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ERRATUM

OBSERVATION OF THREE P STATES IN THE RADIATIVE DECAY OF $\Upsilon(2S)$*

R. Nernst, D. Antreasyan, D. Aschman, D. Besset, J. K. Bienlein, E. D. Bloom, I. Brock, R. Cabenda, A. Cartacci, M. Cavalli-Sforza, R. Clare, G. Conforto, S. Cooper, R. Cowan, D. Coyne, D. de Judicibus, C. Edwards, A. Engler, G. Folger, A. Fridman[†] J. Gaiser, D. Gelphman, G. Godfrey, F. H. Heimlich, R. Hofstadter, J. Irion, Z. Jakubowski, S. Keh, H. Kilian, I. Kirkbride, T. Kloiber, W. Koch, A. C. König, K. Königsmann, R. W. Kraemer, R. Lee, S. Leffler, R. Lekebusch, P. Lezoch, A. M. Litke[‡] W. Lockman, S. Lowe, B. Lurz, D. Marlow, W. Maschmann, T. Matsui, F. Messing, W. J. Metzger, B. Monteleoni, C. Newman-Holmes, B. Niczyporuk, G. Nowak, C. Peck, P. G. Pelfer, B. Pollock, F. C. Porter, D. Prindle, P. Ratoff, B. Renger, C. Rippich, M. Scheer, P. Schmitt, M. Schmitz, J. Schotanus, A. Schwarz, D. Sievers, T. Skwarnicki, K. Strauch, U. Strohbusch, J. Tompkins, H.-J. Trost, R. T. Van de Walle, U. Volland, K. Wacker, W. Walk, H. Wegener, D. Williams, P. Zschorsch

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1. Change DESY 85-019 to DESY 85-018 on title page.
2. Table I, footnote *a* on page 10:

   line 4 – Change $1 + \frac{1}{3}\cos^2\theta$ to $1 - \frac{1}{3}\cos^2\theta$; and

   line 5 – Change $^2P_0$ to $^3P_0$

* This work was supported in part by the Department of Energy under contracts DE-AC03-81ER40050 (CIT), DE-AC02-76ER03066 (CMU), DE-AC02-76ER03064 (Harvard), DE-AC02-76ER03072 (Princeton), DE-AC03-76SF00515 (SLAC), and DE-AS03-76SF00326 (Stanford), by the National Science Foundation under Grants PHY75-22980 (CIT), PHY84-07870 (HEPL), and PHY82-08761 (Princeton), by the Bundesministerium fuer Forschung und Technologie (Erlangen, Hamburg, Würzburg), and by the Deutsche Forschungsgemeinschaft (Hamburg).

Table I. Photon Lines from Inclusive $\Upsilon(2S)$ Decay

	Photon Energy (MeV)	Branching Ratio (%)
This Experiment[a]	$110.4 \pm 0.8 \pm 2.2$	$5.8 \pm 0.7 \pm 1.0$
	$130.6 \pm 0.8 \pm 2.4$	$6.5 \pm 0.7 \pm 1.2$
	$163.8 \pm 1.6 \pm 2.7$	$3.6 \pm 0.8 \pm 0.9$
	$\langle 430 \rangle$	$3.6 \pm 0.7 \pm 0.5$
CUSB[2]	$108.2 \pm 0.3 \pm 2$	6.1 ± 1.4
	$128.1 \pm 0.4 \pm 3$	5.9 ± 1.4
	$149.4 \pm 0.7 \pm 5$	3.5 ± 1.4
	$427.0 \pm 10 \pm 8$	4.0 ± 1.0
CLEO[3]	$109.5 \pm 0.7 \pm 1$	$10.2 \pm 1.8 \pm 2.1$
	$129.0 \pm 0.8 \pm 1$	$8.0 \pm 1.7 \pm 1.6$
	$(158.0 \pm 7.0 \pm 1)$[b]	$(4.4 \pm 2.3 \pm 0.9)$
ARGUS[4] Preliminary	$109.0 \pm 1.0 \pm 1.0$	$8.9 \pm 3.0 \pm 1.2$
	$129.8 \pm 0.8 \pm 1.0$	$8.8 \pm 2.2 \pm 1.0$
	$147.2 \pm 1.4 \pm 1.0$	$4.0 \pm 1.8 \pm 1.0$

