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The diffuse cosmic gamma rays

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Abstract. A careful and objective analysis is made of the available experimental observations which claim evidence for the existence of a shoulder in the spectrum of the diffuse cosmic gamma rays in the energy range of 1–40 MeV. In this, special cognisance is taken of the experimental data and theoretical calculations of the Bombay Group. These considerations cast serious doubts on the reliability of the high flux values obtained by many experimenters in this energy region emphasizing thereby the need for great caution in interpreting the shoulder as due to cosmological effects with far reaching implications.

Keyword. Cosmic gamma rays.

1. Introduction

Although the existence of a finite flux of diffuse cosmic x-rays was established more than a decade ago, it was only after the first encouraging satellite observations of Clarke *et al* (1968) at 100 MeV, that a spate of new data in the gamma ray energy range of 1–200 MeV has appeared in the literature from balloon and space craft experiments. Nevertheless, the situation in this energy region is far from satisfactory in that the results of some of the experimenters are in serious disagreement with those of others. Furthermore, there has grown, during the last few years, a body of observations claiming evidence for a shoulder or bulge in the energy spectrum between about 1 and 30 MeV over the power law spectrum joining the diffuse cosmic x-ray fluxes in the 0·1–0·5 MeV range and the results from the SAS-2 experiment of Fichtel *et al* (1973, 1975) in the 35–170 MeV range. This apparent shoulder in the diffuse cosmic gamma ray energy spectrum is now being interpreted, with far reaching implications, as due to cosmological effects of red shifted gamma rays resulting from the decay of neutral pions produced at an appropriate early epoch (Stecker 1973 and references therein). Therefore, in view of the confusing observational situation in this energy domain, and our own experimental and theoretical results which are not consistent with the existence of the shoulder to the extent it is claimed now, we have critically examined and evaluated the available experimental data in a careful and objective manner. Such an analysis seems to cast serious doubts about the validity of the high flux values obtained by some experimenters in the 0·5–40 MeV region.

2. A critical review of available data in the 0·5–200 MeV region

In the 0·1–0·5 MeV range, there seems to be general agreement between the observations of various workers for a power law spectrum with an index close to — 2·1 (Yash Pal 1973). In the region beyond this, but below 200 MeV, there are, to our knowledge, data available from 15 experiments; these are summarised in figure 1. For purposes of the present discussions, we will consider the information available in the two energy bands 0·5–10 MeV and 10–200 MeV separately. Though each experiment may have in its instrumentation and analysis, its own advantages and strong points, it is its weakness that ultimately determines the accuracy and reliability of the results. It is therefore only natural that in the present consideration, our remarks will refer primarily to the weaknesses, if any, of the various experiments.

