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A Study of the Semileptonic Decay Mode $D^0 \to K^- e^+ \nu_e$*

The Tagged Photon Spectrometer Collaboration

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ABSTRACT

We present an analysis of the exclusive semileptonic decay mode $D^0 \to K^- e^+ \nu_e$. We have measured the ratio of decay rates $\Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^0 \to K^- \pi^+)$. After correcting for the reconstruction efficiencies and subtracting the contribution from other decay modes, we have found the ratio to be equal to $0.91 \pm 0.07(stat) \pm 0.11(syst)$, corresponding to a $D^0 \to K^- e^+ \nu_e$ branching fraction of $(3.8 \pm 0.5 \pm 0.6)\%$. Combining our result with a measurement of the D^0 lifetime, we find $\Gamma(D^0 \to K^- e^+ \nu_e) = (9.1 \pm 1.1 \pm 1.2) \times 10^{10} s^{-1}$. We have also measured the vector form factor $f_+(t)$ and find that it is consistent with the single pole form where the pole mass $M_{D_s^*} = 2.11\ GeV/c^2$.

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The study of exclusive semileptonic decays is particularly interesting because of the simplicity of the underlying interaction and the wide scope of physics one can learn from it. Cabibbo-favoured decays can proceed only through flavour decay (spectator) processes and thus, unlike hadronic decays, there is no uncertainty due to the presence of other diagrams. Moreover, there is no possibility of interference between the leptons and the hadrons in the final state. The matrix element for semileptonic decays is the product of a hadronic part and a leptonic part. Since the leptonic part of the matrix element is well understood, semileptonic decays probe the structure of the hadronic part of the matrix element.

The decay $D^0 \to K^- e^+ \nu_e$ has been widely discussed in the literature[1]. (Throughout the paper the charge conjugate states are implicitly included.) Because of the $V - A$ nature of the weak current and because the D and K mesons are pseudoscalars, the $D - K$ interaction is a pure vector. The relevant matrix element is given by

$$M = \frac{G}{\sqrt{2}} V_{cs}[(p_D + p_K)_\alpha f_+(t) + (p_D - p_K)_\alpha f_-(t)] \times \bar{u}_\nu \gamma^\alpha (1 + \gamma_5) u_e \tag{1}$$

where p are the four-momenta, u are Dirac bispinors, and t is the four-momentum transfer from D to K (or $M^2_{e\nu}$). According to the Dirac equation, the terms involving the form factor $f_-(t)$ always appear in the final result proportional to the electron mass, and their contribution to the decay rate can be neglected. The decay rate can then be shown in the D^0 center of momentum system to be proportional to

$$\Gamma \propto G^2 |V_{cs}|^2 |f_+(t)|^2 [(E_K)^2 - (M_K)^2 - (M_D - E_K - 2 \times E_e)^2] \tag{2}$$

From the observed t distribution one can extract the functional form of the vector form factor $f_+(t)$. Using the D^0 semileptonic branching fraction, the D^0 lifetime and a theoretical calculation[2,3] of $f_+(0)$), one can determine the $|V_{cs}|$ element of the Kobayashi-Maskawa (K-M) matrix.

This paper presents results from E691, a high energy photoproduction experiment performed at the Fermilab Tagged Photon Spectrometer. The detector, a two-magnet spectrometer of large acceptance, very good mass resolution, particle identification (Čerenkov counters, electromagnetic and hadronic calorimetry, muon filter) and equipped with a high resolution silicon microstrip detector, has been described elsewhere[4]. The electron identification used (a)the ratio of energy seen in the electromagnetic calorimetry to track momentum, (b)the sizes of the signals in the electromagnetic and hadronic calorimeters, (c)the transverse shower shapes, and (d)the difference between the projected track position and that of the calorimeter shower centroid. The electron efficiency and the pion misidentification probability, while being position and energy dependent, had (for the cuts used) typical values of 72% and 0.5% respectively. The incident photons, produced via the bremsstrahlung of 260 GeV electrons, had an average tagged energy of 145 GeV. We used an open trigger, based on the total transverse energy detected in the calorimeters. This accepted $\sim$ 30% of the total hadronic cross section while being $\sim$ 80% efficient for charm. The experiment recorded 10^8 triggers. This paper is based on an analysis of the full data sample.

