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THE ORIGIN OF THE SPURIOUS 17 keV NEUTRINO SIGNAL OBSERVED IN ^{35}S BETA-DECAY

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The Origin of the Spurious 17 keV Neutrino Signal Observed in ^{35}S beta-decay

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Abstract

An exhaustive study has been made of the β spectrum of ^{35}S, recorded with a Si(Li) detector. A variety of different geometries were used and the collimation was also varied. Proton microprobe studies, yield of barium X-rays and source tilting have shown that the ^{35}S sources, prepared by chemical adsorption of $Ba^{35}SO_4$, are clumped and locally thick, causing an energy loss ~ 0.3 keV at 150 keV electron energy. The spectra are well fitted without any 17 keV neutrino admixture if this is taken into account; neglect of this additional energy loss mimics presence of a 17 keV neutrino and the mechanism giving rise to this mimicry is elucidated.

The significant distortion in the ^{35}S β spectrum some 17 keV below the end point, reported three years ago and interpreted as evidence for a 17 keV neutrino, arose primarily because the sources were assumed thin. Neglect of scattering effects and of a low energy pile-up correction also contributed to the misinterpretation of those data.

1. Introduction

Experiments carried out at Oxford in 1990 on the beta-decay of ^{35}S yielded a significant distortion in the β-spectrum 17 keV below the end-point [1]. This distortion was interpreted as further evidence for the existence of a 17-keV neutrino admixture at the 1% level, in support of the hypothesis first put forward by Simpson in 1985 following an experiment on the β-decay of tritium [2]. Experiments carried out at Berkeley in 1990 also yielded positive evidence in the beta-spectrum of ^{14}C [3]. However, no evidence had been found in a very careful experiment using a magnetic spectrometer [4], and experiments continued at Oxford in an attempt to gain further understanding of the phenomenon.

The controversy was largely resolved at the "Neutrino 92" conference in Granada [5] when the results from high precision experiments were announced. One on ^{35}S, which was carried out with a solid-state detector, used a magnetic field to collimate the electrons and suppress back-scattering [6]. An experiment on ^{63}Ni, which had very high statistics, used a magnetic spectrometer [7], as did another experiment on ^{35}S [8]. All reported null results. Recent measurements of the β-spectrum of ^{35}S have employed a magnetic spectrometer [9] and silicon detectors in a magnetic field [10], which gave virtually total suppression of the back-scattering and set a stringent limit on the existence of a 17 keV neutrino.

This letter reports the results of the further measurements carried out at Oxford during 1992 and 1993 on the beta spectrum of ^{35}S, using the same apparatus as in the original work [1]. These measurements have enabled us to identify the origin of the spurious 17 keV neutrino signal reported in [1] and set our own stringent limit.

2. The Experiment

The apparatus and electronics were as described in the original paper [1], but the geometry of source and detector and the collimation were varied. Two different cooled Ortec Si(Li) detectors, both 5 mm thick, and three sources were used for the measurements. The sources of $Ba^{35}SO_4$ were deposited on 100 Å of gold on 3.5μm thick mylar substrates. Sources #1 and #2 were made by the technique of chemical adsorption as in [1] and #3 by evaporating a drop of $Na_2{}^{35}SO_4$ on a thin layer of barium (3.5μg cm^{-2}) deposited on the gold, followed by washing away soluble residues. Fourteen different runs were made, each lasting typically 8 days, using a chamfered anti-scatter baffle, the original square cut 0.8 mm thick aluminium baffle (see figure 1 of [1]), as well as with no baffle between the source and detector.

The active pile-up rejection circuit incorporated in the Ortec 672 amplifier rejected all pile-up pulses except those arising from pulses occurring within the resolving time ($\sim$ 350 ns), or those which were below the threshold ($\sim$ 11 keV) of the pile-up rejection circuit. The former gave rise to sum pile-up events, the latter to a small pile-up toe correction. This toe took the form of an approximately triangular spectrum extending from a monoenergetic signal to $\sim$ 11 keV above that signal and it was studied by operating a pulser above the end point of the β spectrum. The amplitude depended linearly on rate, being 0.4% at 3.5×10^3 electrons s^{-1} in the detector. This effect was not suspected in [1].

3. Analysis of the data

The response to a monoenergetic electron of incident energy E_i was modelled by a gaussian-shaped peak centred at an energy E_0, where $E_0 = E_i - \Delta_i$, together with an energy loss component peaked at an energy $E_0 - B$ and a back-scattering part. Energy loss occurs when the electrons pass through the gold contact and thin SiO_2 deadlayer of the Si(Li) detector and also when they pass out of the source. Back-scattering of the electrons from the detector has an $\sim$ 13.5% probability for 100–200 keV electrons [11]. The functional forms used for the energy-loss and backscattering parts were:

$$\left(\frac{dN}{dE}\right)_{eloss} = \frac{1.042A_0.B.(E_0-E)}{(E_0-E)^3+2B^3} \quad \text{with} \quad A_0 = A_K\left(\frac{v_K}{v_0}\right)^2 \qquad (3.1)$$

$$\left(\frac{dN}{dE}\right)_{bscat} = \frac{1}{E_0}\left[S(E_0-E)/E_0+F\right] \qquad (3.2)$$

where A_0 gives the amount of energy loss component at an electron energy E_0 and velocity v_0 and A_K is the amount at $E_K = 61.5\,\text{keV}^{\dagger}$; S is the slope and F the amount of flat component of the back-scattering response. The flat component was also used to account for the effects of electrons scattered before reaching the detector. The form (3.1) represents some average over electron binding energies, the parameter B corresponding to an effective ionisation potential. Fitting to the ^{109}Cd K, L and M conversion electron spectra over the range 30–88 keV established that this parametrisation gave a good fit to the data with $S = 0.44$ and $B = 0.20\,\text{keV}$. (This value for the slope is very similar to that found for 100–200 keV electron backscattering [11].) The fit was improved by addition of a second term of form (3.1), with a higher effective ionisation potential $B' = 1.2\,\text{keV}$ and fraction $A'_K = 0.013$ at the ^{109}Cd K line. This was included in the response function but A'_K was held constant in the analysis of the ^{35}S spectra. The energy loss component of the electron response determined with a ^{57}Co source was consistent with the dependence of A_0 on v_0 assumed above.