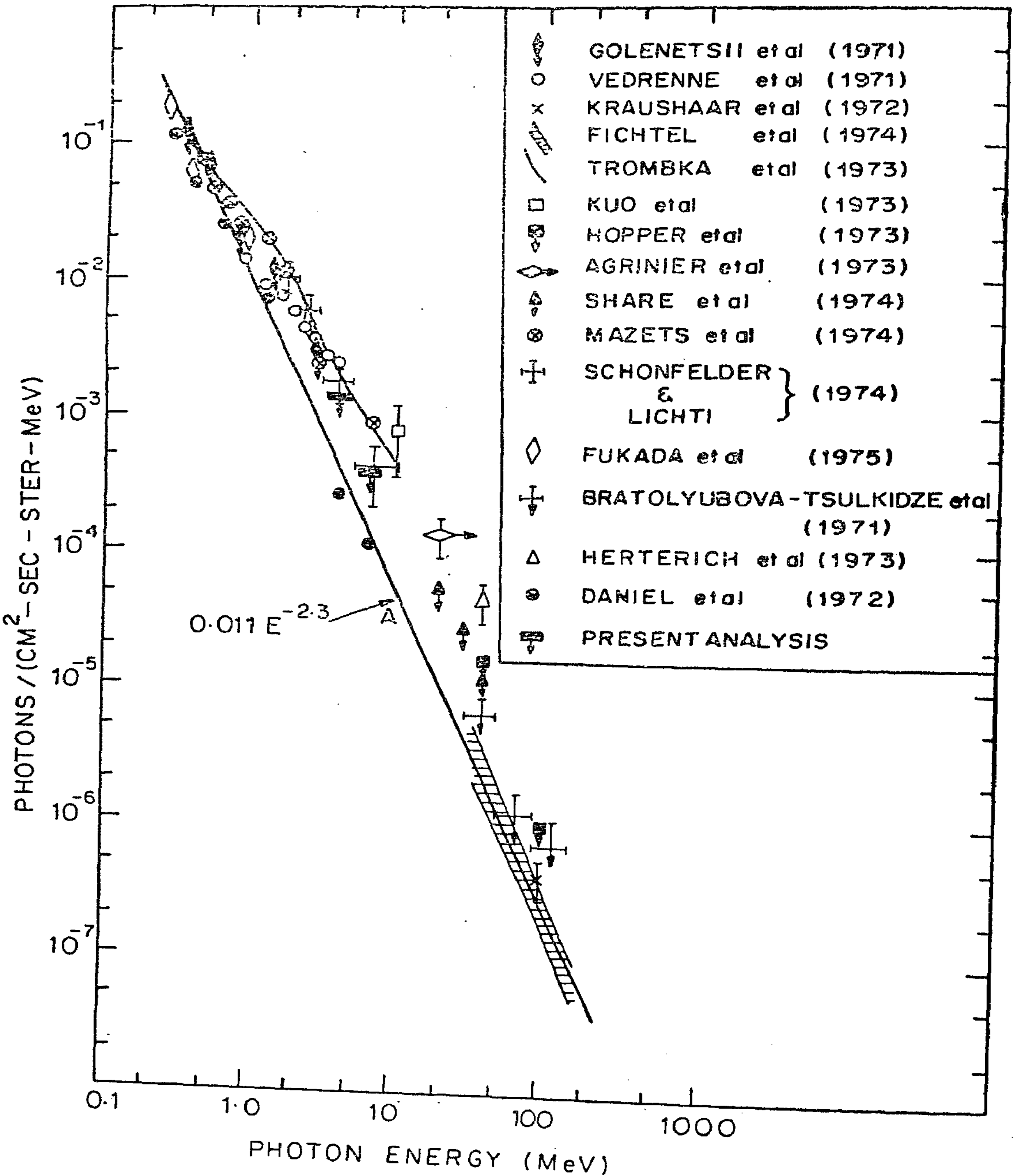

Figure 1. Summary of all available experimental data on diffuse cosmic gamma rays.

2.1. *0·5–10 MeV*

The seven experiments performed so far in this energy interval can be broadly divided into two categories: (*a*) those which are designed to detect the cosmic isotropic flux using space crafts, thus avoiding the effect of the earth's atmosphere (Trombka *et al* 1973; Golenetskii *et al* 1971; Mazets *et al* 1974), and (*b*) those which attempt to measure the cosmic flux from balloon experiments using assumed depth dependence of the growth of secondary gamma rays in suitable atmospheric depths (Vedrenne *et al* 1971; Daniel *et al* 1972; Schonfelder and Lichti 1974; Fukada *et al* 1975). Some of the relevant details of these experiments are summarised in table 1. We will now examine these experiments in some detail.

The results of Trombka *et al* (1973) obtained from deep space measurements during the Apollo–15 mission are extensively quoted by other workers in this field as providing evidence for the shoulder. However, a careful examination reveals that this experiment is faced with a number of serious uncertainties and criticisms, the important of which are listed below. (i) The charged particle shield does not cover the photomultiplier-end of the main crystal. This could have an important effect at energies above 1 MeV because it is found that the measured ratios of counting rates of particulate cosmic rays to that of gamma rays (as measured by their "anti-off" and "anti-on" counting modes) rapidly grows from a value of about 1·4 at 1 MeV to 65 at about 20 MeV. Also, the efficiency of charged particle rejection of the instrument was not measured before launch to the required accuracy. (ii) According to the authors "systematic errors, which are difficult to estimate, completely dominate the statistical uncertainties in this analysis"; corrections made for these systematic errors include contributions from nuclear lines, spallation and spacecraft continuum, and attenuation in the 5 gcm^{-2} of an equivalent shell of aluminium surrounding the detector. It is also seen that in addition to an uncertainty of 20% in estimating the equivalent photon spectrum. there is the correction due to spallation which is known poorly to the extent that the authors are forced to adopt rather arbitrary procedures of correction; in fact one notes that if the calculations employed by them are to be taken seriously, the flux seen in the 1–2 MeV can be explained wholly as due to spallation. (iii) In the case of the 0·51 MeV line due to positron annihilation, after secondary corrections are made, there is still a significant residual line intensity which the authors consider to be too large and inconsistent with the upper limits of the cosmic flux of 0·51 MeV line so far obtained in balloons (Chupp *et al* 1970) and on Ranger–3 (Metzger *et al* 1964). They indicate as possible sources of this, the production of positrons from spallations in the local mass and low energy cosmic ray positrons typically of 2 MeV. While the authors themselves do not seem to be sure about the quantitative contribution of the former, the latter is expected to be important equally in Ranger–3 and Apollo–15 missions since 2 MeV electrons have a range of only about 1·5 $\mathrm{g\,cm}^{-2}$ in aluminium. Thus, there is a real difficulty in understanding the observations on the 0·51 MeV line from this experiment, and one is tempted to propose that perhaps the data have been undercorrected for local production of nuclear gamma rays including the 0·51 MeV line. (iv) Finally, one is unable to explain satisfactorily the earlier results of the same group (Vette *et al* 1970) from ERS–18 in which a flux value of about 5 times that of Trombka *et al*