We have selected the candidate events through the cascade decay $D^{*+} \rightarrow D^0\pi^+$ followed by $D^0 \rightarrow K^-e^+\nu_e$. The technique used is based on the fact that it is possible to reconstruct the missing neutrino momentum providing that the D^0 direction is measured with sufficient precision in the vertex detector. The algebra is easiest in the Lorentz frame with z-axis chosen along the D^0 path, and such that p^Z_{Ke} is equal to zero, where one writes

$$p^Z_\nu = p^Z_D \tag{3}$$

$$\vec{p}\,^T_\nu = \vec{p}\,^T_{Ke} \tag{4}$$

$$E_D = E_{Ke} + E_\nu \tag{5}$$

Setting $M_{Ke\nu} = M_D$ and $M_\nu = 0$, one can easily obtain the longitudinal component of the neutrino momentum, p^Z_ν :

$$(p^Z_\nu)^2 = \frac{F^2}{4 \times (E_{Ke})^2} - (p^T_{Ke})^2 \tag{6}$$

$$\begin{aligned} F &= (M_D)^2 - (p^T_{Ke})^2 - (E_{Ke})^2 \\ &= 2 \times E_{Ke}E_\nu \geq 0 \end{aligned} \tag{7}$$

Because of the finite vertex position resolution, F and $(p^Z)^2$ can acquire non-physical, negative values. We have required $F > 0$, which reduces background considerably while keeping about 60% of signal. In the case of $(p^Z_\nu)^2 < 0$ (about 40% of events), we have set[5] $(p^Z_\nu)^2 = 0$. In the remaining events, because equation (6) is quadratic there exist two solutions for the $E_{Ke\nu}$. In some cases, one of them is non-physical and can be discarded (e.g. $E_{Ke\nu} > 260\ GeV$). In the remaining events, for every π^+ we will obtain two D^{*+}

solutions, corresponding to the two p_ν^Z solutions. We choose the one which gives the *lower* D^* mass[5].

The experimental procedure consists of selecting K^-e^+ pairs originating from a common vertex significantly separated from a primary one, solving for the $\vec{p}_\nu$, and then combining the $K^-e^+\nu_e$ four-momentum (constrained to M_D) with that of a π^+ candidate. Background distributions were obtained using the same approach, but using the *wrong charge* $K^+e^+\nu_e\pi^+$, $K^+e^+\nu_e\pi^-$ and $K^+e^-\nu_e\pi^+$ combinations. These were added together, and subtracted from the final $M_{K^-e^+\nu_e\pi^+}$ distribution after being normalized to the integral over the mass interval $2.03 - 2.40\ GeV/c^2$.

We required the kaon and electron candidates to be good quality and well identified tracks. The K^-e^+ vertex was required to be well separated from the primary vertex ($\Delta\vec{x} \geq 7\sigma_{\vec{x}}$) and both vertices were required to be well constrained. The primary vertex has to contain at least two tracks, with a bachelor pion from the D^* decay being one of them. A cut on electron momentum, $p_e \geq 12\ GeV/c$ was applied to suppress electrons from pair conversions from π^0 decays. Due primarily to this momentum cut-off the event detection efficiency is sensitive to the electron radiation in the material dowstream of the decay vertex and the radiative corrections, including real and virtual photons[6]. The combined effect of these corrections is to change the reconstruction efficiency by a factor of 0.84 ± 0.04.

