THE THERMAL DETECTION EFFICIENCY FOR RECOILS INDUCED BY LOW ENERGY NUCLEAR REACTIONS, NEUTRINOS OR WEAKLY INTERACTING MASSIVE PARTICLES

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Abstract

We report the first direct measurements on the energy dependence of the thermal detection efficiency for heavy recoiling nuclei. Two bolometers made by TeO_2 crystals facing each other were operated at low temperature and read-out independently, while coincidence-anticoincidence techniques were used for particle discrimination. The experiment was carried out underground after implantation of both crystals with a source of ^{228}Ra . The relative response for alpha particles and nuclear recoils with respect to electrons of the same energy (Quenching Factor) was found to be compatible with or slightly larger than unity. Deviations from constancy with energy of the QF for nuclear recoils in α decays of ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Po and ^{212}Bi were not observed .

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1. Introduction

Measurements of the recoiling energy of heavy nuclei are of considerable interest in nuclear physics. Typical examples are experiments on spontaneous fission [1], on the recoil range in nuclear reactions [2], on rare α decays and on radioactivity involving protons, carbon and heavier clusters [1]. In particular the detection of a nuclear recoil in association with time-of-flight measurements can be complementary with other techniques like those based on nuclear activation [3] or Doppler shift [4]. In subnuclear and astroparticle physics the interest is related to measurements of nuclear recoils induced by neutrinos or by Weakly Interacting Massive Particles (WIMPs) as candidates for the invisible Dark Matter [5]. The relevant parameter in these experiments is the so called Nuclear Recoil Quenching Factor (QF) defined as the ratio between the amplitudes of the signals induced in the detector by a recoiling nucleus and by an electron of the same energy. Most of these experiments have been carried out with "conventional" detectors like semiconductors or scintillators. Such devices usually have a nuclear recoil QF much lower than unity [6-8], and the alternative use of thermal detectors, where this QF is expected to be near unity, is suggested [9-12]. In these detectors, in fact, any kind of deposited energy is expected to be converted into heat, and can be recorded by a suitable thermometer provided that the heat capacity of the absorber be lowered enough by operating the detector at low temperatures. Two "thermal" experiments on Dark Matter have already been carried out underground: one with a 24 g sapphire crystal [13] and another with an array of four 340 g TeO_2 crystals [14]. Many experiments on thermal detection of WIMPs are planned [9,15], one is already taking data [16] and another will be in operation soon [17]. Detectors capable of recording simultaneously ionization or scintillation and heat have been successfully operated [9-12], and the nuclear recoil QF for the ionization signal of a Ge diode has been determined under the reasonable assumption that this factor was equal to one for the thermal signal [10].

The QF for nuclear recoils of ^{206}Pb in TeO$_2$ bolometers was determined from the energy split in "doublets" due to α- decays of ^{210}Po nuclei which normally contaminate Tellurium [14] or by exposing directly a thermal detector to the ^{206}Pb nuclear recoils [13,18]. In all these experiments QF's compatible with unity have been obtained for a fixed recoiling energy around 100 keV. Direct measurements on the energy dependence of the Nuclear QF have been performed for conventional detectors by exposing them to neutrons and measuring the neutron scattering angle [5]. No similar measurement exist for thermal detectors even if a neutron scattering facility is being installed by the Oxford group [19]. Aim of the present experiment is the direct determination the QF for a thermal detector at different recoiling energies.

2. Experimental details

The experiment has been performed with an array of two parallel crystals of TeO$_2$ of 20x20x30 mm^3 facing each other along their longer axes and separated by 2 mm (Fig.1). Each crystal was held by 32 spring-loaded tips to a copper frame screwed to the mixing chamber of a dilution refrigerator. Thermal pulses were detected by means of two Neutron Transmutation Doped Ge thermistors in thermal contact with their corresponding crystals. Pulses from each thermistor were read out independently and their time correlation established off-line. In order to minimize problems due to threshold, both channels were acquired when there was a trigger in either of the crystals. The dilution refrigerator was operated in the Gran Sasso Underground Laboratory in order to minimize the background induced by cosmic rays. The shields against environmental radioactivity and electromagnetic background as well as the electronic read-out system were similar to those adopted in a previous series of ββ decay experiments [20].