Table 1. Relevant details of experiments carried out in the 0·5–10 MeV region

Authors	Detector*	Exposure†	Energy range	Remarks
Trombka *et al* (1973) ..	NaI (Tl) 7 cm × 7 cm	In deep space on boom of Apollo-15	0·3 – 27 MeV	Evidence for shoulder claimed between 0·5 and 27 MeV
Golenetskii *et al* (1971) ..	NaI (Tl) 4 cm × 4 cm	Cosmos 135 & 163 with booms; $\Lambda = 0$ to $\pm 49°$	0·3 – 3·7 MeV	Only upper limits
Mazets *et al* (1974) ..	NaI (Tl) 7 cm × 7 cm No particle shield	Cosmos 461 with boom; $\Lambda = 0$ to $\pm 69°$	0·028 – 4·1 MeV	Shoulder claimed above 0·4 MeV
Vedrenne *et al* (1971) ..	Stilbene 2·5 cm × 2·5 cm	Balloon flights at $\Lambda = 10°$ N, 46° N & 62° N	0·7 – 4·5 MeV	Evidence for shoulder seen only beyond 1·5 MeV
Daniel *et al* (1972) ..	NaI (Tl) 7·5 cm × 7·5 cm	Balloon; $\Lambda = 8°$ N	0·1 – 8 MeV	No evidence for shoulder
Fukada *et al* (1975) ..	NaI (Tl) 7·5 cm × 7·5 cm with active shutter	Balloon; $\Lambda = 8°$ N	0·1 – 4 MeV	Consistent with a hump around 1 MeV
Schonfelder and Lichti (1974)	Double Compton scattering technique; directional	Balloon; $\Lambda = 41°$ N	1 – 10 MeV	Evidence for shoulder claimed

* All detectors except the last one have isotropic response; † Λ is the geomagnetic latitude.

is obtained at ≈ 5 MeV using a very similar detector system. At this point a pertinent general comment may also be added that some of these uncertainties perhaps arise from the fact that in deep space, all matter is continuously subject to the bombardment by the full spectrum of galactic and solar cosmic rays enhancing thereby all local radiation of primary and secondary origin.

The experiment of Golenetskii *et al* (1971) made from near-earth satellites in the 0·3–3·7 MeV range yielded only upper limits to the cosmic flux while the same group following a similar analysis procedure in a later experiment (Mazets *et al* 1974), but without any active charged particle shield to the main detector, has obtained finite fluxes in the same energy range with values generally higher than the earlier upper limits; however, no satisfactory explanation is offered in the paper as to how this can be understood. In this situation it is not possible to make useful comments on these results except to seriously question in the latter experiment the reliability of making corrections for charged particle contribution while arriving at the cosmic gamma ray flux in the MeV region.

Vedrenne *et al* (1971) also claim that their results in the 0·7–4·5 MeV range are in agreement with those of Trombka *et al*. However, these results are also subject to a number of serious criticisms. (i) The organic stilbene scintillator of size 2·5 cm × 2·5 cm is not the best detector that one could use for gamma rays either in terms of size or in composition for this energy range. (ii) The anticoincidence particle shield did not cover the entire 4π geometry. (iii) The presence of a finite flux of cosmic gamma rays over the geomagnetic latitude $\Lambda = 10°$ N is hinged on the claim that there is a "sharp increase" in the ratio of the flux of gamma rays to neutrons at altitudes above 20 mb whereas such an increase is not seen at $\Lambda = 46°$ N and 62° N; however, this statement is based only on a single data point whose enhancement is not adequately convincing. (iv) Finally, their cosmic flux values show an enhancement only for energies > 1 MeV and at 1·5 MeV is about a factor of about 2 lower than that of Trombka *et al*.

