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Abstract:

We report the results of a search for monoenergetic photons in the decay of both the $\Upsilon(1S)$- and the $\Upsilon(2S)$-meson. Photons converted in the beam tube or the drift chamber inner wall, and photons detected with the barrel shower counters of the ARGUS detector, respectively, have been used in the analysis. No narrow peak is observed in the energy interval $0.5\ \mathrm{GeV} \leq E_\gamma \leq 4.0\ \mathrm{GeV}$.

1. Introduction

The study of radiative decays of bound quark-antiquark systems into lighter states is a promising means of searching for new phenomena. The high mass of heavy $q\bar{q}$ systems gives access to a wide mass interval for any new states. In addition, the narrow width of such heavy systems results in a favourable ratio of radiative to hadronic decays. Furthermore, results can be interpreted easily, since the initial state has a quantitatively understood dynamics [1] and well defined quantum numbers. A further advantage is the copious production of these states in electron-positron annihilation. The detection of the emitted photons allows the investigation of inclusive final states not biased by assumptions about specific decay channels of the new light system. A Higgs meson is an especially interesting example of a state accessible in such an investigation. It has been shown [2] that in nonminimal schemes the Higgs mass can be smaller than the Υ-mass and the branching ratio can be large enough to result in a statistical significant signal with our currently recorded luminosities.

The recently reported enhancement in the decay channel $\Upsilon(1S)\to\gamma X$ at a photon energy of $E_\gamma = 1.07$ GeV [3] has stimulated numerous theoretical investigations. These show that various proposed extensions of the standard model allow for states with $M < 9.5\ \frac{\mathrm{GeV}}{c^2}$, which can be reached by radiative decays of the $\Upsilon(1S)$ and $\Upsilon(2S)$ with comfortable branching ratios. Models with two Higgs doublets [2], heavy gluonium states [4], bound states of supersymmetric particles [5] and new coloured scalars [6] as well as four quark molecules [7] have been discussed in this context. However, upper limits for the branching ratio of the radiative Υ decay to some of these proposed new states, derived from general principles [8], are too low to explain the results of ref. [3].

In this paper we report on investigations of the $\Upsilon(1S)\to\gamma X$ and $\Upsilon(2S)\to\gamma X$ inclusive decays. Results on the decay channel $\Upsilon(1S)\to\gamma\tau^+\tau^-$ have already been published [9].

2. Data analysis

The data used for the study were collected with the ARGUS detector at the DORIS II electron positron storage ring. The detector, its trigger and the selection criteria for hadronic events are described in ref. [10]; i.e., essentially we require ≥3 charged tracks coming from the vertex. The particle identification capabilities are discussed in ref. [11]. The event sample consists on the $\Upsilon(1S)$ ($\Upsilon(2S)$-) resonance of 321 k (309 k) multihadron events corresponding to an integrated luminosity of 23.6 pb^{-1} (38.6 pb^{-1}). The data on the $\Upsilon(1S)$ were collected with two detector configurations differing slightly by the amount of material between the interaction region and the drift chamber. Therefore, the data sets were analyzed separately and only the final results were combined. Two independent methods have been applied in searching for monochromatic photons. These are discussed separately in the following sections.

2.1 Measurement of the photon energy with the barrel shower counters

The shower counters of the ARGUS detector [12] have been used to measure the energy of single photons emitted in $\Upsilon(1S)$ and $\Upsilon(2S)$- decays. Only photons detected in the barrel shower counters ($|\cos\theta_\gamma|\leq 0.7$) were used because the background from radiative Bhabha scattering is negligible in this region. This requirement has the further advantage of improving the energy resolution, which is better for the barrel shower counters than for the endcap shower counters ($0.7 < |\cos\theta_\gamma| < 0.94$).