An area of about 0.5 cm^2 in the center of the surface of crystal A facing crystal B had been previously exposed to a ^{228}Ra source in radioactive equilibrium with its daughters [21]. A similar exposure had been successively performed on the surface of crystal B facing A. As a result of the exposures, the first α active nucleus of the chain, ^{228}Th, implants into the crystal the nucleus ^{224}Ra which decays with a half-life of 3.66 days into ^{220}Rn, followed by ^{216}Po, ^{212}Pb, ^{212}Bi and ^{212}Po. We produced in this way a source of α particles and recoils internal to each crystal ; but very close to its surface. When the implanting source is taken away, a chain in radioactive equilibrium with its ^{224}Ra progenitor, whose lifetime is much longer than those of its descendants, is established. For each α decaying nucleus inside one crystal both products of the decay can be fully contained in it, in which case the entire transition energy is observed (events *a* and *b* of Fig.1). Since, however, the radioactive nuclei are near the surface, either the α particle or the recoiling nucleus can leave the crystal and be revealed by the facing detector, since an almost 2π geometry is realized (events *c* to *f*). We would also like to note that in our set-up, operated in vacuum, there are no "dead regions", since the entire volume of the absorber is active unlike the situation for many conventional detectors such as those based on semiconductors.

The detectors were operated at a temperature of about 22 mK for 40 hours of effective running time. In order to test their stability and determine their QF for α particles and nuclear recoils relative to electrons, they were exposed during the entire run to γ sources of ^{22}Na, ^{62}Co, and ^{232}Th. The FWHM energy resolution in the final spectra ranged from 3 to 6 keV in the energy region from 20 to 3000 keV.

4. Data analysis and results

The off line data analysis was performed using the coincidence-anticoincidence method to discriminate different kinds of events [14,22]. We have first analysed the spectrum of detector A(B) *in anticoincidence* with detector B(A). This procedure selects α decays in which the full transition energy is recorded in A(B). As a consequence, in addition to the γ ray lines , only those peaks corresponding to the entire α transition energies (α + recoil) appear in the spectrum. The most relevant peaks are around 5790, 6207, 6404, 6906 and 8953 keV, as expected. The thermal pulse height is not linear with respect to the released energy, but a simplified electro-thermal model [23] allows to establish a correlation between the energies of the γ ray lines and the corresponding pulse amplitudes. This model can also be applied to the entire set of lines (γ - rays and fully contained α decays) with the QFs of α particles and nuclear recoils assumed as two additional free parameters, independent of energy. From the fit to all relevant lines, quenching factors relative to electrons of $1.020 \pm .005_{stat} \pm .005_{syst}$ and of $1.025 \pm .01_{stat} \pm .02_{syst}$ are obtained for α particles and recoils , respectively. The systematic error has been calculated with a Monte Carlo method, and is mainly due to the spread of implantation depths. A QF lower than unity is definitely excluded both for α particles and for nuclear recoils.

Complementary results have been obtained by operating the two detectors *in coincidence* . The scatter plot of the energy measured in A (α particle energy region) versus the corresponding one measured in B (recoil energy region) is shown in Fig. 2. A similar scatter plot is obtained when the "nuclear recoil" energy in A is plotted versus the "α particle" energy in B. An intercept with the vertical axis in Fig.2 corresponds to a decay where the entire recoil and α particle energies are released in A (event *a* of Fig.1). The plot can be fitted with five straight lines with a -1 slope, and their intersections with the vertical axis are compatible with the expected total transition energies when the above mentioned quenching factor is taken into account. There is no evidence down to 20 keV for a deviation from a straight line behavior which would be the consequence of energy dependence of the nuclear recoil and α particle Quenching Factors.

