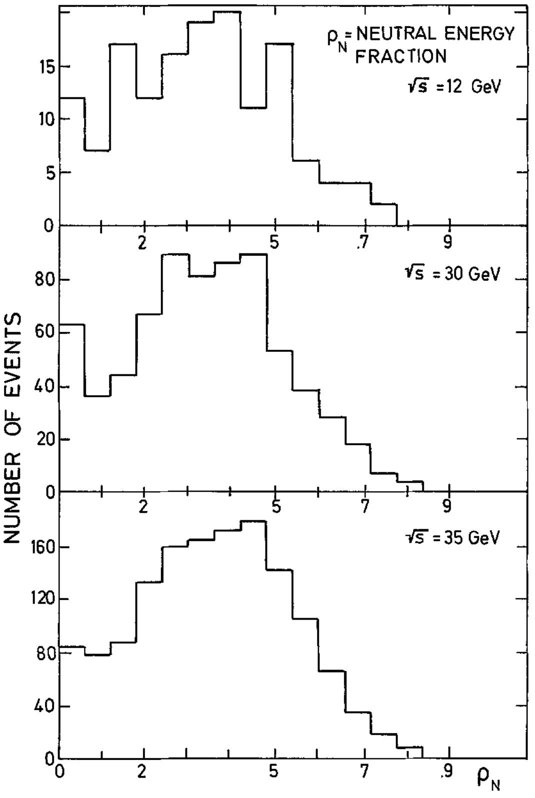

Fig. 2. The distributions of neutral energy fraction event by event for three centre-of-mass energies, computed under the approximations described in the text

The corrected mean neutral energy fractions for the three centre-of-mass energies are listed in Table 1. The

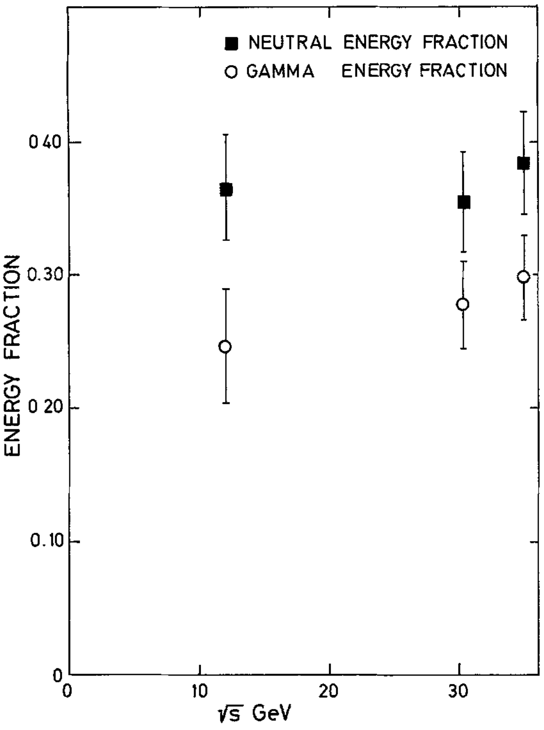

Fig. 3. The corrected mean gamma ray and neutral energy fractions versus centre-of-mass energy

Table 2. The gamma ray and neutral particle energy fractions without correction for strange particle decay compared to a model calculation

$\sqrt{s}$ (GeV)		ϱ_γ	ϱ_N
12.00	Data	0.26±0.04	0.33±0.04
	Monte Carlo	0.28±0.01	0.36±0.01
30.30	Data	0.29±0.03	0.32±0.03
	Monte Carlo	0.29±0.00	0.38±0.00
34.89	Data	0.31±0.03	0.35±0.04
	Monte Carlo	0.29±0.00	0.37±0.00

indicated uncertainties are mainly systematic. They are largely due to momentum measurement errors for the highest energy tracks and to the various effects of nuclear interactions in the material between the jet chamber and the beam axis.

The energy fractions ϱ_γ and ϱ_N are plotted in Fig. 3 as a function of the centre-of-mass energy $\sqrt{s}$. Both fractions are independent, within experimental errors, of the centre-of-mass energy.

It is of interest to determine ϱ_γ and ϱ_N for the subclass of planar events alone. These events are believed to be due to gluon bremsstrahlung and the relative energy fractions may be different for quark and gluon fragments. Planar events are defined by the criteria $Q_2 - Q_1 > 0.07$ and $Q_1 < 0.06$, where the quantities Q are the eigenvalues of the normalized sphericity tensor ordered $Q_1 < Q_2 < Q_3$ (For details see [3].)