[a] The first error is statistical and the second is systematic.
The angular photon distributions assumed are:
$1 + \frac{1}{13}\cos^2\theta$ for the line at $E_\gamma \simeq 110$ MeV ($^3P_2$ hypothesis),
$1 - \frac{1}{3}\cos^2\theta$ for the line at $E_\gamma \simeq 131$ MeV ($^3P_1$ hypothesis),
$1 + \cos^2\theta$ for the line at $E_\gamma \simeq 164$ MeV ($^3P_0$ hypothesis).
A flat distribution for the line at $E_\gamma \simeq 164$ MeV would lower the branching ratio by about 10%. For the secondary transitions at $\langle E_\gamma \rangle \simeq 430$ MeV a flat angular distribution is assumed.

[b] The third photon line at $E_\gamma = 158$ MeV is not clearly implied by the data.

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OBSERVATION OF THREE P STATES IN THE RADIATIVE DECAY OF $\Upsilon(2S)$*

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ABSTRACT

The inclusive photon spectrum in hadronic decays of the $\Upsilon(2S)$ is measured with the Crystal Ball detector at DORIS II. Four well separated photon lines, which are consistent with the decay hypothesis $\Upsilon(2S) \to \gamma\ {}^3P_{2,1,0}$ and ${}^3P_{2,1} \to \gamma\ \Upsilon(1S)$, are observed. The energies of the lines from the primary transitions are $E_{\gamma 1} = (110.4 \pm 0.8 \pm 2.2)$ MeV, $E_{\gamma 2} = (130.6 \pm 0.8 \pm 2.4)$ MeV and $E_{\gamma 3} = (163.8 \pm 1.6 \pm 2.7)$ MeV; the branching fractions are $(5.8 \pm 0.7 \pm 1.0)\%$, $(6.5 \pm 0.7 \pm 1.2)\%$ and $(3.6 \pm 0.8 \pm 0.9)\%$ respectively. The secondary transitions center at $\langle E_\gamma \rangle \simeq 430$ MeV with a combined branching fraction of $(3.6 \pm 0.7 \pm 0.5)\%$.

According to quarkonium potential models, the $\Upsilon(2S)$ $b\bar{b}$ resonance is expected to decay radiatively to three P states: $2\ ^3S_1 \rightarrow \gamma\ +\ 1\ ^3P_{2,1,0}$. The P states can decay hadronically or via emission of a second photon to the $\Upsilon(1S)$. The determination of the P state energies yields insight into some aspects of the interquark potential[1]. Until now only two of the three expected primary photon transitions have been observed with good statistical significance[2,3,4].

Here we present an analysis of the inclusive photon spectrum $\Upsilon(2S) \rightarrow \gamma$ + hadrons using the Crystal Ball detector at the DORIS II storage ring. This analysis is based on $(193 \pm 15) \cdot 10^3$ produced $\Upsilon(2S)$ and corresponds to an integrated luminosity of $\int L\mathrm{d}t \simeq 61\ \mathrm{pb}^{-1}$.

The main Crystal Ball detector consists of a spherical, segmented shell of NaI(Tl) shower counters which cover 93% of the full solid angle. The coverage is increased to 98% of 4π by NaI(Tl) endcaps. The thickness of the NaI(Tl) shell corresponds to 16 radiation lengths and to one nuclear absorption length. The direction of charged particles is measured by three double layers of proportional tube chambers with charge division readout. The Crystal Ball in its configuration at the SPEAR storage ring has been described in detail elsewhere[5,6]. At DORIS II the endcaps and the luminosity monitor system were modified to allow the installation of mini-beta quadrupoles.

The energy resolution for photons is measured to be $\frac{\sigma(E)}{E} = \frac{(2.7\pm0.2)\%}{E^{1/4}}$ (where E is the energy of the photon in GeV) and the angular resolution is 1-2 degrees (slightly energy dependent). The distribution of energy deposited by charged hadrons in the NaI(Tl) crystals peaks around 210 MeV due to minimum ionizing charged particles and has a long tail toward higher energies due to nuclear interactions.