The amount of flat, F, depended on the geometry and collimation, and varied between 1–4½% for the ^{109}Cd spectra and between 2–6½% for the ^{35}S spectra; these values were found to be correlated and the presence of scattering is indicated. During a ^{35}S run there was a small amount of ice build-up on the cooled Si(Li) detector, typically $\sim 50\mu\text{g cm}^{-2}$, which was monitored by taking ^{109}Cd spectra before and after each run. The amplitude A_K of the energy loss

† 61.5 keV is a convenient benchmark, being the energy deposited in the detector by the ^{109}Cd K IC line.

component, determined with ^{109}Cd, changed from ~ 0.4 before a ^{35}S run to ~ 0.6 after and the peak shift Δ_i from $\sim 100\,\mathrm{eV}$ to $\sim 200\,\mathrm{eV}$, at $E_i = 61.5\,\mathrm{keV}$.

4. Results

The expression for the raw beta spectrum used a relativistic Fermi function with a screening potential of 1.73 keV, as described in [1]. This spectrum was convoluted with the model electron response function, in which the pile-up toe was included, and used to generate a spectrum consisting of both single and pile-up events. This was fitted to the data, the fit extending beyond the end point to 200 keV. The activity, end point, flat component, amplitude of the energy loss A_K and the proportion of sum pile-up were all varied in the fit.

The energy loss A_K was found to be consistently larger than deduced from the ^{109}Cd data, implying either that the ^{35}S source was thicker than the ^{109}Cd source or some unknown effect was mimicking increased energy loss. Eleven runs were made with one source under a wide variety of source, detector and collimator geometries and all required a similar excess, ΔA_K. This suggested that the change in response function was caused by increased energy loss in the ^{35}S source and we present in section 6 below independent evidence that the source was indeed of the right thickness to cause this additional energy loss.

The results of the fits to the fourteen runs are presented in table 1. Good fits to all of the runs were obtained with the hypothesis of no heavy neutrino and the fit to one of the runs, 5, is shown in figure 1. The end-point of the ^{35}S spectrum, determined from all 14 runs, is $167.39 \pm 0.04\,\mathrm{keV}$, where the error is estimated from the variance of the results. The mean value for ΔA_K for source #2 is 0.48 ± 0.05 and this corresponds to the energy loss of electrons passing through $140 \mu\mathrm{g\ cm}^{-2}$ of $BaSO_4$. The statistical error on each determination of A_K from fitting ^{35}S spectra was typically 0.10; the error on ΔA_K is estimated from the variance of the results and uncertainties in the modelling of the electron response function.

Testing for the hypothesis of a 0.8% 17 keV neutrino admixture gave consistently worse χ^2; for these fits A_K was restricted to be greater than or equal to the value deduced from the ^{109}Cd data. The amount of flat component was very similar to that found when fitting with no heavy neutrino, being determined by the long range curvature of the Kurie plot. Fits were also made allowing both A_K and the amplitude of a 17 keV neutrino, $\sin^2\theta$ [1], to vary, as well as the activity, end-point, flat component of the electron response function and amount of sum pile-up. The maximum amplitude found was 0.25%, with eleven runs yielding less than 0.1% of a 17 keV neutrino admixture. The mean amplitude was −0.02% with a standard deviation determined from the results of the 14 runs $\sigma = 0.05\%$ from which we estimate an upper limit on the admixture of a 17 keV neutrino as $\sin^2\theta < 0.1\%$ (95% CL).

The experiment differs from that reported in the original paper [1] in that in 11 of the 14 runs a chamfered rather than a square cut antiscatter baffle was used. (Of three runs with the square cut baffle two showed evidence for increased scattering reasonably modelled by a flat component — these runs had the geometry of the original experiment.)

The analysis differed in that the pile-up toe was included, the flat component in the response was allowed to vary and above all the energy loss was fitted and not fixed at the value determined from ^{109}Cd. In the original analysis the ^{35}S source was assumed to be locally thin — ours were not (section 6).

If the thickness of the ^{35}S sources is ignored then the data *appear* to support the hypothesis of a heavy neutrino admixture. As an example, consider the data from run 5 fitted assuming no heavy neutrino and a thin source: the residual shape factor $RS(= S - 1)$ is displayed in fig.2, where the shape factor S is the data divided by the fit. The residual shape factor kicks sharply upwards, passing through zero at ~ 160 keV. This behaviour is characteristic of the presence of a neutrino of mass ~ 17 keV (for this run the best fit assuming a thin source gave

0.43% for a 17 keV neutrino) but is also characteristic of excess energy loss (see fig.4). Neglect of excess energy loss mimics a heavy neutrino admixture and this can be understood analytically.

5. Effect of energy loss on the residual shape factor

One would suppose that fitting a β spectrum in the presence of unsuspected energy loss would generate a kick down in the residual shape factor, rather than a kick up at the end, for the shape factor due to neglect of some energy loss turns down sharply as the end point is approached (fig.3). Were the end point kept fixed, a kick down would be obtained, but because the end point is not sufficiently well known it is essential to allow it to vary in the fit. The origin of a kick up is then easily understood.

The shape factor due to energy loss is quite well represented by

$$S = 1 - \frac{a}{\sqrt{Q-T}} \qquad (Q - T > 1\,\mathrm{keV}) \tag{5.1}$$

and a spectrum of form $x^2(1 - ax^{-1/2})$ is to be fitted with a form $(1-\alpha)(x+\epsilon)^2$ where $x = Q - T$ and α, ϵ are parameters in the fit and represent varying the activity and end-point of the allowed beta spectrum. To lowest order in small quantities, the best match is obtained by minimising

$$\chi^2 = \int_0^{x_0} [-ax^{1/2} - 2\epsilon + \alpha x]^2 dx \tag{5.2}$$

with respect to ϵ and α simultaneously. (The integrand is the square of the difference, divided by x^2 — this is an analytic χ^2 minimisation.) This yields

$$\begin{aligned} \alpha &= \frac{4}{5} a\, x_0^{-1/2} \\ \epsilon &= -\frac{2}{15} a\, x_0^{1/2} \end{aligned} \tag{5.3}$$

and the residual shape factor is

$$RS = -a\, x^{-1/2} + \alpha - 2\epsilon x^{-1}. \tag{5.4}$$

If a is positive, corresponding to excess energy loss, then ϵ is negative — the fitted end point is $< Q$. This residual shape function is plotted in fig.4(a); the energy loss shape function $1 - a\, x^{-1/2}$ and the shape function resulting from a shift in the end point $1 - \alpha + 2\epsilon x^{-1}$ are plotted in fig.3. The limit of integration is $x_0 = 47\,\mathrm{keV}$, corresponding to fitting ^{35}S from 120 keV kinetic energy to $\sim$ the end point. The energy loss parameter a is $0.1\,\mathrm{keV}^{1/2}$, corresponding to unsuspected energy loss equivalent to $A_K \sim 0.5$.