The experiment of Daniel *et al* (1972) carried out using a standard 7·5 cm × 7·5 cm NaI(Tl) detector over an equatorial balloon station with its associated very low atmospheric gamma ray background, led to finite fluxes of cosmic gamma rays all of which were well below the observations of Trombka *et al* in the 0·3–10 MeV energy region. These values were obtained by a method of linear extrapolation on a log-log plot of the growth curves between 10 and 40 g cm^{-2} of residual air and attributing the flattening of the growth curve below 10 g cm^{-2} as due to the cosmic component. Nevertheless, since we are presently examining the credibility of the evidence for the existence or otherwise of the shoulder, we reconsidered our earlier measurements to take into account the sensitivity of the method of extrapolation in estimating the cosmic flux. As a first step, we noted that in the case of the four data points between 0·1 and 2 MeV, the flattening of the growth curves below 10 g cm^{-2} are quite significant and the diffuse flux values estimated assuming the flattening as wholly due to the cosmic component are statistically quite reliable and have standard deviations ranging between 25 and 30%. In contrast, the data points at 4 and 6·5 MeV in the crucial energy region of the bulge have relatively larger statistical uncertainties arising from the less pronounced growth curve flattening. We have, therefore, estimated as an extreme case the "cosmic" flux values corresponding to two standard deviations for these two data points; these plotted as upper limits in figure 1 are still significantly below the curve due to Trombka *et al.* It is necessary at this stage to point out that the straight line extrapolation of atmospheric gamma rays, particularly for detectors with isotropic response in the MeV energy range, has been seriously questioned; and indeed the calculations of Danjo (1972) have provided strong support for a tendency for the growth curves to flatten gradually for atmospheric depths below about 10–20 g cm^{-2}. Hence, our observed flattening cannot be wholly due to cosmic gamma rays; in this case all the data points in our experiment will become overestimates; they will still be all well below the observations due to Trombka *et al.*

In the experiment of Fukada *et al* (1975) the main detector is surrounded by a massive active particle shield of NaI (Tl) of 10 cm thickness in the shape of a cup with a movable active shutter of NaI (Tl) of thickness 5 cm. By attributing the difference in the counting rates with the shutter at the " on " and " off " positions as due to the down moving cosmic and atmospheric gamma rays, and making use of an assumed atmospheric growth curve below 60 g cm^{-2}, these authors find that their results on the cosmic flux of gamma rays are " consistent with the presence of a hump in the MeV region ". Three major criticisms can be levelled against this experiment. (i) Since there is no charged particle shield above the main crystal when the shutter is in the " off " position, corrections are made for atmospheric electrons using the calculations of Daniel and Stephens (1974); these corrections become quite substantial at energies > 1 MeV and, as it appears, overwhelming at about 6 MeV. However, at the MeV region, which is the lowest energy tail of the calculations, the calculated values are expected to be underestimates because account has not been taken for contributions due to back scattering of the large flux of upward moving electrons in the atmosphere. (ii) It is assumed by the authors that the reduction in the counting rate with the shutter " on " is due to the blocking of downward moving gamma rays. However, it is necessary to note that in this position, a small fraction of the upward moving gamma rays which are responsible for the very large counting rate in the " off " position of the shutter, would also be rejected whenever they, after depositing some energy in the main crystal, happen to pass through the geometry of the shutter and release in it an energy above the low threshold for the active shutter. This effect will give rise to an additional decrease in the counting rate in the " on " position of the shutter and hence it becomes important to know its magnitude. (iii) The observed spectra, both with the shutter " on " and " off ", show a very pronounced line emission at about 1·4 MeV presumably due to ^{40}K contamination, which will also contribute the Compton tail at lower energies; this Compton tail contribution is likely to be reduced when the shutter serves as an anti-Compton shield during the " on " position. The paper does not mention about the magnitude of this effect also. It will be noted that all these three factors will effectively reduce the apparent cosmic component of gamma rays.