The values of ϱ_γ and ϱ_N for planar events are listed in Table 1 along with the corresponding values for the full set of events. The fractions ϱ_γ and ϱ_N for the planar events are not significantly different from those for the full sample.

An additional indication that gluon fragments do not differ greatly from quark fragments in terms of the relative amounts of gamma ray or charged particle energy carried by their decay products can be obtained by reconstructing three jets within the planar events. The method of Ellis and Karliner [9] is then used to assign particles to the three jets. The three jets are labelled "slim" (quark), "quark" and "gluon" by criteria which depend upon their relative directions [10]. For the 35 GeV data we present the observed ratios of gamma ray energy to charged particle energy separately for the three jets. We cannot obtain the fractions ϱ_γ and ϱ_N for the individual jets because the total energies of the jets, including the energies of unobserved K_L^0's, neutrons and neutrinos, are unknown. The average ratios of gamma ray to charged particle energy are 0.47±0.01, 0.46±0.01, and 0.44±0.02 for the "slim", "quark" and "gluon" jets respectively. Differences in acceptance for the three jets are small and have not been accounted for. Thus only statistical errors are presented.

It is interesting to compare the charged and gamma ray energy fractions extracted from the data with those given by the model of [5]. Since the model does not include the production of baryons, we remove the corrections to ϱ_γ and ϱ_N due to Λ decay and also, for reasons of convenience, the corrections due to K_s^0 decay. ϱ_γ and ϱ_N then refer to a time after Λ's and K_s^0's have decayed. Table 2 shows these quantities, with statistical and systematic errors, compared to the Monte Carlo simulation of [5]. The errors on the Monte Carlo results are statistical only. The agreement between the model and the data is good.

A theoretical upper bound on ϱ_N of 0.77 has been obtained [11] under the assumption that multihadron final states consist only of pions and are isospin eigenstates with eigenvalue 0 or 1. Lower bounds, based on the same assumption, are only available for the mean multiplicity of π^0's [12]. For isospin 0 the upper and lower limits coincide and the multiplicity must average just 1/3 the total number of pions. For isospin 1 the analogous fraction is bounded from below by a limit which tends to 1/5 as the number of pions becomes large. The limit is lower for finite numbers. If we make the hypothesis that all pions have the same mean energy and neglect low multiplicity final states, we thus obtain a lower limit on ϱ_N of 20%. Our data on ϱ_N are within these bounds.

The high energy data of this experiment may be compared to measurements performed at SPEAR by the SLAC-LBL collaboration [13] and the Crystal Ball experiment [14]. Early data from SPEAR seemed to indicate that ϱ_N was rising with energy. It now appears that this 'energy crisis' is not real. The observed fraction can be reproduced by a plausible model of multihadron final states consistent with the existing data but not verified in detail [13]. The more recent data from the Crystal Ball experiment indicate that the observed neutral energy fraction is about 0.3 between 4 and 5.2 GeV. This indicates practically constant neutral fractions from charm threshold up to 35 GeV.

The difference $\sigma_N - \varrho_\gamma$ provides an upper limit on the amount of energy carried by neutrinos. For the purpose of estimating the neutrino energy fraction we remove the K_s^0 and Λ corrections explained above because they introduce a correlation of errors on ϱ_γ and ϱ_N. Instead we take the neutral and gamma ray energy fractions at a time after the K_s^0's and Λ's have decayed. The result is that 7.6 ± 5.7, 3.2 ± 4.8, and 4.1 ± 4.8% of the centre-of-mass energy is carried by neutrinos and long-lived neutral hadrons at 12, 30, and 35 GeV, respectively. Then using the available data on K_L^0 [6] and n, $\bar{n}$ [7] production we derive the neutrino energy fractions given in Table 1. From these numbers one obtains a 95% C.L. upper limit of about 10% on the fraction of energy carried away by neutrinos. This upper limit strongly disfavours the Pati-Salam model [1], which predicts that multihadronic final states are produced in e^+e^- collisions via free quarks of unit charge which decay into hadrons and neutrinos, giving rise to a neutrino energy fraction between 18% and 28%. The observed number however is in accord with models assuming confined quarks. The model of [5] for instance assumes a neutrino energy fraction of about 2%.

Acknowledgement. We acknowledge the efforts of the PETRA machine group, who provide us with the opportunity of doing this experiment, and also the efforts of the technical support groups of the participating institutes in the construction and maintenance of our apparatus. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Education Ministry of Japan and by the U.K. Science Research Council through the Rutherford Laboratory. The visiting groups at DESY wish to thank the DESY directorate for their hospitality.

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