The largest physics background comes from another semileptonic decay mode, namely $D^0 \rightarrow K^-e^+\pi^0\nu_e$. The observed mass spectrum is the sum of contributions from the $K^-e^+\nu_e$ and $K^-e^+\pi^0\nu_e$ modes. To estimate the feedthrough from the $D^0 \rightarrow K^-e^+\pi^0\nu_e$ channel, we use Monte Carlo simulation. We have adopted the theoretical description of the $K^-e^+\pi^0\nu_e$ mode of Wirbel, Stech and Bauer[2]. To determine the number of produced $D^0 \rightarrow K^-e^+\pi^0\nu_e$ events we use the relation $\Gamma(D^0 \rightarrow K^*e\nu) = \Gamma(D^+ \rightarrow \overline{K^{*0}}e\nu)$ (which follows from isospin invariance), the E691 measurement of $\Gamma(D^+ \rightarrow \overline{K^{*0}}e^+\nu_e)$, and the assumption of K^* dominance in $D^0 \rightarrow K^-e^+\pi^0\nu_e$ channel. (In a parallel analysis[7], we have measured $\Gamma(D^+ \rightarrow \overline{K^{*0}}e^+\nu_e) = (4.1 \pm .7 \pm .5) \times 10^{10}\ s^{-1}$, and found that $K^-\pi^+$ system is dominated by $K^*(890)$). The net effect of this correction is small, 7% of the total $D^0 \rightarrow K^-e^+\nu_e$ rate.

In Figures 1a,1b and 1c we present $M_{Ke\nu\pi}$ distributions for the signal, normalized background and background subtracted signal respectively. We find 347 events in the signal region ($2.000 - 2.025\ GeV/c^2$), and 250 events after background subtraction. The reconstruction efficiency for this set of cuts was 1.45%.

The reconstruction efficiencies were obtained using Monte Carlo generated events. The Monte Carlo $K^- e^+ \nu_e$ events were weighted to reproduce the t distribution expected from a form factor with a single pole form

$$f_+(t) = f_+(0) \times \frac{M^2_{D^*_s}}{M^2_{D^*_s} - t} \tag{8}$$

with $M_{D^*_s} = 2.11\ \ GeV/c^2$, as measured by Mark III[8].

To estimate the systematic error due to the background subtraction and the uncertainties of the Monte Carlo simulation, we varied the cuts on vertex separation, track quality cuts, and particle identification of the electron and kaon candidates. The uncertainty in the electron reconstruction efficiency is estimated to be 5%. The systematic error and statistical error in the reconstruction efficiencies were combined in quadrature. The number of events *produced* in the mode $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- e^+ \nu_e$, after being corrected for the reconstruction efficiencies and for the feedthrough from $K^- e^+ \pi^0 \nu_e$ channel, is compared with the number of events *produced* in the mode $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ to deduce the ratio of decay rates $\Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^0 \to K^- \pi^+) = 0.91 \pm 0.07(stat) \pm 0.11(syst)$. Using the Mark III[9] branching fraction $B(D^0 \to K^- \pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ we obtain the result

$$B(D^0 \to K^- e^+ \nu_e) = (3.8 \pm 0.5 \pm 0.6)\%$$

This measurement agrees well with the Mark III measurement[10] $B(D^0 \to K^- e^+ \nu_e) = (3.9 \pm 0.6 \pm 0.6)\%$. Our measurement of the semileptonic braching fraction can be combined with the E691 measurement of D^0 lifetime[4] to obtain the semileptonic partial rate $\Gamma(D^0 \to K^- e^+ \nu_e) = (9.1 \pm 1.1 \pm 1.2) \times 10^{10}\ s^{-1}$.

Figure 2 presents the distribution of the four-momentum transfer t (or $M^2_{e\nu}$). If this distribution is fit to a form factor with a single pole, we find that the mass of the exchanged particle is, $M_{D^*_s} = 2.1 \pm^{0.4}_{0.2}\ GeV/c^2$. This is consistent with the value of $M_{D^*_s} = 2.11\ \ GeV/c^2$ measured *directly* by Mark III[8]. With the value of $M_{D^*_s}$ fixed at $2.11\ GeV/c^2$ we can use equation (2) to determine $\Gamma(K^- e^+ \nu_e) = |V_{cs}|^2 |f_+(0)|^2 1.82 \times 10^{10} s^{-1}$.