Energy clusters resulting from the overlap of hits by charged and neutral particles in neighbouring shower counters are identified by the analysis program and removed from further consideration. The main background to single photon decays of the Υ-mesons is due to photons from π^0 decay. This background is suppressed by two different cuts, which turn out to be effective in different energy regions. To reject clusters where the small opening angle between photons from a π^0 decay does not allow

separation of the energy deposited in the shower counters, we have applied a cut which exploits the characteristic shape of transverse energy deposition for electromagnetic particles interacting in the counters [13]. This cut effectively suppresses overlapping photons from the decay of high energy π^0, and consequently it reduces the background mainly in the high energy part of the photon spectrum ($E_\gamma \geq 0.9$ GeV) as shown in fig. 1. To suppress the contribution from π^0 decays to photons of low energy and wide opening angle, we have rejected all photons which, when combined with another photon in the event, form a π^0 within the mass resolution of the detector. This cut reduces the background mainly for the low energy part ($E_\gamma < 1$ GeV) of the photon spectrum (fig. 1).

The measured photon spectrum after application of these cuts is shown in fig.1. No narrow peak is observed. To convert this to a quantitative limit for the branching ratio, we have fitted the observed spectrum using two exponentials to model the background, and assume any signal would be a gaussian with width given by the appropriate detector resolution. From the gaussian likelihood function, $G(N|\mu,\sigma)$, a limit on the number of events, N, from a radiative transition to a narrow new state, is computed from the fit given the values for the mean , μ, and RMS error, σ. The upper limit N_{MAX} (90% confidence level) is then defined by

$$\int_0^{N_{MAX}} G(N|\mu,\sigma)\, dN = 0.9 \int_0^{\infty} G(N|\mu,\sigma)\, dN$$

No significant peak in the energy region from 0.5 GeV to 4 GeV is observed. This allows us to derive an upper limit for the production of a narrow state after correction for efficiency. The losses due to the overlap of a charged or neutral cluster with the detected photon have been determined from geometrical considerations and Monte Carlo calculations: they contribute a maximum of 30%. The loss due to the shape cut is determined from radiative Bhabha events to be 5%. The losses due to the π^0-cut have been derived

from multihadron events collected on the $\Upsilon(1S)$ by treating one charged hadron as a photon with the same three momentum. The energy of the substitute photon has been convoluted with the detector resolution, then paired with the real photons in the event and finally subjected to the same π^o-mass cuts as used in the analysis. The resulting efficiency for a single photon to pass the π^o-mass cut is plotted in fig. 2. It depends strongly on the energy. To determine the branching ratio, we have taken the total number of $\Upsilon(1S)$- ($\Upsilon(2S)$) mesons from the measured excitation curve.
The detection and reconstruction efficiency for hadronic decays of the produced state X has been determined from Monte Carlo calculations. At large m_X the decay $X \to c\bar{c}$ and $X \to gg$ were used, while for $m_X \sim 3$ GeV a phase space decay was assumed. The efficiency is larger than 0.9. The upper limits (90% confidence level), determined in the energy interval 0.5 GeV $\leq E_\gamma \leq 4.0$ GeV, are summarized in figs. 3a, b for the decay $\Upsilon(1S) \to \gamma + X$ and $\Upsilon(2S) \to \gamma + X$ respectively.

2.2 Measurement of the energy spectrum of converted gammas

A second, statistically independent search for narrow states is based on the analysis of photons converted in the beam tube or in the inner wall of the drift chamber. The advantage of this analysis is the high resolution achieved (σ_γ = 10 MeV at E_γ = 1 GeV), the disadvantage is the low detection efficiency of ≈2% after application of all cuts. These numbers can be compared with the resolution of 28 MeV and efficiency of 18% quoted in ref. [3].

The analysis starts from the same data sample as discussed in section 2.1. A candidate for a converted photon has to fulfill the following criteria:

- two tracks of opposite sign are produced at a common secondary vertex whose position coincides, within errors, with either the beam tube or the inner wall of the drift chamber.
- the χ^2 of the vertex fit has to be small
- the opening angle of the pair is smaller than 18° and the p_T of the charged tracks with respect to the reconstructed direction of the converted photon is less than 0.02 $\frac{\text{GeV}}{c}$.