The hadronic $\Upsilon(2S)$ event sample is obtained by removing background due to beam-gas interactions, cosmic rays, 2 photon events and QED events. The remaining data sample contains contributions from the resonance and the continuum in a ratio of approximately 1 to 1. The efficiency for the selection of hadronic decays of the $\Upsilon(2S)$ is calculated to be $\epsilon_h = (86 \pm 7)\%$ using a Monte Carlo simulation of the properties of the detector. Further details of the event selection and the efficiency determination can be found in Reference 7.

The photon selection is described next; it is designed to remove charged particles, photons from π^odecays, and photons whose showers are contaminated by energy depositions of nearby particles. A photon must lie within an angular range defined by $|\cos\Theta| \leq 0.75$ (Θ is the photon angle with respect to the positron beam). This cut ensures coverage by all three tracking chambers. The photon has to be 'neutral' which means that no crystal contributing to the photon shower is correlated with hits in the tracking chambers. To minimize distortion of the photon energy we require that the energy cluster of any photon candidate is well separated from all other clusters by at least 30^0. The lateral energy distribution in the crystals must be consistent with the pattern of a single electromagnetic shower, and photon pairs which can be fit to $\pi^o \rightarrow \gamma\gamma$ decays are removed.

The photon selection efficiency for these cuts is $\epsilon_\gamma = (15.2 \pm 1.5)\%$, independent of energy for $50 \leq E_\gamma \leq 500$ MeV. Details on the method of the photon efficiency calculation can be found in Reference 6.

Figure 1 shows the energy spectrum, with a logarithmic energy scale, of photons satisfying the above requirements. Three clearly separated peaks in the region between 100 to 170 MeV and another around 430 MeV are visible. The shoulder at 210 MeV is due to misidentified charged particles. We fit the spectrum from $E \simeq 50$ MeV to $E \simeq 650$ MeV using the sum of the following terms: (1) A fourth order Legendre polynomial series representing the photon background. (2) A charged particle spectrum with variable amplitude to take account of the remaining charged particle contamination (The shape of this spectrum is obtained by taking genuine charged particles as defined by the three tracking chambers and applying the photon selection cuts). (3) Three Gaussian distributions with widths determined by the known energy resolution to describe the signals in the 100-170 MeV region. (4) Two Gaussian distributions to describe the Doppler broadened secondary lines around 430 MeV, at energies fixed by the two lower energy lines and the known Υ(2S)-Υ(1S) mass difference[8,9]. We assume here and below that the line around 430 MeV is due to the secondary transitions $^3P_{2,1} \rightarrow \gamma\,\Upsilon(1S)$, where the $^3P_2$ and $^3P_1$ are assumed to be the 2 more massive of the 3 observed states[10]. The $^3P_0 \rightarrow \gamma\,\Upsilon(1S)$ branching ratio is expected to be small[11]. This is indicated by a previous experiment[12] and our studies[13] of the exclusive channel $\Upsilon(2S) \rightarrow \gamma\gamma\,\Upsilon(1S) \rightarrow \gamma\gamma\, l^+l^-$.

The result of the fit to the inclusive photon spectrum is shown in Fig. 2. The dashed line in Fig. 2(a) represents the smooth polynomial background. The charged particle 'punch-through' background is given by the difference of the solid line (that excludes the Gaussians) and the dashed line. In Fig. 2(b) this background has been subtracted. The fit has a confidence level of 72%.