Comparing the predicted and measured values of the semileptonic partial rates we find $|V_{cs}|^2 |f_+(0)|^2 = 0.50 \pm 0.07 \pm 0.08$.

If $|f_+(0)|$ were known, this measurement could be translated directly into a measurement of $|V_{cs}|$. If we take $|f_+(0)| = 0.76$ from the calculation of Wirbel, Stech and Bauer[2] and assume a form factor with a single pole, then we have the model dependent result $|V_{cs}| = 0.93 \pm 0.06 \pm 0.08$. Reversing the argument, we can adopt a value of $|V_{cs}| = 0.975$ (assuming three families and imposing the unitarity condition on K-M matrix) and obtain a measurement of $|f_+(0)| = 0.73 \pm 0.05 \pm 0.07$.

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REFERENCES

1. A. Ali and T.C. Yang, Phys. Lett. **65B**, 275 (1976); I. Hinchliffe and C.H. Llewellyn Smith, Nucl. Phys. **B114**, 45 (1976); F. Bletzacker, H.T. Nieh and A. Soni, Phys.Rev. **D16**, 732 (1977); W. J. Wilson, Phys. Rev. **D16**, 742 (1977); V. Barger, T. Gottschalk and R.J.N. Phillips, Phys. Rev. **D16**, 746 (1977); D. Fakirov and B. Stech, Nucl. Phys. **B133**, 315 (1978); X.Y. Pham and J.M. Richard, Nucl. Phys. **B138**, 453, (1978); K. Kudoh, Prog. Theor. Phys. **60**, 1834 (1978); M. Suzuki, Nucl. Phys. **B145**, 420 (1978); N. Cabibbo and L. Maiani, Phys. Lett. **79B**, 109 (1978); G.L. Kane, W.B. Rolnick and K. Stowe, Nucl. Phys. **B152**, 390 (1978); N. Cabibbo, G. Corbo and L. Maiani, **B155**, 93 (1979); M. Gluck, Phys. Lett. **84B**, 459 (1979).
2. M. Wirbel, B. Stech and M. Bauer, Z. Phys. **C29**, 637 (1985);
3. B. Grinstein, M.B. Wise, Phys. Lett. **B197**, 249 (1987); and references therein.
4. J.R. Raab, Phys. Rev. **D37**(1988) 2391; J.R. Raab, Ph.D. Thesis, University of California at Santa Barbara, Report UCSB-HEP-87-8 (1987) and references therein.
5. It has been checked with Monte Carlo events that this procedure does not introduce any serious biases. It removes the ambiguity problem in an experimentally clean way, making the subsequent interpretation of results straightforward.
6. The radiative corrections have been evaluated using the modified calculation of K_{e3} decay, see: M. Dremin, JETP 35 (1959) 355; E. S. Ginsberg, Phys. Rev. **142** (1966) 1035; E. S. Ginsberg, Phys. Rev. **162** (1967) 1570.
7. J.C. Anjos *et al*, The Tagged Photon Spectrometer Collaboration, submitted to Phys. Rev. Letters.
8. R. Schindler, Mark III Collaboration, SLAC-PUB-4055, September 1986.
9. J. Adler *et al*, Mark III Collaboration, Phys. Rev. Lett. **60** (1988) 89.
10. R. Schindler, Proceedings of the XXIII International Conference on High Energy Physics **Vol. I**, page 745, Berkeley (World Scientific, 1986); D. Coffman, Ph. D. Thesis, California Institute of Technology, CALT-68-1415 (1987).