The experiment of Schonfelder and Lichti (1974), carried out using the double Compton scattering technique, is expected to respond only to down moving gamma rays of energy between 1·5 and 10 MeV and has an efficiency which increases from zero at 1 MeV rapidly to about 1% at about 5 MeV. The growth curve obtained from this experiment exhibits considerable flattening below about 10 g cm^{-2}

(curve 1 *b* of figure 2) with respect to the assumed straight line growth curve on log-log scale fitted between 25 and 90 g cm^{-2}; the cosmic flux is then deduced by attributing this effect entirely to a component of cosmic origin. Furthermore, in order to justify the assumption for the linear growth curve, the authors have referred to the calculations of Danjo (1972). However, these calculations apply only to much lower energies of 0·1–1 MeV and even these lead to a linear growth curve, not in the 25 to 90 g cm^{-2}, but only at depths below 10 g cm^{-2}. Curve 1 *a* of figure 2 is the calculated growth curve (Daniel and Stephens 1974) at 5 MeV

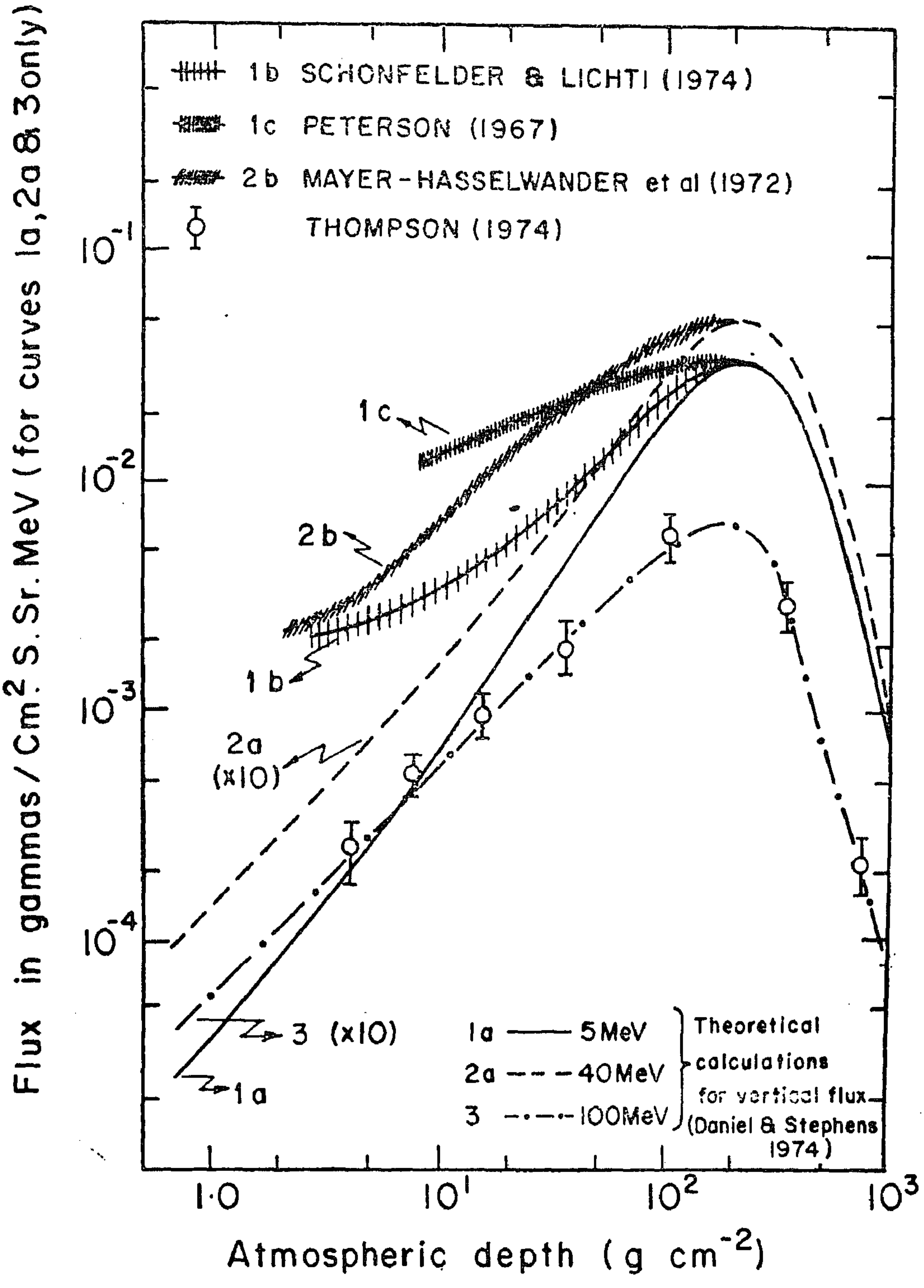

Figure 2. Calculated and experimental atmospheric growth curves.