The spectrum of the recoils of ^{224}Ra in B in coincidence with the corresponding α particle in A is shown in Fig. 3. It can be fitted by a gaussian, unlike the spectra of ^{206}Pb recoils recorded in diamond [16] and TeO_2 [12], where an asymmetry due to autoabsorption in the source was present. This is due in the present experiment to the very small depth of nuclear implantation and to the effect of the coincidence with a pulse corresponding to the full α particle energy . From a fit to the peak in Fig.3 we obtain a recoil energy of 104 ± 1 keV in good agreement with the expected value of 103.4 keV, thus confirming that the QF is close to 1.

4. Conclusions

The present results were made possible by the use of the anticoincidence and coincidence procedure applied for the first time by our group [12,22] to thermal detectors. By operating the detectors in anticoincidence and calibrating them with γ rays we show that the QF of recoiling nuclei with energies from 100 to 170 keV and of α particles with energies ranging from 5.7 to 8.8 MeV is compatible or slightly larger than unity. The measurement in coincidence excludes large deviation from constancy of the QF for nuclear recoils in the energy region between 20 and 170 keV.

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References

[1] See for instance the recent reviews in "Nuclear Decay Modes", ed. by D.N. Poenaru, Inst.of Physics Pu. (Bristol-Philadelphia), 1996

[2] D.J. Parker et al, Phys.Rev. C44 (1991) 1528

[3] E. Gadioli, in Heavy Ion Physics, Vol.2 (1995) 161 , ed by Akademiai Kiado, Budapest 1995

[4] See for instance: Treatise on Heavy-Ion Science, Ed by D.Allan Bromley, Plenum Press (New York and London) Vol.7 (1985)

[5] For recent results on direct detection of WIMPS see L. Mosca, Nucl.Phys. B (Proc.Suppl.) 48 (1996) 34 and R. Bernabei, Rivista del Nuovo Cim. 18 (1995) 1

[6] G. Gerbier et al, Phys.Rev. D 42 (1990) 3211; G. Gerbier et al, Proc. of the Moriond Conf.ed. Frontieres (1991)

[7] G.J. Davies et al, Phys.Lett.B322 (1994) 159

[8] Y. Messous et al, Astropart.Phys. 3 (1995) 361

[9] For recent details on cryogenic detectors see the Proceedings of the VIth Intern.Workshop on Low Temperature detectors, (Beatenberg, Switzerland, Aug.28-Sept.1,1995), Nucl.Instrum.and Meth.in Phys.Res. A 370 (1996)

[10] B. Sadoulet, Nucl.Instrum.and Meth. A370 (1996) 1, also for previous references

[11] D. Twerenbold, Rep.Prog.Phys.59 (1996) 349

[12] N. Booth, B. Cabrera, and E. Fiorini, Ann.Rev.of Nucl.Sci. 46 (1996) 471

[13] A. de Bellefon et al, Astropart.Phys. 6 (1996) 35

[14] A.Alessandrello et al, Phys.Rev.Lett. B 384 (1996) 316

[15] E.Fiorini, Nucl.Phys. B (Proc.Suppl.) 48 (1996) 41, and references therein

[16] P.D. Barnes et al, Nucl.Instrum. and Meth. in Phys. Res. A370 (1996) 233, and private communication by B. Sadoulet

[17] M. Buhler et al, Nucl.Instrum. and Meth.in Phys. Res. A370 (1996) 237

[18] J.W. Zhou et al, Nucl.Instrum. and Meth. In Phys. Res.A349 (1994) 225

[19] M.J.J. van den Putte et al, P.D. Barnes et al, Nucl.Instrum. and Meth. in Phys. Res. A370 (1996) 271

[20] A. Alessandrello et al, Phys.Lett. B335 (1994) 519

[21] Tables of Radioactive Isotopes, Ed. by E. Browne and R.B. Firestone , John Wiley and Sons, Inc., New York -Chichester-Brisbane-Toronto-Singapore, 1986

[22] A. Alessandrello et al, Phys. Rev.Lett. 77 (1996) 3319

[23] A. Alessandrello et al, Study of the nuclear quenching factor for low-temperature phonon -mediated particle detectors, submitted to Nucl.Instrum.and Meth. in Phys. Res.A

Figure captions

Fig.1 : The detection principle of our set-up: events *a* and *b* are fully contained in A and B. In events *c* to *f* part of the decay energy is detected in one crystal, while the remaining energy is detected in the other one. As described in the text all decays occur in central spots of 0.5 cm^2, but in the figure they are shown as occurring in correspondence to the entire facing surfaces of the array for sake of clarity .