FIGURE CAPTIONS

Figure 1. (a) Effective mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations. The mass of $K^-e^+\nu_e$ system constrained to that of a D^0. (b) Effective mass distribution for $K^+e^+\nu_e\pi^+$, $K^-e^-\nu_e\pi^+$ and $K^+e^-\nu_e\pi^+$ combinations (background), normalized to the integral over the mass interval $2.03 - 2.40$ GeV/c^2 of the correct sign (signal) distribution. (c) Background subtracted effective mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations.

Figure 2. Distribution of the four-momentum transfer from D to K ($t = M^2_{e\nu}$). The superimposed curve is the result of a fit to a t-distribution expected, after integration over phase space, from the assumed single pole form for the vector form factor. The fit yields a value of $M_{D^*_s} = 2.1 \pm^{0.4}_{0.2}$ GeV/c^2.

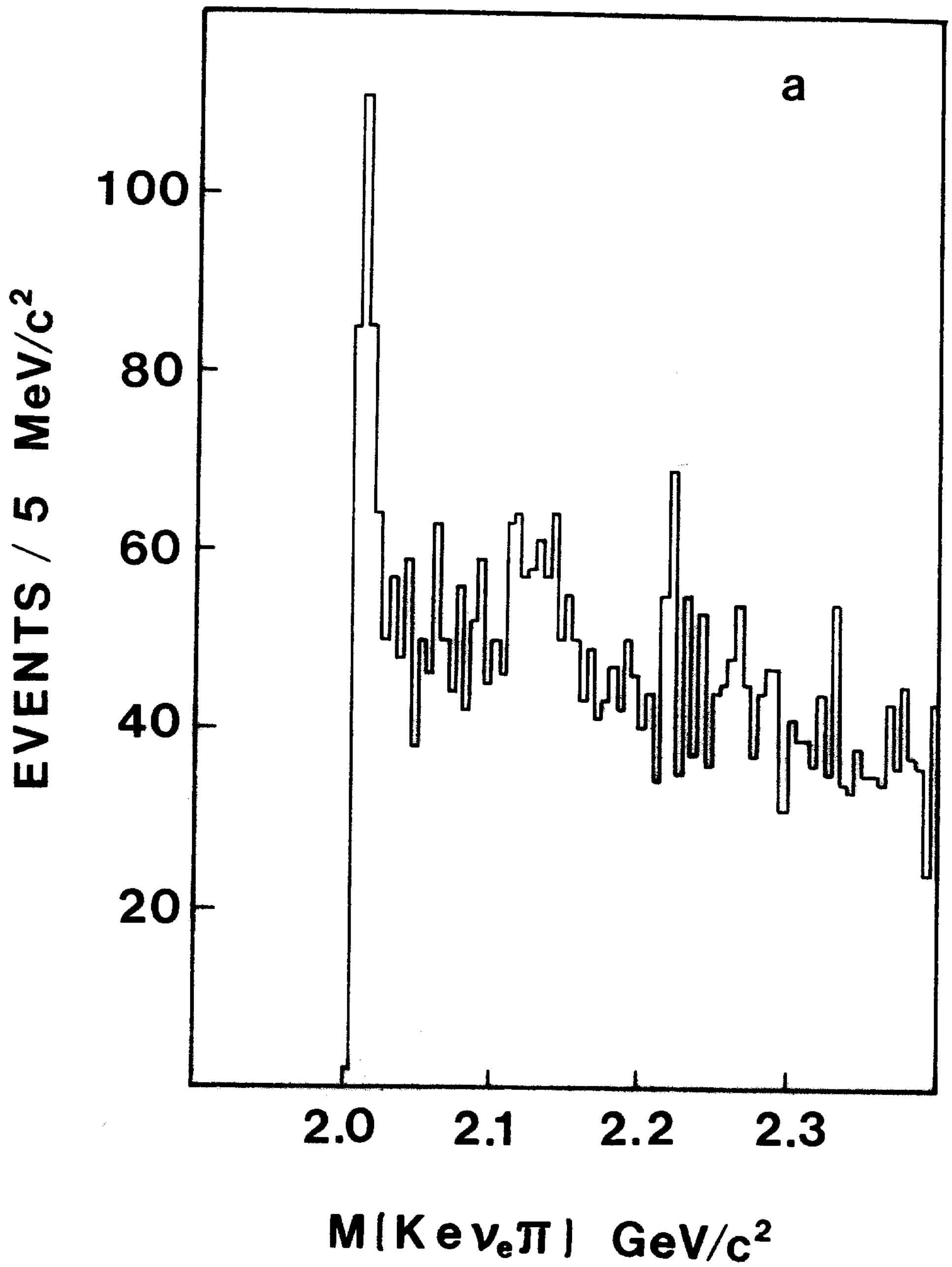

Fig. 1a

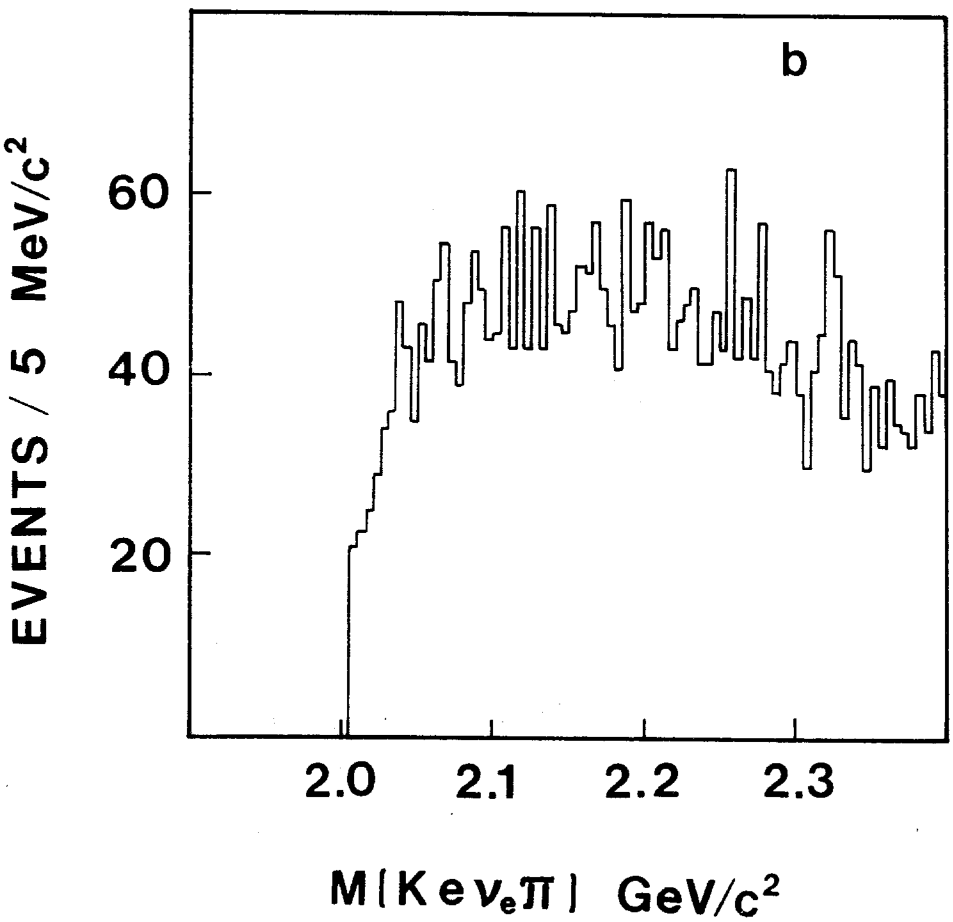

Fig. 1b

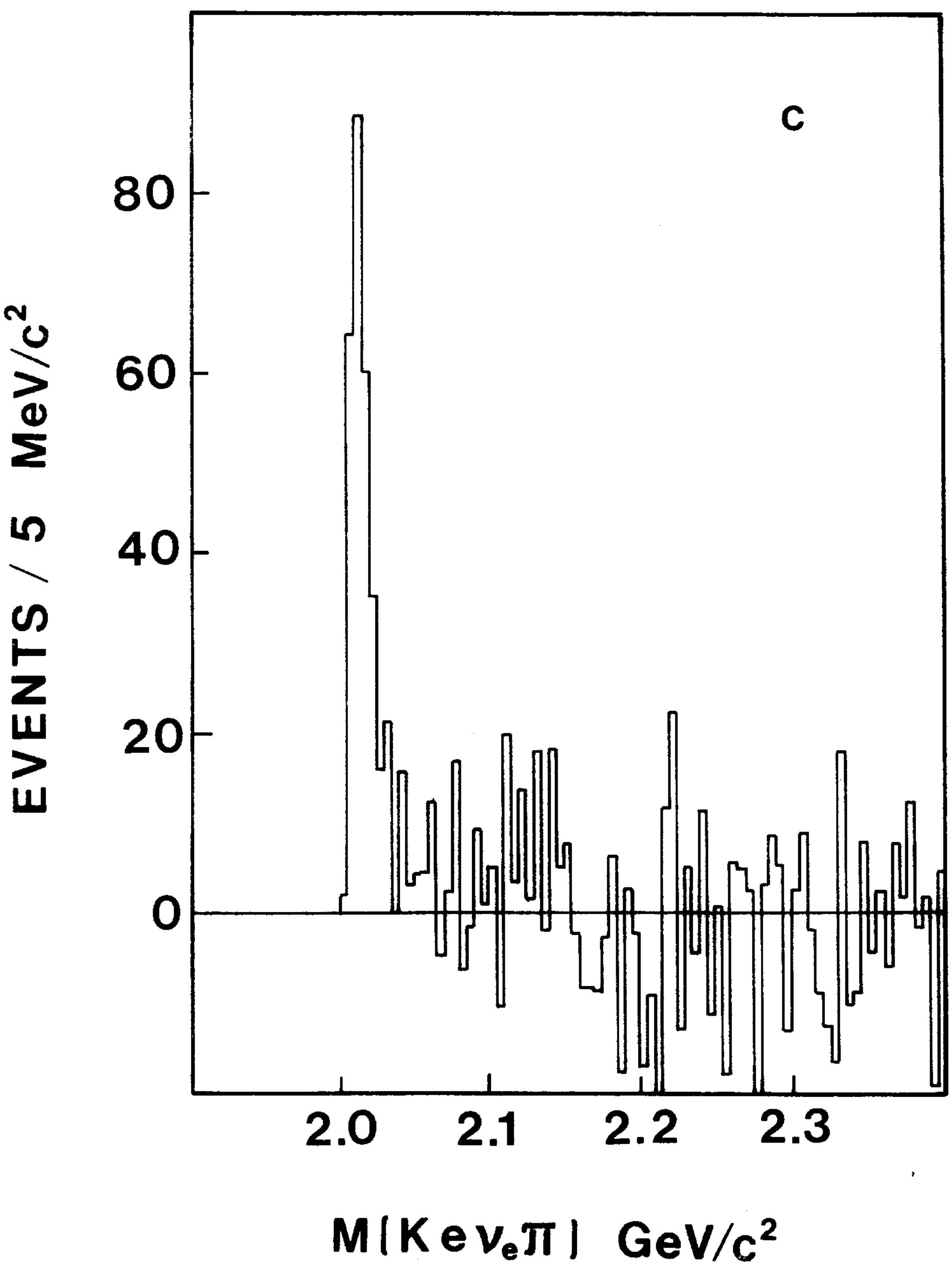

Fig. 1c