To check the quality of the reconstruction procedure, the invariant mass spectrum of two converted photons has been studied and is shown in fig. 4. A clear π^o-signal is observed with a fitted mass of $m_{\gamma_c\gamma_c}$ = (134.8±0.6) $\frac{\text{MeV}}{c^2}$, in good agreement with the table value [14].

From the full data sample we have selected those events with a candidate for a converted photon. To select events where one of the emitted photons was converted, we have applied further cuts. We demand that the invariant mass of the electron-positron pair be small ($m_{e^+e^-} < 0.05 \frac{\text{GeV}}{c^2}$). Moreover, we require the probability to be larger than 1% that the positive and negative track satisfies the electron mass hypothesis. This information is derived from the energy loss (dE/dx) as measured in the drift chamber [15] and - when available - from the time of flight system [16]. The overall efficiency of these selection cuts is ε_1 = (0.79±0.06).

The main background for the measured photon spectrum is due to π^o decays, where one of the decay photons converts. In the kinematical region of interest for the present analysis, these decays often result in a configuration where the energy deposition of one of the particles produced by photon conversion overlaps in the shower counters with the energy cluster due to the second photon from the π^o decay. The contribution of such overlaps is reduced considerably by comparing the energy E deposited by the track in the shower counters with its momentum measured in the drift chamber. This difference was required to be smaller than 1.5 standard deviations for the electron and the positron.
The background from this source was reduced further by a cut on the transverse energy deposition in the shower counters [13].
As an example the resulting photon spectrum from $\Upsilon(1S)$ decays is shown in fig. 5a. No narrow resonance signal is observed. A further background suppression is possible if one applies the π^o mass cut described in chapter 2.1. The resulting photon spectrum is shown in fig. 5b.

Upper limits for the branching ratios of the decays $\Upsilon(1S)\to\gamma X$ and $\Upsilon(2S)\to\gamma X$ were derived after correcting for the losses due to the different cuts. These were determined by Monte Carlo studies and checked by comparing them with experimental results derived from π^o decay and radiative Bhabha events. The overall efficiency for a single photon to pass the cuts applied to suppress contributions from π^o decay is $\varepsilon_2 = 0.84 \pm 0.12$, excluding the π^o mass cut. The conversion and reconstruction efficiency ε_3 of the photons was determined separately for the two data taking periods to allow for the different amount of converter material. The combined efficiency $\varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_3$ is plotted for the two periods in fig. 6 as a function of the energy of the converted photon. The difference between the full and broken curves reflects the reduction of the efficiency ε_2 due to the π^o mass cut.

The upper limit (90% confidence level) for the decay $\Upsilon(1S)\to\gamma X$ and $\Upsilon(2S)\to\gamma X$ was derived from the measured photon spectrum by fitting a third order polynomial and a gaussian of fixed position and width to the data and applying the efficiency corrections discussed. For the $\Upsilon(1S)\to\gamma X$ decay the results are shown separately for the two running periods in fig. 7a, the combined result is plotted in fig. 7b. No statistically significant resonance signal is observed in the whole energy region from 0.5 GeV to 4 GeV. The corresponding result for the decay $\Upsilon(2S)\to\gamma X$ is given in fig. 7c. Again no statistically significant signal of a narrow resonance is observed. One should note that the quoted limits correspond to narrow resonances only and are not relevant for a branching ratio such as Br $(\Upsilon\to\gamma gg)$.

3. Discussion

No signal with a significance of more than three standard deviations is observed. In particular, we do not reproduce the peak observed by the Crystal Ball Collaboration [3] at an energy of $E_\gamma = 1.07$ GeV in either of the two running periods (fig. 7a). The upper limit of < 0.15% at 90% confidence level (figs.3a,7b) is appreciably smaller than the branching ratio of (0.47±0.11)% reported by the Crystal Ball Collaboration. However, due to the large systematical errors of 0.26% quoted in ref [3], the results are still compatible. Upper limits for the decay $\Upsilon(1S)\to\gamma X$ in the photon energy region $E_\gamma > 1.2$ GeV have been published by the CUSB Collaboration [17]. The results presented in this paper extend these data to lower photon energies and improve the limits in certain photon energy regions.