The branching ratios for the observed transitions are calculated according to $B = \frac{N_\gamma}{N_{res} \cdot \epsilon_{tot}}$, where N_γ is the number of photons in a given peak, N_{res} is the number of Υ(2S) resonance decays and ϵ_{tot} is the overall detection efficiency for photons of given energy E. Included in this efficiency is the photon selection efficiency described above, the efficiency to detect the hadronic final state and losses due to conversion of photons in the beampipe and the chambers. The energies[9] of the observed lines, and the measured branching ratios are listed in Table I. The systematic error on photon energies is estimated by studying the effect of varying the criteria used in the photon selection, and from effects of small amounts of energy from interacting hadrons contaminating the photon shower. The systematic error in the branching ratio is largely due to uncertainties in estimating the photon detection efficiency, and uncertainties in fitting the shape of the background under the peaks in the photon spectrum. The relative strengths of the two transitions contributing to the secondary line are poorly determined. We therefore give the sum of the individual product branching ratios for the cascades from the transitions proceeding through the $^3P_2$ - and $^3P_1$ states.

Also in Table I we compare our measurements with the results of the CUSB, CLEO and ARGUS experiments[2,3,4]. There is reasonable agreement for the two lower energy lines, but for the line at $E \simeq 164$ MeV we disagree with CUSB and the preliminary ARGUS result by about 2 standard deviations.

With the mass values of the P states, deduced from the energies of the three primary lines, we calculate their center of gravity[14] to be $M_{COG} = (9899.5 \pm 2.0)$ MeV/c^2. In order to further compare the observed masses of the P states to model predictions it has become customary to use the ratio $r = \frac{M(^3P_2)-M(^3P_1)}{M(^3P_1)-M(^3P_0)} \equiv \frac{D_2}{D_1}$. This ratio has the advantage that the systematic errors of the energy measurements partially cancel. We estimate the errors on the 2 mass differences D_2, D_1 to be $\sigma(D_2) = 2.5$ MeV/c^2 and $\sigma(D_1) = 3.7$ MeV/c^2, where statistical and systematic errors have been added linearly. We obtain $r = 0.61 \pm 0.10$. While we lack the accuracy to distinguish between several quarkonium potential models[15] that give r in the range 0.4-0.8, our result disagrees with higher predictions of r (Reference 16).

In summary, we observe four photon lines in the inclusive photon spectrum obtained from hadronic decays of the $\Upsilon(2S)$. A coherent picture is obtained when these lines are interpreted as resulting from the E1 transitions $\Upsilon(2S) \rightarrow \gamma\ ^3P_{2,1,0}$ and $^3P_{2,1} \rightarrow \gamma\ \Upsilon(1S)$. By clearly resolving all three low energy lines in the inclusive photon spectrum and observing the photon line around 164 MeV with a clear statistical significance, we obtain a complete measurement of the fine splitting of the 1 $^3P_{2,1,0}$ states of the Υ $b\bar{b}$ system.

We would like to thank the DESY and SLAC directorates for their support. Special thanks go to the DORIS machine group and the experimental support groups at DESY. Some of us (A.F., Z.J., B.N., G.N. and T.S.) would like to thank DESY for financial support. A.F. in addition thanks the Deutsche Forschungsgemeinschaft and Hamburg University for financial support. D.W. acknowledges support from a National Science Foundation graduate fellowship. E.D.B., R.H. and K.S. have benefitted from Senior Scientists Awards from the Humboldt Foundation. The Nijmegen group acknowledges the support of FOM-ZWO. The Erlangen, Hamburg, and Würzburg groups acknowledge financial support from the Bundesministerium für Forschung und Technologie. This work was supported in part by the Department of Energy under contracts DE-AC03-81ER40050 (CIT), DE-AC02-76ER03066 (CMU), DE-AC02-76ER03064 (Harvard), DE-AC02-76ER03072 (Princeton), DE-AC03-76SF00515 (SLAC), and DE-AS03-76SF00326 (Stanford), and by the National Science Foundation under Grants PHY75-22980 (CIT), PHY84-07870 (HEPL), and PHY82-08761 (Princeton).