Fig.2 : Scatter plot of the energy released in A in the α particle energy region versus the energy released in B in the nuclear recoil energy region . The complementary plot of the energy released in B in the α particle region versus the energy released in A in the nuclear recoil region is similar.

Fig. 3 : Spectrum of the recoil of ^{224}Ra in detector A in coincidence with the signal of the corresponding α particle in detector B.

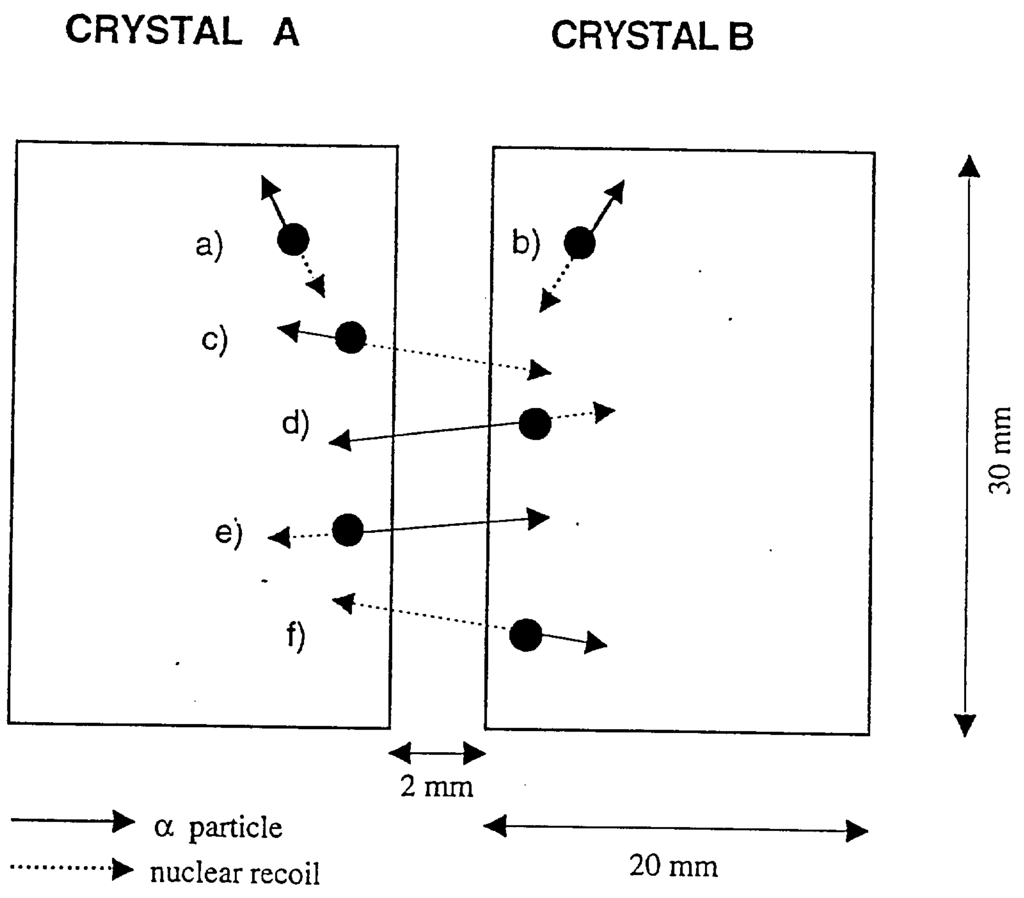
CRYSTAL A
CRYSTAL B
a)
b)
c)
d)
e)
f)
30 mm
2 mm
20 mm
α particle
nuclear recoil