for the down-moving gamma rays at $\Lambda = 41°$, while curve 1 *c* is that experimentally obtained at the same latitude by Peterson (1973) in the 1–3 MeV region with a detector having omnidirectional response; curves 1 *b* and 1 *c* have been normalised at the Pfotzer maximum of the calculated growth curve 1 *a*. The fact that the ratio of the count rate at the Pfotzer maximum to that at 10 g cm^{-2} is about 45 for the calculated curve, 9 for the results of Schonfelder and Lichti and 2·5 for a detector with 4π response, strongly suggests that at these energies the Schonfelder and Lichti's experiment is also accepting directly or indirectly atmospheric gamma rays originating from larger zenith angles. One reason for such a possibility is that at these low energies, a small part of the vast flux of gamma rays moving at angles $\gtrsim 70°$ to the zenith, get scattered downwards from the residual atmosphere above the detector, an effect which has also not been taken into account in the calculations; such a component will become important at altitudes above ≈ 20 g cm^{-2} and its flux will fall off much more gently with altitude compared to genuinely down-moving gamma rays. Mention may also be made here that the calculations of Daniel and Stephens agree generally well with those of Beuermann as can be seen from figures 9 and 16 of their paper (Daniel and Stephens, 1974).

2.2. 10–200 *MeV region*

Of the data available from the eight experiments in this energy range (*see* figure 1), those of Share *et al* (1974), Hopper *et al* (1973) and Bratolyubova–Tsulukidze *et al* (1971) yield only upper limits. Of these, the results of the latter in the energy region 30–150 MeV, lie well above those of SAS–2 observations and hence do not yield any useful information for the present analysis, while it should be noted that the observations of the former two in the energy range 20–50 MeV lie well below the finite values of Agrinier *et al* (1973) and Herterich *et al* (1973).

The results of Kuo *et al* (1973) in the 4–20 MeV range have been obtained from a thin plate spark chamber with a maximum efficiency of only 2×10^{-3} at 10 MeV with a FWHM of 7 MeV. For the final analysis, the authors have accepted gamma rays with zenith angles $< 60°$, and opening angles $< 76°$; however, it is not clear as to what accuracy is attained in the determination of the space angles of the gamma rays. They deduce a finite cosmic flux at 10 MeV by comparing their observed flux at 3·1 g cm^{-2} with the flux values extrapolated in energy and atmospheric depth from the observations of five other investigators whose data refer to widely differing energy regions and varying detector systems obtained from balloon flights made during 1967–71 over stations with geomagnetic cut-off rigidity $R_c \approx 4{\cdot}5$ GV. These extrapolated flux values at 10 MeV and 3·1 g cm^{-2} attributed by the authors as due to purely atmospheric gamma rays, themselves differ by a factor of as much as 5·5 while their own observed total flux is only 30% higher than the highest value. Hence, this evidence should only be considered as very weak.

The experiment of Agrinier *et al* (1973) was carried out using a spark chamber for gamma rays of energy $\gtrsim 20$ MeV. The instrument was flown tilted at 20 and 13·5° to the vertical over two stations with $R_c = 5{\cdot}4$ GV and 12 GV respectively. From a linear plot of the count rate against atmospheric depth between 0 and $\lesssim 30$ g cm^{-2}, the flattening claimed by the authors at depths below about

5 g cm^{-2} is not at all significant nor convincing. Even granting this, the authors themselves have cautioned at length that the finite cosmic flux obtained by them at energies $\geqslant 20$ MeV should be considered as overestimates for three different reasons. Earlier, we had also pointed out that their finite value, which is an integral flux, is larger than the upper limit of Share *et al* in the same energy region by a factor as much as 2·5. Under these circumstances the results of these authors cannot be accepted as convincing.