To lowest order, the shape of the residual function is independent of the amount of energy loss, because both α and ϵ depend linearly on a. For the particular choice $a = 0.1\,\mathrm{keV}^{1/2}$ and $x_0 = 47\,\mathrm{keV}$, $\alpha = 0.0117$ and $\epsilon = -0.091\,\mathrm{keV}$. The residual shape factor for a 0.8% admixture of 17 keV neutrino is shown in figure 4(b). The shapes differ significantly only below 155 keV and in this region the errors on individual bins are, for a single run, similar to or greater than the differences (see fig.2).

6. Evidence that the sources are thick

Proton Microprobe Studies

When source #1 was $\sim$ 8 half lives old it was cut out and mounted in the beam of the Oxford Proton Microprobe [12], information on the composition of a thin sample being obtained from proton induced X-ray emission (PIXE) and from Rutherford back scattering of the microprobe beam. Scanning a square of side 2.5 mm with coarse resolution yielded an area density of barium of 34 ng cm^{-2}, a factor $\sim$ 3 greater than would be expected were the barium deposited only in association with radioactive ^{35}S. Scanning areas $100\mu\mathrm{m}$ square, mapping barium L X-ray emission, local concentrations of barium were located. These clumps had areas ranging from $100\mu\mathrm{m}^2$ to $1000\mu\mathrm{m}^2$ and thicknesses between $70\mu\mathrm{g\ cm}^{-2}$ and $\geq 400\mu\mathrm{g\ cm}^{-2}$. The material was composed primarily of barium and calcium silicates and sulphates.

These results can only be indicative, for less than 1% of the active source was scanned with sufficient resolution to detect concentrations of dimensions $\sim 10\mu$m. However, it is clearly not safe to assume the sources are locally thin and it is not safe to assume the composition of the source layer to be predominantly barium sulphate.

Detection of barium K_α X-rays

We have detected barium K_α X-rays superimposed on the cumulative ^{35}S β spectrum from 86 days of data taking with source #2, $\sim$ 460 KHz days of electrons incident upon the detector. The X-rays follow ionisation of the barium K shell by the electron flux and the number is given by the mean thickness of barium passed through by decay electrons, the product of the K ionisation cross section and K fluorescent yield and the number of electrons incident upon the detector. The cumulative source #2 data yielded a signal of $1.19 \times 10^5 \pm 0.23 \times 10^5$ barium K_α X-rays, see fig.5. We have also detected gold L X-rays from the source substrate.

In order to estimate the effective source thickness, we took for the mean cross section for ionisation of inner shells by electrons the expression [13]

$$\langle \sigma_{n\ell} \rangle = \frac{\pi e^4}{Q E_{n\ell}} Z_{n\ell} b_{n\ell} \left\langle \frac{Q}{T} \ln \frac{c_{n\ell} T}{E_{n\ell}} \right\rangle \qquad (6.1)$$

where Q is the end point of the β spectrum, T is electron kinetic energy and $E_{n\ell}$ the ionisation energy of electrons with quantum numbers (n, ℓ). The quantity $Z_{n\ell}$ is the number of electrons in the shell. We chose $c_{n\ell} = 1$ and for barium K shell ionisation we took $b_K = 0.95$, determined from matching extensive low energy data on ionisation of silver [14]. For gold L, $b_L = 1.05$ matches the cross sections measured at $\sim$ 50 keV [15]. Averaging over the ^{35}S β spectrum, we find $\langle \sigma_K \rangle_{Ba} = 1.4 \times 10^{-23}$ cm^2 and the fluorescent yield of barium K_α X-rays is 0.73 [16]. An effective thickness of 100μg cm^{-2} of barium then yields a calculated number of 1.77×10^5 barium K_α X-rays reaching the detector for 460 KHz days, 4×10^{10} electrons incident on the detector. The detector is

5mm thick and transmits 0.44 of the incident barium K X-rays. We detected $1.19 \times 10^5 \pm 0.23 \times 10^5$ and so infer an effective thickness of barium of $120 \pm 24 \mu$g cm^{-2}, a total effective thickness of $204 \pm 40 \mu$g cm^{-2} if all the material is $BaSO_4$.†

This inference has been checked to some extent by detection of gold $L_{\alpha,\beta}$ X-rays, for which we find $\langle \sigma_L \rangle_{\mathrm{Au}} = 7.1 \times 10^{-22}$ cm^2, with a fluorescent yield of 0.32 [17]. In the cumulative source #2 spectrum we found $1.05 \times 10^6 \pm 0.25 \times 10^6$ gold L X-rays, where the error is an estimate of the systematic uncertainty of modelling background. In a run of source #1 with the detector screened by 0.0125 g cm^{-2} of aluminium, we found 3253 ± 304 gold L X-rays, which after correction for absorption in the screen becomes 4485 ± 420 gold L X-rays for 2.1 kHz days, in excellent agreement with the number extracted from the cumulative source #2 runs. These numbers correspond to effective thicknesses of 38 ± 9, $36 \pm 4 \mu$g cm^{-2} of gold at the source backing. The perpendicular thickness of gold on the substrate is 21μg cm^{-2} and the majority of electrons striking the substrate do so at very oblique angles. The effective thickness depends on how rapidly such electrons are scattered out of the film of gold; we estimate an effective thickness of only $\sim 20 \mu$g cm^{-2} before allowing for electrons which are scattered back into the gold from the plastic backing. These might contribute an additional $\sim 5 \mu$g cm^{-2}.