Note that the limits determined in this analysis for the decays $\Upsilon(1S)\to\gamma X$ and $\Upsilon(2S)\to\gamma X$ already place interesting limits on the Higgs production in two doublet models [2] . These models provide the following relationship between the branching ratio $\Upsilon(nS)\to\gamma H$ in the doublet and standard Higgs model [2,18].

$$BR(\Upsilon\to\gamma H)_D = \rho^2 \cdot BR(\Upsilon\to\gamma H)_S$$

where

$$\rho^2 = \frac{v_1^2 + v_2^2}{v_1^2}$$

and v_1 and v_2 are the vacuum expectation values of the two Higgs fields in the doublet model. Combining the upper limits determined in our experiment (figs. 3a, 7b and figs. 3b, 7c) and dividing by the prediction of the standard Higgs model [18] we arrive at upper limits (90% confidence level) for ρ^2 plotted in figs. 8a,b for the decays $\Upsilon(1S)\to\gamma H$ and $\Upsilon(2S)\to\gamma H$ respectively. The ratio ρ^2 is larger than 1, reflecting the fact that the production of the standard Higgs particle [18] cannot be excluded by the present data set, but the result places constraints on nonminimal Higgs schemes.

4. Conclusion

In conclusion, we have measured the photon spectrum from $\Upsilon(1S)\to\gamma X$ and $\Upsilon(2S)\to\gamma X$ decays. No narrow photon line with a significance of more than three standard deviations is observed in the energy interval 0.5 GeV $\leq E_\gamma \leq$ 4.0 GeV. The upper limits for the branching ratio are roughly a factor of five to ten larger than the predictions of the standard Higgs model [18]. The upper limit (90% confidence level) for a narrow photon line at E_γ = 1.07 GeV is 0.15%, while the Crystal Ball Collaboration [3] has reported a signal at this position with a branching ratio of (0.47±0.11)%.

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Figure Captions

Fig. 1: Gamma spectrum observed with the barrel shower counters. The different curves correspond to successively stricter cuts applied in order to suppress contribution from $\pi^0 \to 2\gamma$ decays.
+++ raw data
—— data after shower shape cut
--- data with π^0-mass cut

Fig. 2: Reconstruction efficiency of single photons considering the shower shape cut (——) and the π^0-mass cut (---) discussed in the text.

Fig. 3: Upper limit (90% confidence level) for the branching ratio for the decay $\Upsilon(1S) \to \gamma X$ (a) and $\Upsilon(2S) \to \gamma X$ (b).

Fig. 4: Invariant mass of pairs of converted photons. The mass of the observed π^0 corresponds to $(134.8 \pm 0.6)\ \frac{MeV}{c^2}$.

Fig. 5: Spectrum of photons from the decay $\Upsilon(1S) \to \gamma X$ converted in the beam tube or the inner chamber wall of the ARGUS detector a) without and b) with π^0 mass cut described in the text.

Fig. 6: Efficiency for detection of a converted photon for the two running periods with (- - -) and without (——) π^0 mass cut.

Fig. 7: Upper limits (90% confidence level) for the branching ratio for $\Upsilon(1S) \to \gamma X$ from converted photons, a) for the two running periods separately (—— data taken 1984, --- data taken 1983) and b) combined result. c) Corresponding result for the decay $\Upsilon(2S) \to \gamma X$.

Fig. 8: Upper limits (90% confidence level) for the ratio of vacuum expectation values of the doublet Higgs model [2] and the standard Higgs model [18] as derived from the upper limits for the decays a) $\Upsilon(1S) \to \gamma X$ and b) $\Upsilon(2S) \to \gamma X$.