The data point due to Herterich *et al* (1973) at 40 MeV is a reanalysis of the data from one of the two flights reported earlier by the same group (Meyer–Hasselwander *et al* 1972) after calibration experiments were carried out at accelerators. In the reanalysis the data points are plotted on a linear scale for depths less than 40 g cm^{-2}; and by assuming that the growth curve is a straight line passing through 0 g cm^{-2}, the cosmic flux is deduced from the observed enhancement of the data points at depths less than 5 g cm^{-2} with respect to the straight line fitted. The growth curve experimentally observed by the group at and above the Pfotzer maximum is shown as curve 2 *b* of figure 2 normalised at the Pfotzer maximum of the growth curve 2 *a* calculated for down-moving atmospheric gamma rays at 40 MeV and $R_c = 4 \cdot 5$ GV (Daniel and Stephens 1974). An important observation which becomes evident from this figure is that the ratio of the flux at the Pfotzer maximum to that at 10 g cm^{-2}, has a value of ≈ 25 for the calculated down-moving gamma rays, while the observations give a value of only about 7. Since the calculations at these energies can be inaccurate to no more than about 20%, as is evident from comparisons with various observations as also the calculations of Beuermann (1971), the slow growth curve seen by Herterich *et al* can only result, if events other than genuinely down-moving gamma rays are also recorded. In the present case one category of events which, in principle, can simulate down-moving gamma rays is the back scattering of electrons within the detector. Finally, mention may also be made that if one is to accept the straight line fit made by Herterich *et al* (1973) for their data, then one finds that between 10 and 40 g cm^{-2}, all except one of their 10 points lie above the line. Another very serious discrepancy is that their diffuse cosmic flux value is larger than that of Fichtel *et al* (1975) by a factor of about 15, and lies significantly above the upper limits of Share *et al*, Hopper *et al* and Bratolyobova-Tsulukidze at about 40 MeV.

The SAS–2 observations of Fichtel *et al* (1975) in figure 1 cover the energy range 35–170 MeV. The main detector consisting of a digitised wire grid spark chamber used in this experiment has been extensively calibrated at energies between 20 and 140 MeV and flown many times in balloons. Furthermore, the atmospheric growth curve determined over Texas (Thompson 1974) using a near-identical detector system agrees excellently with the shape and absolute fluxes calculated by Daniel and Stephens (1974) at an energy of ≈ 100 MeV; for example the calculated flux at the Pfotzer maximum for gamma rays of energy > 30 MeV is $2 \cdot 7 \times 10^{-1}$ per cm^2. s.sr. compared to the observed value of $3 \cdot 0 \pm 0 \cdot 7 \times 10^{-1}$ obtained by Thompson (1974). In figure 2, curve 3 represents the calculated down-moving secondary gamma rays at $R_c = 4 \cdot 5$ GV and an energy of 100 MeV; it is seen that the experimental data points in this figure due to Thompson normalised at the Pfotzer maximum agree extremely well with the calculations. Thus, the observations of Fichtel *et al* (1974) on the cosmic gamma ray flux from SAS–2 in the energy region 35–170 MeV seem to be reliable and self-consistent. Finally, the observations of Kraushaar *et al* (1972) from OSO–3 are in agreement, within errors, with those of Fichtel *et al* as can be seen from figure 1.

3. Discussion

In summary it is seen that all finite flux values for the diffuse cosmic gamma rays in figure 1 which lie significantly above the power law spectrum A with an index $-2\cdot3$ obtained by joining the data points below 1 MeV and those from SAS–2, have significant and serious uncertainties associated with them. In this connection special attention should be drawn to two very unfavourable experimental situations which apply to the energy region of 0·5–30 MeV where the bulge has been claimed. (i) Locally produced nuclear gamma rays become important from precisely the same energy region (0·5 to a few MeV) where the shoulder sets in. (ii) The energy region of 1–30 MeV is known to be experimentally most difficult for detection of gamma rays. When considered as a function of energy between 0·1 and 200 MeV, four important quantities which go into the final estimation of the diffuse photon flux, namely directionality, energy estimation, charged particle interference and conversion of count rates to photon fluxes, all lead generally to low effectiveness in the performance of the detector system in the energy domain of 1–30 MeV where precisely the shoulder has been seen. While it is not to say that these arguments preclude the possible existence of the shoulder, all that has been stated above emphasizes the need to be extra-cautious about accepting these claims and attributing weighty interpretations to them. Rather our main objective has been to highlight the difficulties encountered and to focus pointed attention to the weaknesses of the existing evidence for the shoulder in the hope that new and qualitatively improved experiments will be carried out in the future in this energy range.

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