The barium K_α X-rays imply a mean distance in $BaSO_4$ for all decay electrons $\sim 200 \mu$g cm^{-2}. This is *conclusive* evidence that source #2 is not locally thin. It is not possible to turn this effective thickness into a mean perpendicular thickness because the detailed topography of the source is unknown. (If plates of

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† We also searched for barium L X-rays, in a 24 hour run of source #1 under high dispersion. We expect $\sim 2 \times 10^4$, but they lie in a deep trough and uncertainties in the shape of that background made it impossible to extract a reliable number. We estimate $\sim 10^4$ but any number between 0 and 2×10^4 is possible.

$BaSO_4$ are of an area such that horizontal electrons are scattered out rather than leaving through the edges, then the perpendicular thickness is approximately equal to the effective thickness. If the source is dominated by crystals for which the base is approximately equal to the height, the perpendicular thickness is approximately twice the effective thickness.) The microprobe studies show that a significant mass of calcium compounds may be mixed with the barium.

The mean thickness of material passed through by electrons reaching the detector, required to fit the end of the β spectra without a 17 keV neutrino, $\Delta A_K = 0.48 \pm 0.05$ corresponds to $140 \pm 15\mu g\ cm^{-2}$ of $BaSO_4$ ($0.3\mu m$) and probably represents half the perpendicular thickness.

Effects of source thickness on the low energy end of the β spectra.

The energy spectrum of ^{35}S falls monotonically from zero energy, but when the electrons pass through a thin absorber the low energy end is relatively depleted and the measured spectrum exhibits a peak. The position of this peak increases with the thickness of material. We were able to measure the difference in thickness between the sources from the shift in the peak of the β spectra and also attempt a measurement of the absolute thicknesses through the time honoured technique of tilting the source foils. The calibration was established from the difference in energy loss at the beginning and end of $\sim$ 8 day runs, as determined from ^{109}Cd IC line sources† and the shifts of the spectral peaks during those same runs as ice built up on the detector. We found that the form

$$\frac{dA_K}{dn_{peak}} = a + bn_{peak} \tag{6.2}$$

fits the data well for n_{peak} corresponding to electron energies 10–15 keV (channels 120–180), with $a = -3.15 \times 10^{-3}$, $b = 5.35 \times 10^{-5}$. Beyond channel 180 we have only two less well determined points.

† The Cd sources are thin, $\Delta A_K < 0.1$. This was established by the absence of any peak shift of low energy Auger electrons and IC lines on tilting the source foil.

At the beginning of a run, before any significant ice built up on the detector, source #1 peaked at ~channel 108, source #2 at ~ 135 and source #3 at ~ 104. These results alone show that source #2 is thicker than #3 and #1 by $\Delta A_K \sim 0.1$. Systematic studies of sources #2 and #3 yielded results summarised in Table 2. The peak shift between given configurations decreases as the mean peak position increases, as expected from (6.2).

The data in Table 2 were fitted with the three variables t_2 (thickness of source #2), $t_2 - t_3$ (difference in thickness between #2 and #3) and a channel shift c, to be subtracted from the peak shift Δn_{peak} before matching to the change of thickness, which accounts for a change in back diffusion from the source of low energy electrons as the angle of the source is changed. This effect constitutes the principal uncertainty in the measurement of the absolute source thicknesses: we have studied saturation back diffusion of ^{109}Cd electrons from plastic and estimate an upward shift of only a few channels, due to back diffusion, when the source is tilted through 40°.

We have found

$$
\begin{aligned}
t_2 &= 0.35 \pm 0.05 \pm 0.05 \\
t_2 - t_3 &= 0.095 \pm 0.007 \pm 0.002 \qquad (6.3) \\
c &= 6 \pm 3 \pm 5
\end{aligned}
$$

where the thicknesses are given in the units of A_K, the first error is statistical and the second an estimate of the effects of uncertainty in back diffusion, and in calibration beyond channel 180. The disparate data in Table 2 are well fitted and the internal consistency, in conjunction with the barium K X-ray yield, makes it beyond belief that the ^{35}S sources are not in fact thick.

7. Remarks on the conditions of the original experiment

Run 9 was carried out under conditions which reproduced as closely as possible those of the original experiment [1]. When analysed as described in section 4 an admirable fit was obtained with no 17 keV neutrino, but the parameter ΔA_K was large (Table 1). Analysed without allowance for the effect of the pile-up toe and assuming a thin source, but allowing the flat component in the electron response function to vary, results very similar to those reported in [1] were obtained: the fit required $0.75\% \pm 0.12\%$ of 17.3 ± 0.6 keV neutrino (χ^2 172/155).

It has been suggested [18] that the original result was due to neglect of scattering from the square cut "anti-scatter" baffle. To the extent that scattering is modelled by a flat component, this is not supported by our results. However, although the ^{109}Cd IC response function for run 9 is reasonably well represented with a flat component, it is better represented with a flat component and an additional component peaked at ~ 0.92 of the incident energy and containing 1.2% of the intensity. In fitting to the ^{35}S data of run 9, such a peaked scattering term can absorb at most 0.2 units of ΔA_K, or 0.15% of 17 keV neutrino. Neglect of the pile-up toe generates 0.15% of 17 keV neutrino and so we find that in run 9, under the conditions of the original experiment, the major effect is energy loss in the source, accounting for more than 0.6 of the spurious 17 keV neutrino signal.

8. Conclusion

An exhaustive study of the β spectrum of ^{35}S has revealed no evidence for the existence of a 17 keV neutrino. The results of 14 separate runs together yield an admixture $\sin^2\theta = -0.02\% \pm 0.05\%$, or $\sin^2\theta < 0.1\%$ (95% CL). The end point of the ^{35}S β spectrum was found to be $Q = 167.39 \pm 0.04$ keV.