Fig. 1

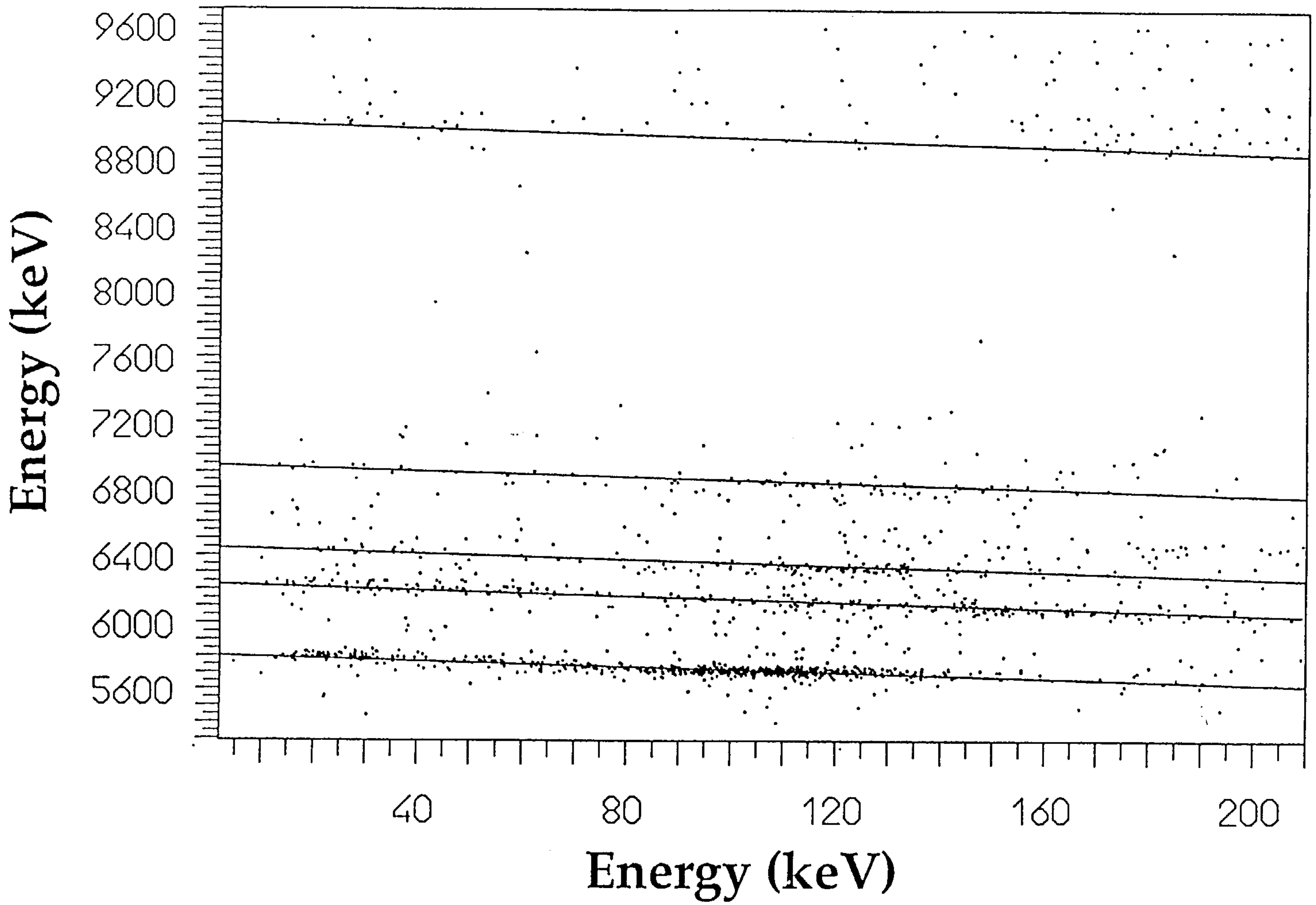
9600
9200
8800
8400
8000
7600
7200
6800
6400
6000
5600
Energy (keV)
40
80
120
160
200
Energy (keV)