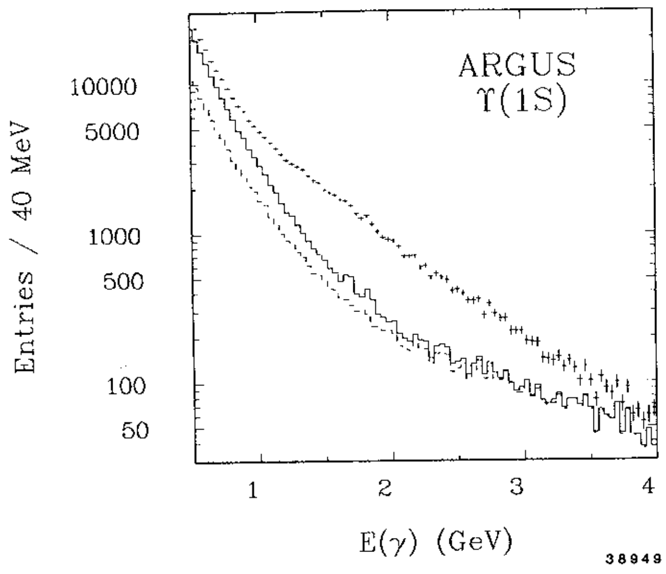

Fig. 1

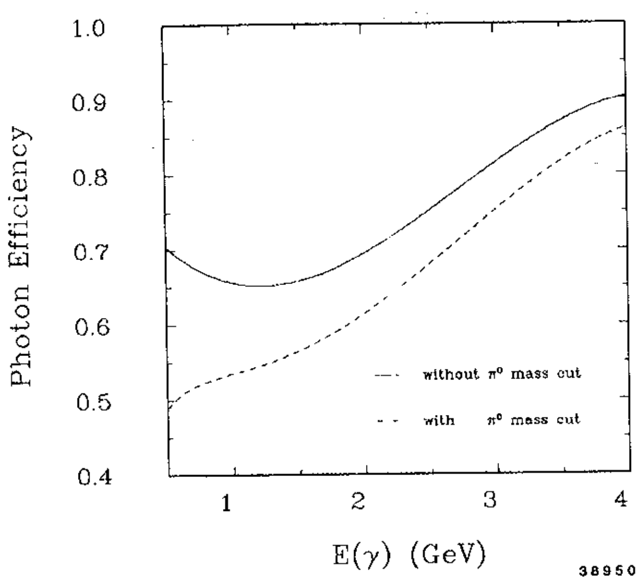

Fig. 2

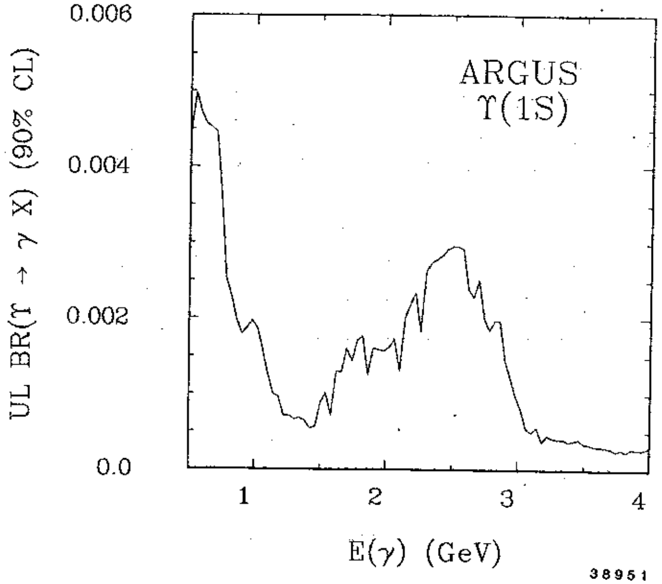

Fig. 3a