It has been shown to be impossible to predetermine, with sufficient accuracy, the electron response function in the region of 100–167 keV. We have found that the energy loss component cannot be taken from ^{109}Cd or ^{57}Co IC lines, because the $BaSO_4$ sources are locally thick. We have found a component in the response function, modelled by a flat term, which is geometry dependent and is attributed to scattered electrons. Such a term gives rise to a long range curvature in the Kurie plot, which has to be fitted. The distortion in the original experiment, which was interpreted as evidence for a 17 keV neutrino, was undoubtedly caused primarily by neglecting energy loss in the source. The neglect of scattering effects and the presence of the low energy pile-up toe also contributed to the misinterpretation of those data.

D.H. Perkins made valuable contributions in the early stages of this work. We thank D. Wark for showing us microprobe evidence that $BaSO_4$ sources prepared by chemical deposition could be locally thick and G.W. Grime for making the proton microprobe studies of source #1.

Table 1

Results of fitting 14 ^{35}S β spectra over the range 100–200 keV. Columns 3–5 give results of fitting with no heavy neutrino; ΔA_K is a measure of the source thickness (see text). Column 6 lists χ^2 obtained when fitting with an admixture of 0.8% of 17 keV neutrino. In both cases the number of degrees of freedom was 156.

		No heavy neutrino			0.8% 17 keV ν
Run	**Source #**	Q	ΔA_K	χ^2	χ^2
1	1	167.202	0.29	141	180
2	1	167.733	0.40	124	144
3	2	167.406	0.36	137	182
4	2	167.486	0.41	168	213
5	2	167.479	0.54	166	200
6	2	167.396	0.32	158	228
7	2	167.513	0.48	160	184
8	2	167.495	0.49	162	182
9	2	167.304	0.66	147	159
10	2	167.273	0.57	163	175
11	2	167.223	0.49	171	209
12	2	167.261	0.45	166	196
13	2	167.366	0.48	153	157
14	3	167.321	0.30	149	172

Table 2

Measurements of change of thickness between sources

Measurement	**Change of thickness**	**Mean n_{peak}**	Δn_{peak}
0°	$t_2 - t_3$	130	29 ± 4
40°	$1.305(t_2 - t_3)$	152	24 ± 3
0°	$t_2 - t_3$	163	16 ± 3
0°	$t_2 - t_3$	200	14 ± 4
40°	$1.305(t_2 - t_3)$	218	10 ± 4
Measurements of change of thickness on tilting sources			
40° − 0°	$0.305t_3$	130	30 ± 4
40° − 0°	$0.305t_3$	192	22 ± 3
40° − 0°	$0.305t_2$	152	25 ± 3
45° − 0°	$0.414t_2$	154	34 ± 3
40° − 0°	$0.305t_2$	220	18 ± 3

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Figure Captions

1. Results of fitting run 5 assuming no heavy neutrino and allowing energy loss to vary. The difference between data and the fitted spectrum is displayed in units of the statistical error, for each bin. The end point is indicated by a vertical arrow.

2. The residual shape factor resulting from fitting run 5 with no heavy neutrino and with an amount of energy loss determined from ^{109}Cd IC lines. The kick up beyond 160 keV can only be removed by increasing the amount of energy loss, or introducing $\sim 0.4\%$ of ~ 17 keV neutrino. Increased energy loss gives the better fit (Table 1).

3. The solid curve shows the shape factor induced by energy loss, for the parameter $a = 0.1\,\text{keV}^{1/2}$ (see text). The shape factor here is the spectrum obtaining in the presence of energy loss, divided by the original β spectrum. The broken curve is the shape factor resulting from fitting the spectrum with energy loss with a pure β spectrum in which the end point was allowed to vary in the fit. The difference of the two curves (fig.4a) yields the residual shape factor obtained when fitting in the presence of unsuspected energy loss, with the end point of the fitted spectrum a variable. The lower scale is electron kinetic energy T for ^{35}S, the upper $Q - T$. The end point is indicated by a vertical arrow.

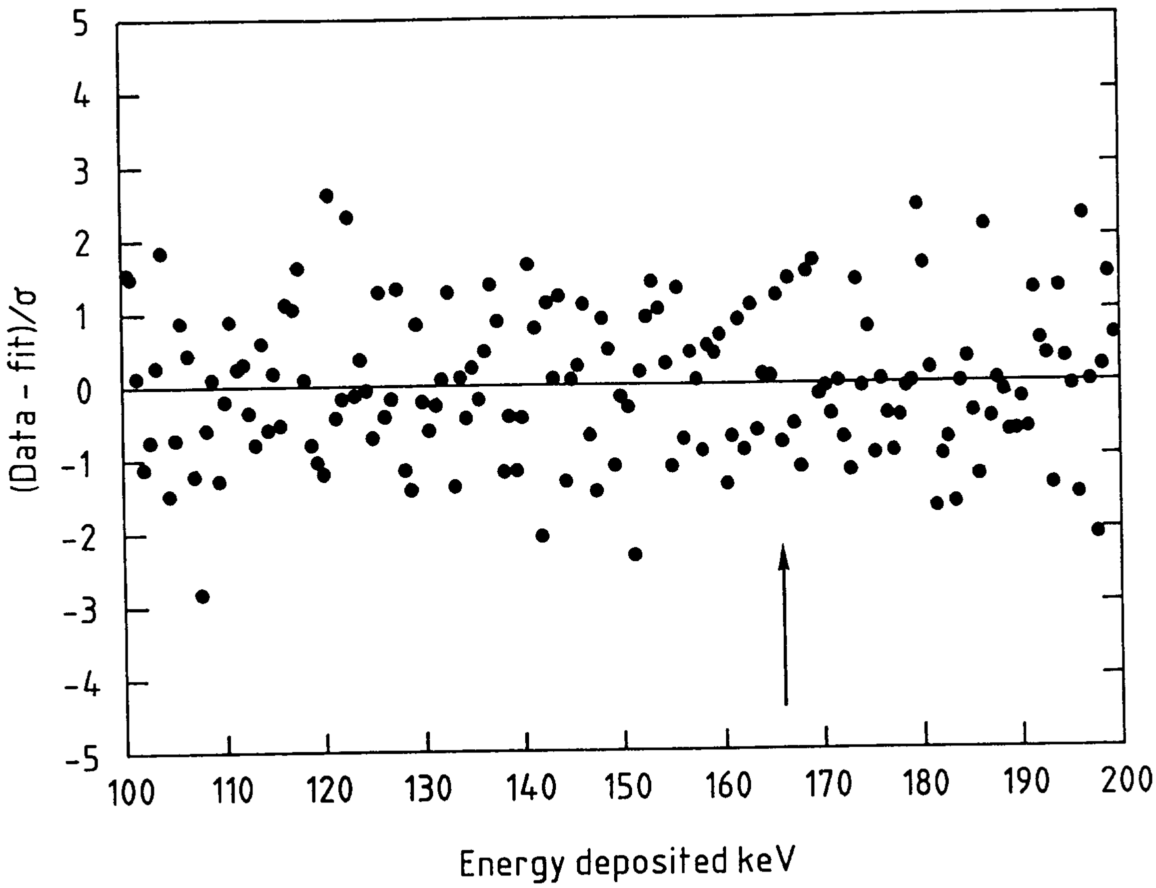
4.a) The residual shape factor obtained when fitting a β spectrum in the presence of unsuspected energy loss, with the end point of the fitted spectrum a variable.