REFERENCES

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1. For recent reviews of potential models see, for example, E. Eichten, Proc. of the 11^{th} SLAC Summer Institute on Particle Physics, Stanford, July 18-29, 1983, and J. L. Rosner, Enrico Fermi Institute Report No. EFI 83/17, 1983. See References 15 and 16 for several potential models.
2. C. Klopfenstein *et al.*, Phys. Rev. Lett. 51, 160 (1983).
3. P. Haas *et al.*, Phys. Rev. Lett. 52, 799 (1984).
4. ARGUS Collaboration, Proc. of the XXII International Conference of High Energy Physics, Leipzig, German Democratic Republic, July 19-25, 1984.
5. M. Oreglia *et al.*, Phys. Rev. D 25, 2259 (1982). M. Oreglia, SLAC Report 236 (1980), Ph.D. Thesis, Stanford University, unpublished.
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7. C. Edwards *et al.*, SLAC-PUB-3030 (1983). R. Nernst, Ph.D. Thesis, Hamburg University, (1985), unpublished.
8. D. P. Barber *et al.*, Phys. Lett. 135B, 498 (1984). A. S. Artamonov *et al.*, Phys. Lett. 137B, 272 (1984). W.W. McKay *et al.*, Phys. Rev. D 29, 2483 (1984).
9. In the energy region of interest the photon energy calibration used to obtain Fig. 1 and Fig. 2 results in a small ($\simeq 2\%$) energy shift towards lower γ

energies. This is determined from the observed mass values of reconstructed π^0 and η particles. The value of the $\Upsilon(2S) - \Upsilon(1S)$ mass difference used in the fit takes this shift into account. The final photon energies listed in Table I are corrected for the shift.

10. The photon energies of the secondary transitions are too closely spaced to be resolved by our detector.

11. See for example V. A. Novikov *et al.*, Phys. Rep. 41C, 1 (1978).

12. F. Pauss *et al.*, Phys. Lett. 130B, 439 (1983).

13. W. Walk *et al.*, SLAC-PUB-3575 and DESY 85-019 (1985), to be published in Physical Review D.

14. M_{COG} is defined as $M_{COG} = \frac{\sum(2J+1)M(^3P_J)}{\sum(2J+1)}$.

15. A. Khare, Phys. Lett. 98B, 385 (1981). S. N. Gupta, Phys. Rev. D 26, 3305 (1982). W. Buchmüller, Phys. Lett. 112B, 479 (1982). P. Moxhay and J. L. Rosner, Phys. Rev. D 28, 1132 (1983). R. McClary and N. Byers, Phys. Rev. D 28, 1692 (1983). M. Bander *et al.*, Phys. Lett. 134B, 258 (1984). M. Bander *et al.*, Phys. Rev. D 29, 2038 (1984).

16. E. Eichten and F. Feinberg, Phys. Rev. D 23, 2724 (1981).

Table I. Photon Lines from Inclusive $\Upsilon(2S)$ Decay

	Photon Energy (MeV)	Branching Ratio (%)
This Experiment[a]	$110.4 \pm 0.8 \pm 2.2$	$5.8 \pm 0.7 \pm 1.0$
	$130.6 \pm 0.8 \pm 2.4$	$6.5 \pm 0.7 \pm 1.2$
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	$\langle 430 \rangle$	$3.6 \pm 0.7 \pm 0.5$
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	$128.1 \pm 0.4 \pm 3$	5.9 ± 1.4
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	$427.0 \pm 10 \pm 8$	4.0 ± 1.0
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[a] The first error is statistical and the second is systematic.
The angular photon distributions assumed are:
$1 + \frac{1}{13}\cos^2\theta$ for the line at $E_\gamma \simeq 110$ MeV ($^3P_2$ hypothesis),
$1 - \frac{1}{3}\cos^2\theta$ for the line at $E_\gamma \simeq 131$ MeV ($^3P_1$ hypothesis),
$1 + \cos^2\theta$ for the line at $E_\gamma \simeq 164$ MeV ($^3P_0$ hypothesis).
A flat distribution for the line at $E_\gamma \simeq 164$ MeV would lower the branching ratio by about 10%. For the secondary transitions at $\langle E_\gamma \rangle \simeq 430$ MeV a flat angular distribution is assumed.

[b] The third photon line at $E_\gamma = 158$ MeV is not clearly implied by the data.

FIGURE CAPTIONS

Fig. 1. The inclusive photon spectrum from the $\Upsilon(2S)$ hadronic decays selected with the cuts described in the text.