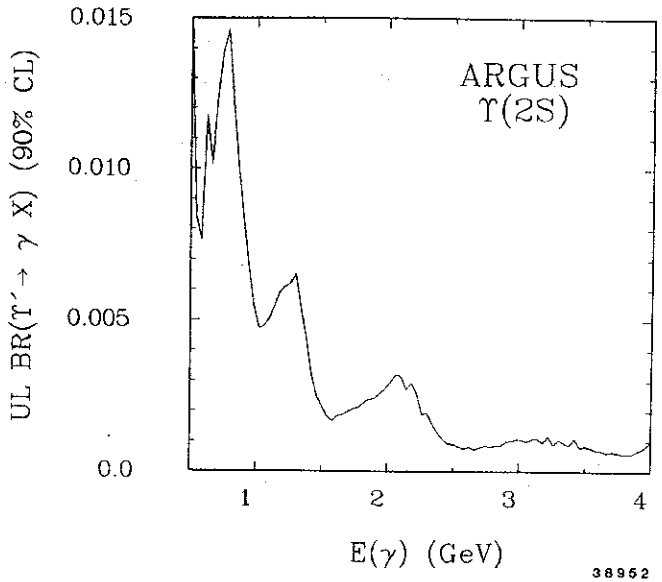

Fig. 3b

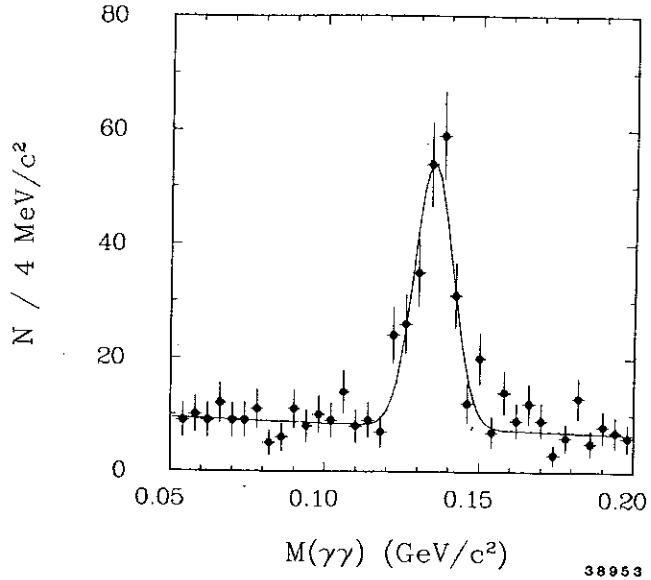

Fig. 4

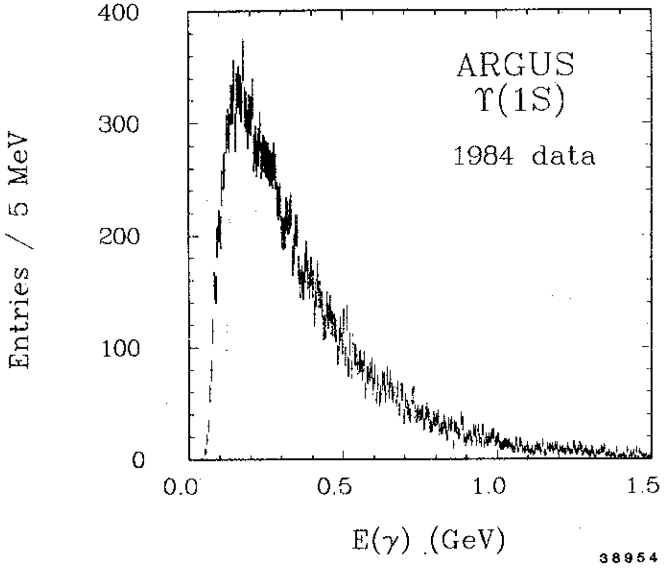

Fig. 5a

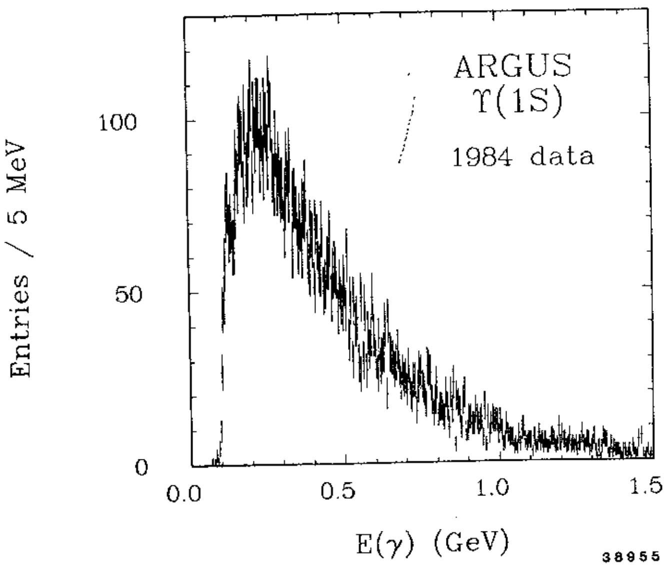