Fig. 2

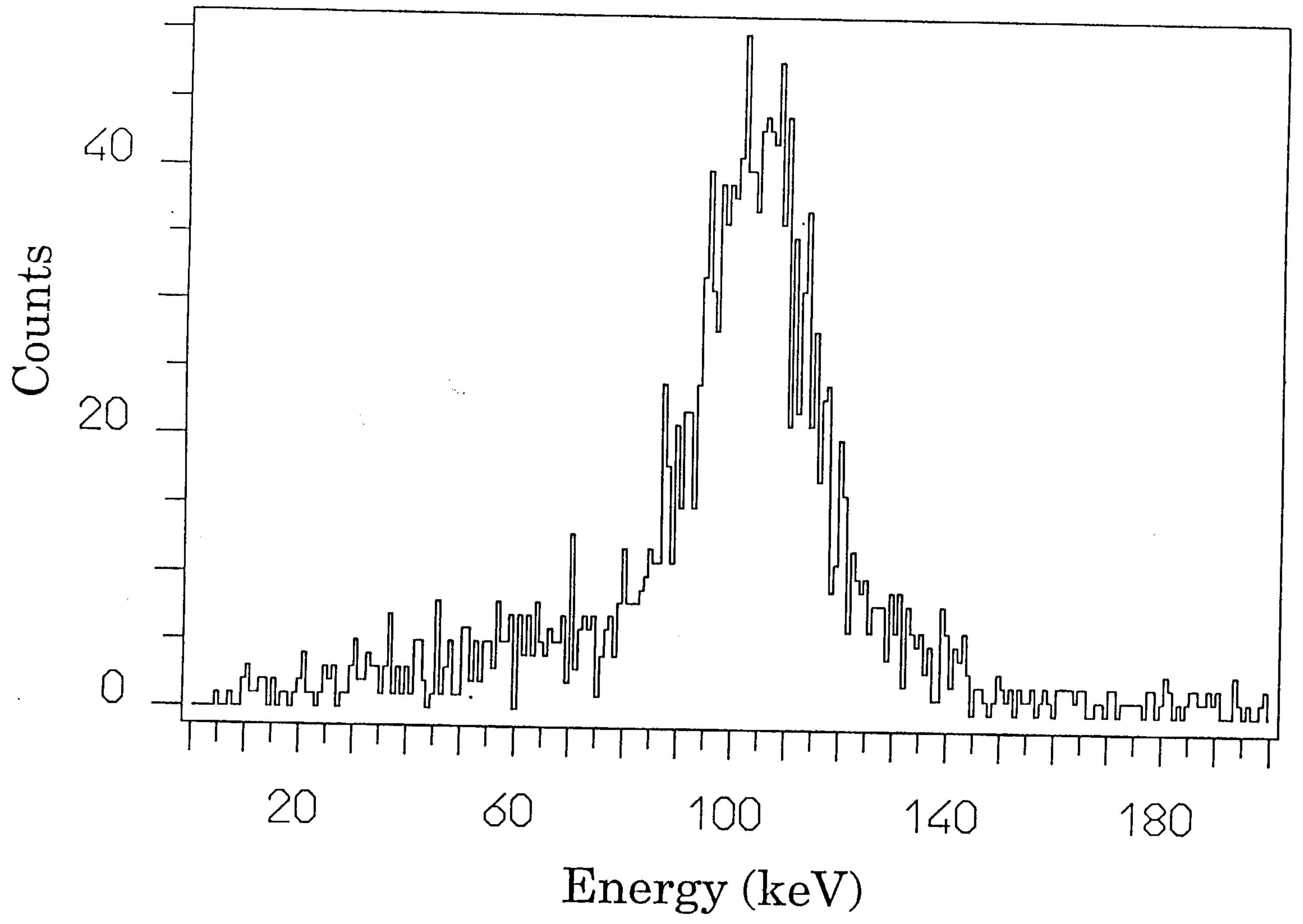

Fig. 3