Fig. 2. (a) The fitted part of the photon energy spectrum. As described in the text, the curves represent the result of the fit. (b) The same distribution after background subtraction. Only error bars are shown for clarity. The data points are in the middle of the error bars.

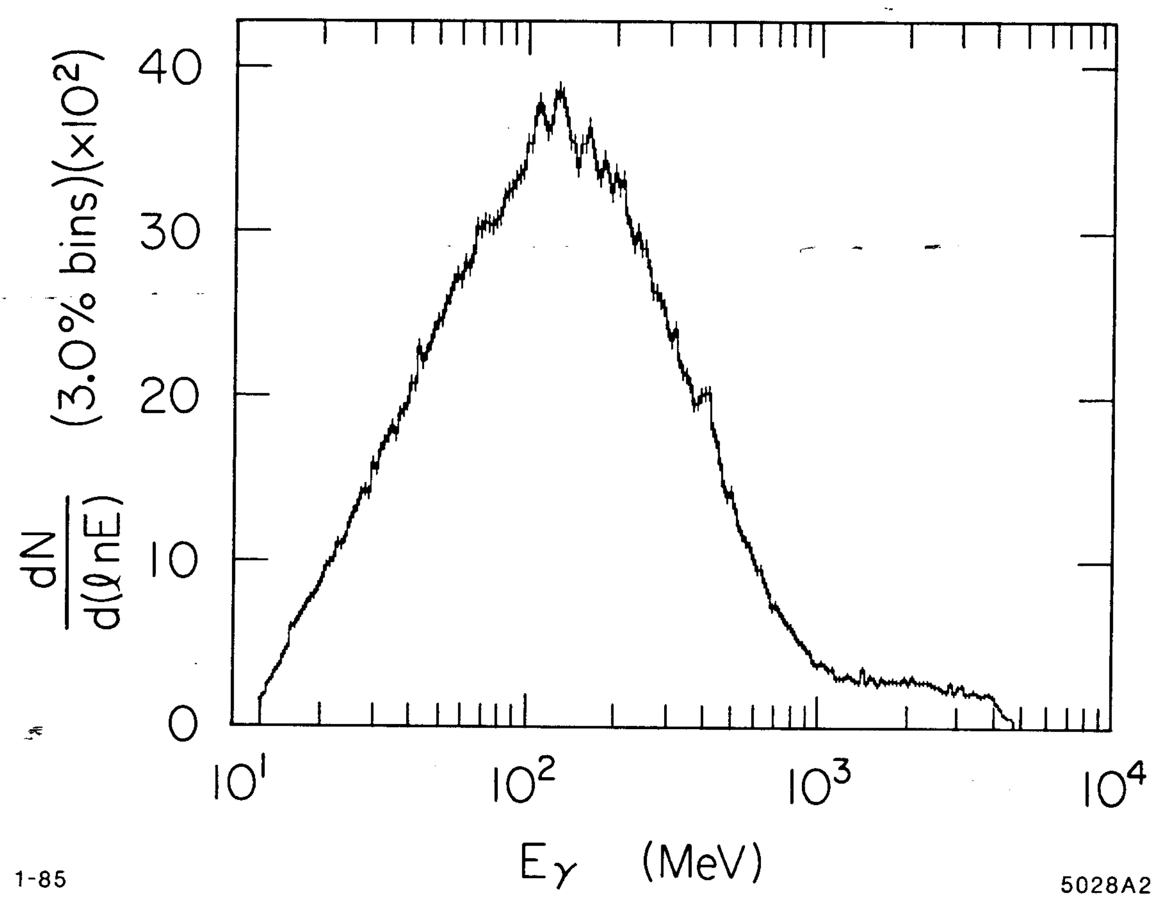
40
30
20
10
0
$\frac{dN}{d(\ell nE)}$ (3.0% bins)(×10²)
10¹
10²
10³
10⁴
Eγ (MeV)
1-85
5028A2