Fig. 5b

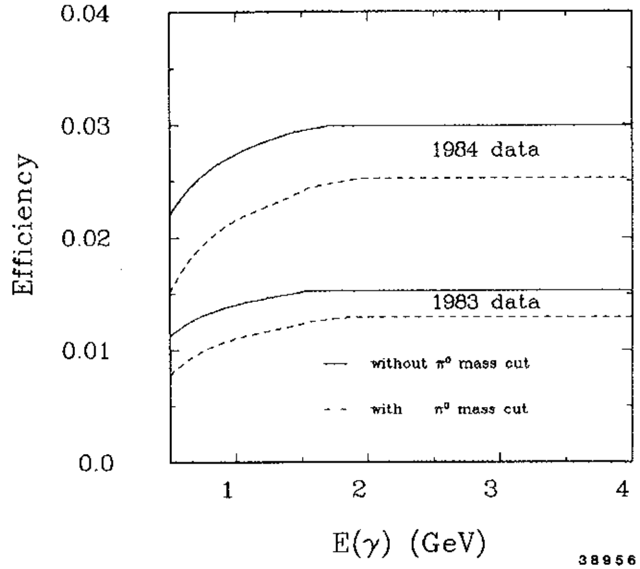

Fig. 6

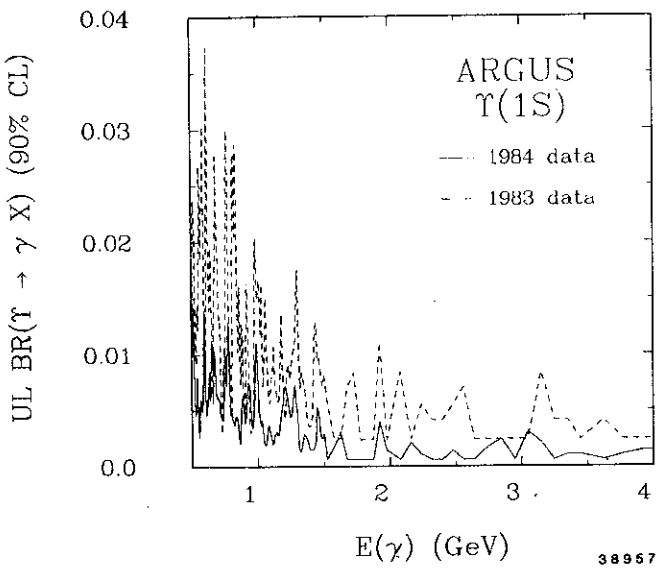

Fig. 7a

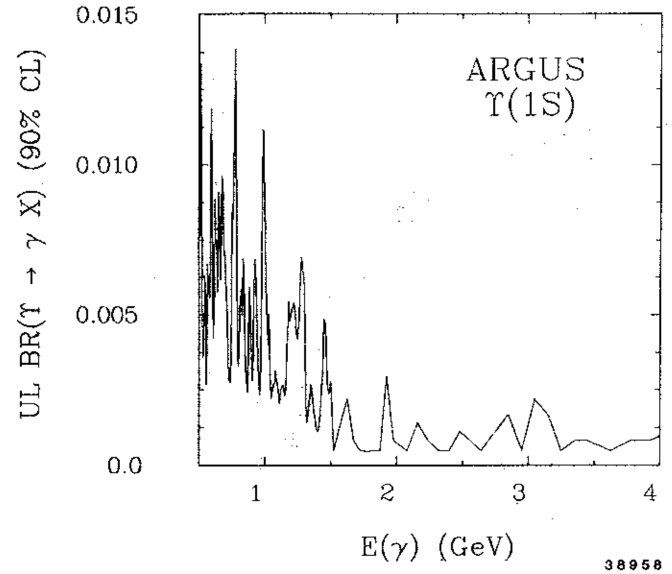