b) The residual shape factor obtained when fitting a β spectrum containing 0.8% of 17 keV neutrino with a spectrum which has none, the end point a variable.

The two shapes are significantly different only below 155 keV, where the statistical errors on individual data points are, for a single run, of the same order as the difference.

The lower scale is electron kinetic energy T for ^{35}S, the upper scale in a) is $Q - T$. The end point is indicated by vertical arrows.

5. The extracted barium K_α X-ray signal, from the summed runs 3–13 (source #2). The data were fitted locally with a second order background and the barium K_α profile; the difference from the smooth background is displayed. Each bin contained approximately 1.1×10^8 counts before subtraction of the background. A typical error bar is shown.



5
4
3
2
1
0
-1
-2
-3
-4
-5
(Data - fit)/σ
100
110
120
130
140
150
160
170
180
190
200
Energy deposited keV

Fig. 1

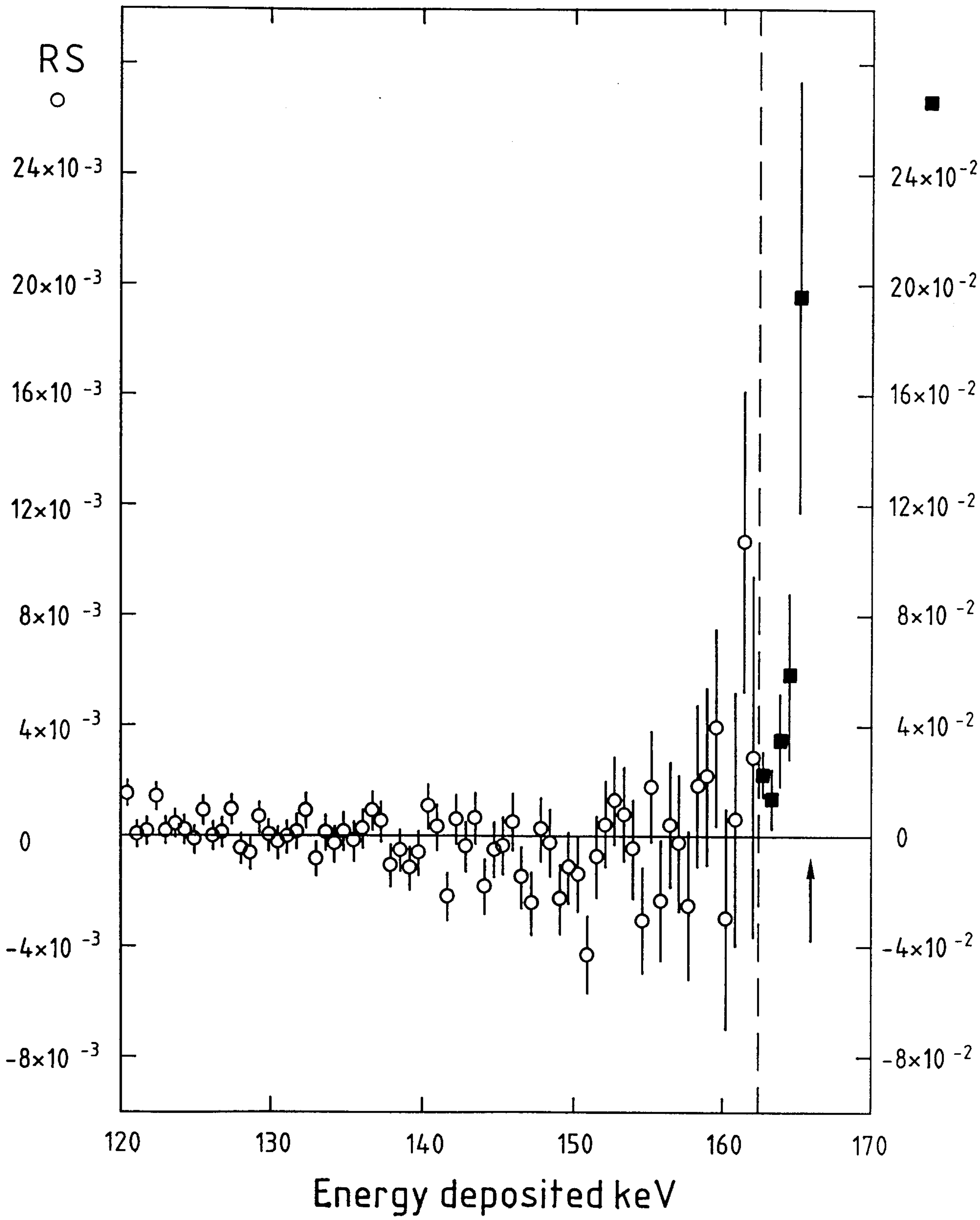

RS
24×10 -3
20×10 -3
16×10 -3
12×10 -3
8×10 -3
4×10 -3
0
-4×10 -3
-8×10 -3
24×10 -2
20×10 -2
16×10 -2
12×10 -2
8×10 -2
4×10 -2
0
-4×10 -2
-8×10 -2
120
130
140
150
160
170
Energy deposited keV