Fig. 1

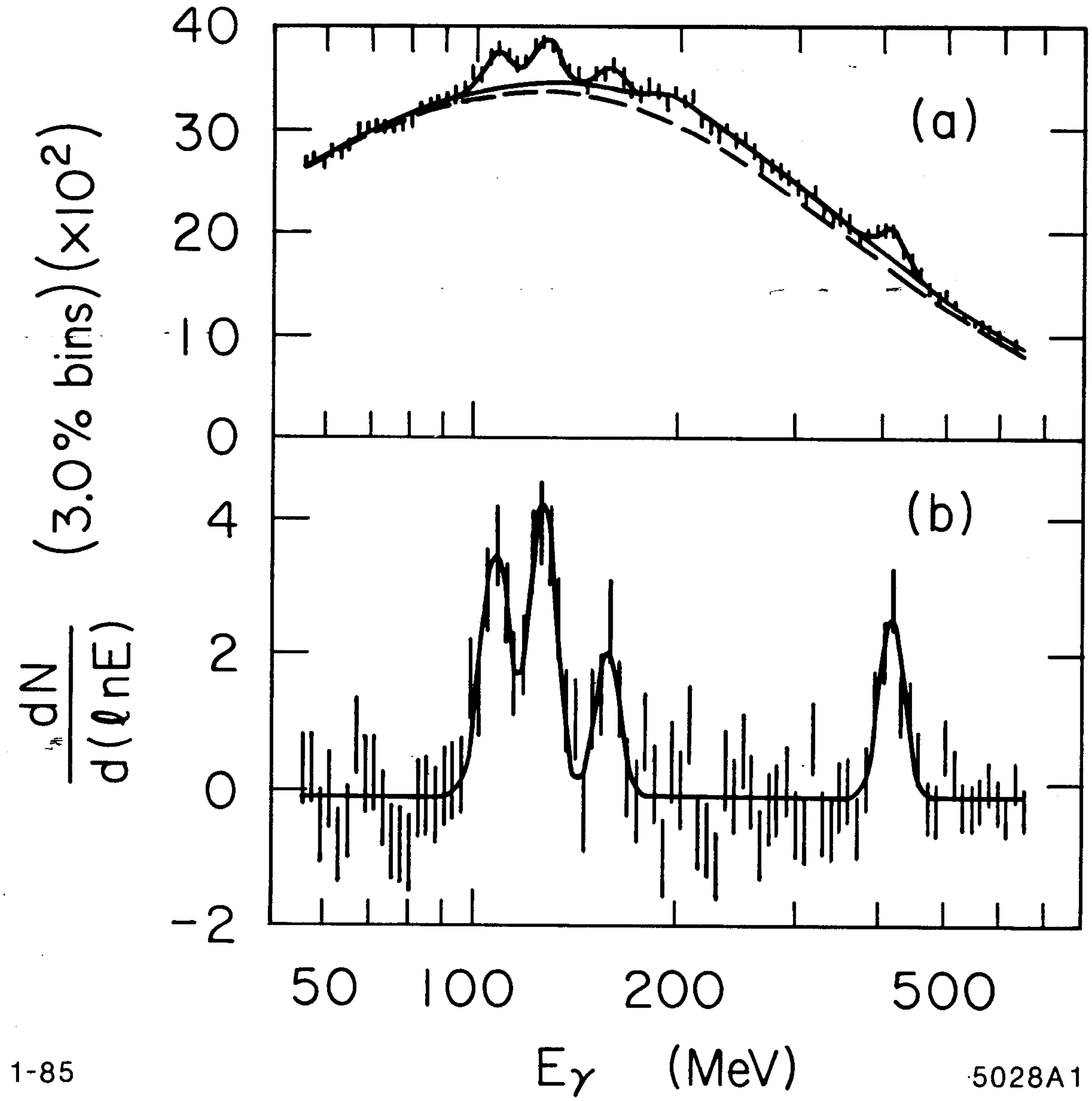
40
30
20
10
0
4
2
0
-2
(a)
(b)
$\frac{dN}{d(\ell nE)}$ (3.0% bins) (x10^2)
50
100
200
500
E_γ (MeV)
1-85
5028A1

Fig. 2