Fig. 7b

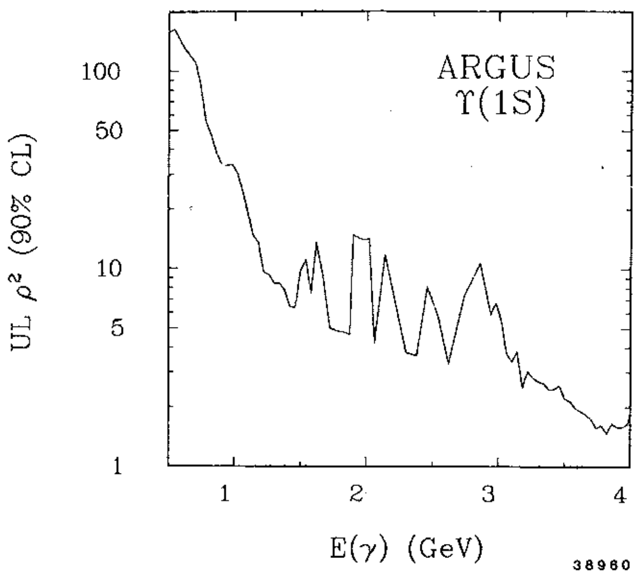

Fig. 8a

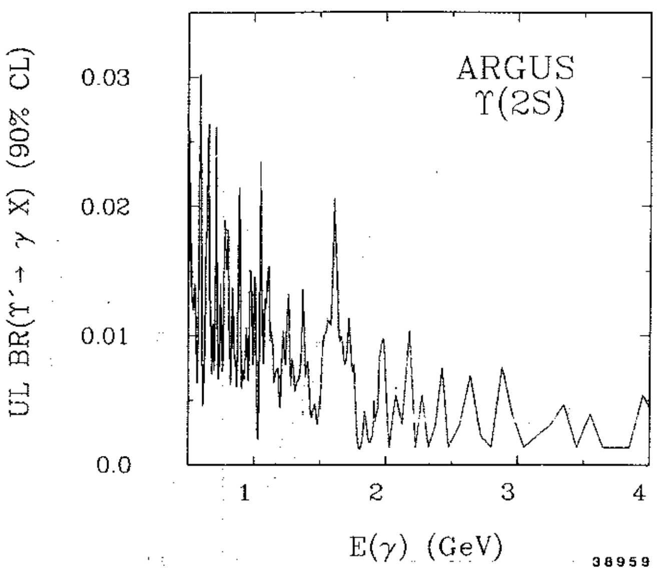

Fig. 7c

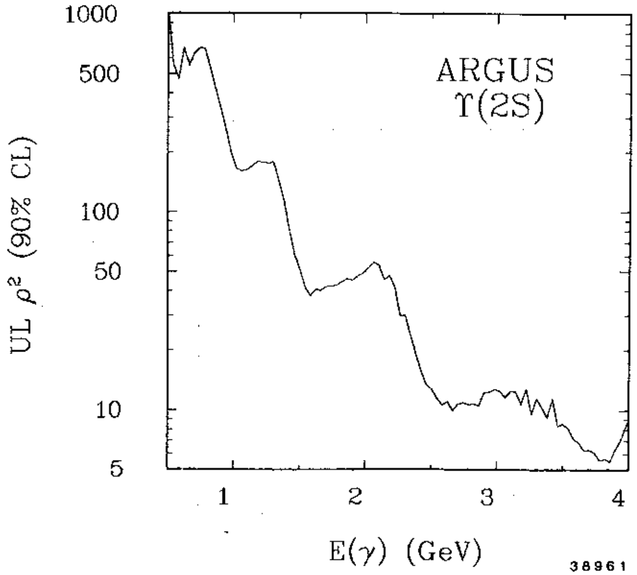

Fig. 8b