Fig. 2

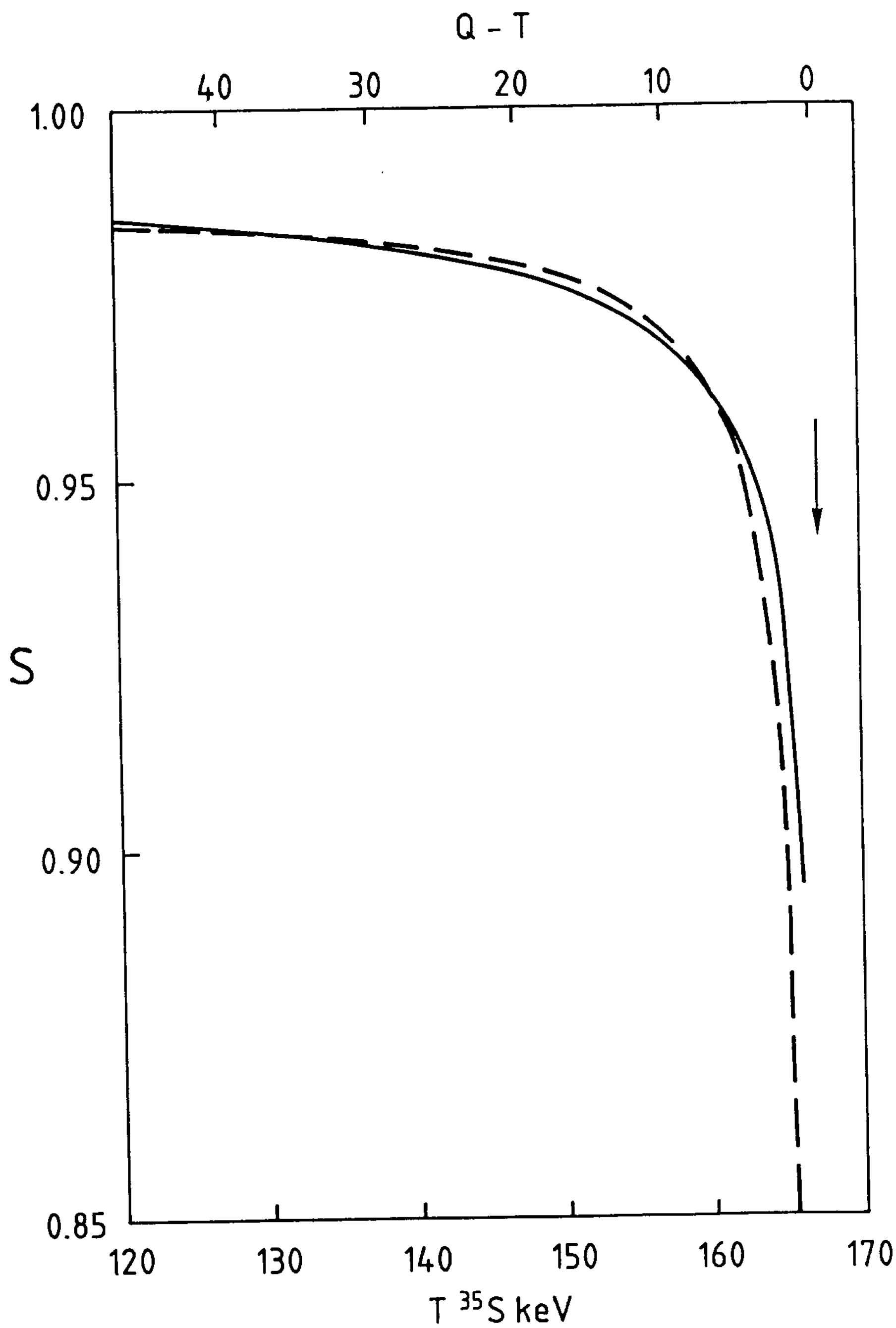


Fig. 3

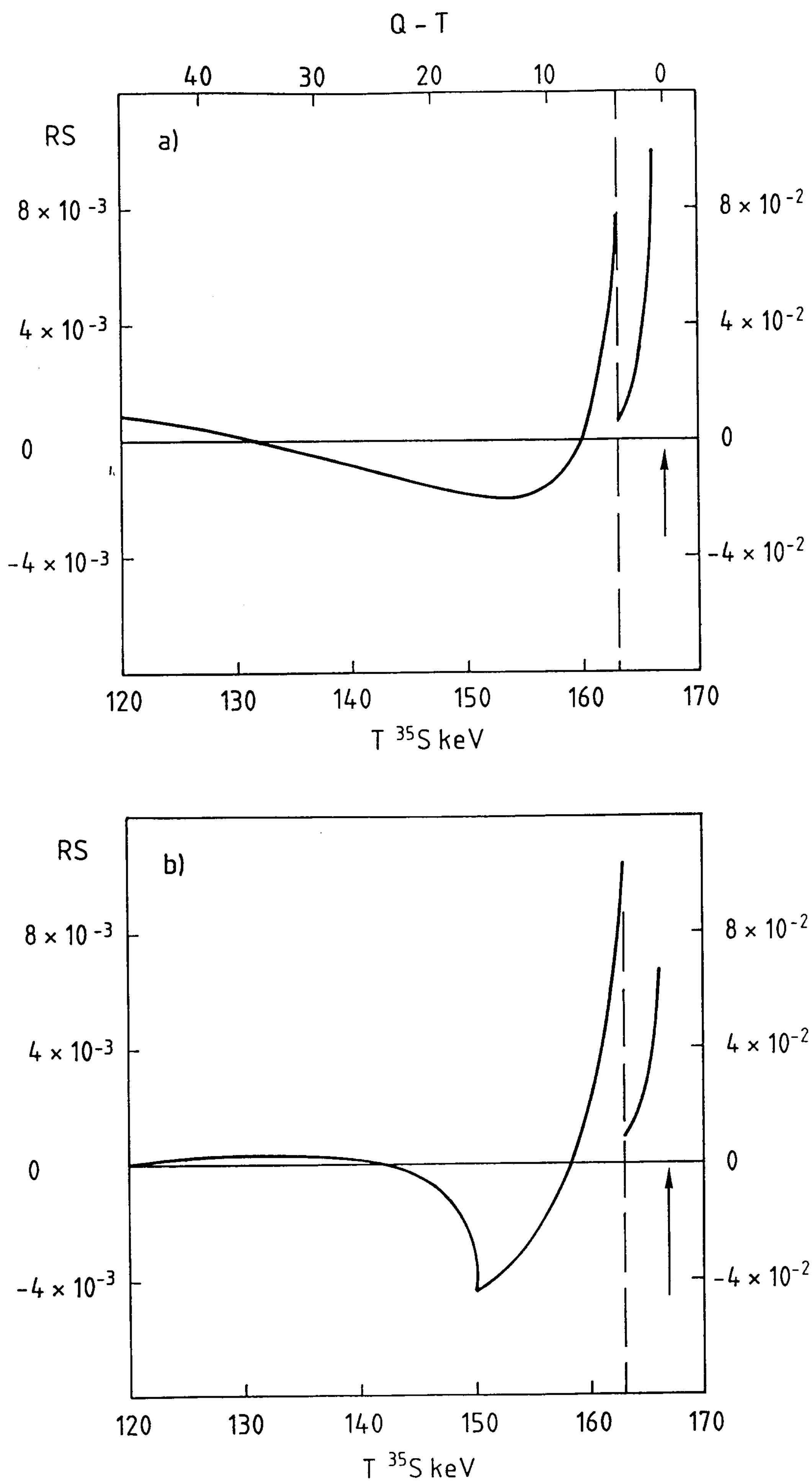

Q - T
40
30
20
10
0
RS
a)
8 × 10 -3
4 × 10 -3
0
-4 × 10 -3
8 × 10 -2
4 × 10 -2
0
-4 × 10 -2
120
130
140
150
160
170
T 35S keV
RS
b)
8 × 10 -3
4 × 10 -3
0
-4 × 10 -3
8 × 10 -2
4 × 10 -2
0
-4 × 10 -2
120
130
140
150
160
170
T 35S keV

Fig. 4

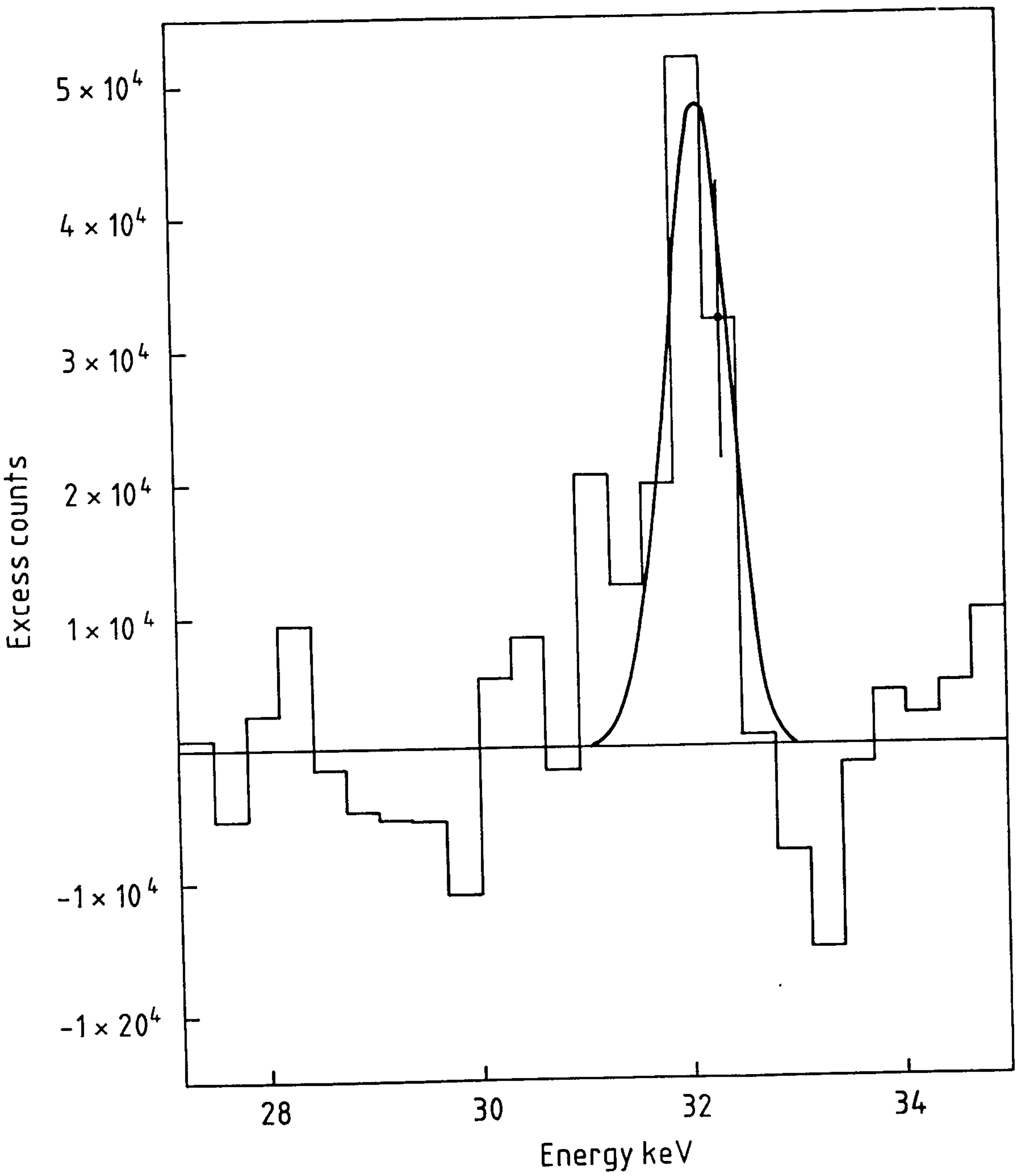

5 × 10⁴
4 × 10⁴
3 × 10⁴
2 × 10⁴
1 × 10⁴
-1 × 10⁴
-1 × 20⁴
Excess counts
28
30
32
34
Energy keV

Fig. 5