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PROPERTIES OF THE LIGHTEST KNOWN CAESIUM ISOTOPES, $^{114-118}$Cs

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ABSTRACT

Neutron-deficient caesium isotopes with mass numbers from 114 to 118 have been studied at the ISOLDE facility. Half-lives have been determined from counting of beta particles, beta-delayed protons, and gamma-rays. A short-lived isomer ($T_{\frac{1}{2}}$ = 0.7 sec) in ^{116}Cs has been observed and the new delayed-particle precursors ^{116}Cs (protons and alphas), ^{115}Cs (protons), and ^{114}Cs (protons and alphas) have been identified. Coincidences between delayed particles and gamma-rays have been measured for ^{118}Cs (pγ and $\alpha\gamma$) and ^{116}Cs (pγ). A search for the possible proton-radioactive isotope ^{113}Cs has been performed and an upper limit for its production yield is given.

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RADIOACTIVITY $^{114-118}$Cs [from La(p,3pxn), chem. mass separation], measured β-delayed protons, β-delayed alphas, $β^+$-rays, γ-rays, $T_{½}$, E_p, $I(E_p)$, $E_α$, $I(E_α)$, $E_γ$, $β^+γ$ coinc., pγ coinc., αγ coinc. : deduced P_p, $P_α$, $P_p/P_α$, $Q_{EC} - B_p$ and levels in ^{116}Xe. Natural target, Ge(Li), NaI(Tl), Ne 110 plastic scintillator, surface-barrier Si detectors, position-sensitive Si detector.

1. INTRODUCTION

On-line mass-separated caesium isotopes produced in targets of molten lanthanum [1] (by spallation reactions) and uranium carbide [2] (by high-energy proton-induced fission) have been extensively studied with the ISOLDE facility at CERN over the past few years. The mass numbers so far identified range from 114 to 147 and thus represent the largest number of isotopes from a single element yet known. Systematic investigations, such as mass measurements [3], measurements of nuclear spins and moments [4], and determinations of level schemes [5] have been performed. The neutron-deficient isotopes ^{118}Cs and ^{120}Cs were shown [6] to emit both beta-delayed protons and beta-delayed alpha particles. In this paper we present studies of the most neutron deficient nuclides: those between mass 114 and 118. Half-lives have been determined from counting of high-energy positons, beta-delayed particles, and beta-delayed gamma-rays. Singles delayed-particle spectra have been measured and the feedings of excited final states after delayed particle emission have been determined in delayed-particle gamma-ray coincidence experiments. A search for the possible proton radioactive isotope ^{113}Cs is also described in the context of a general discussion on the possibility of finding this type of radioactivity as yet unobserved from a nuclear ground state.

2. EXPERIMENTAL TECHNIQUES

The neutron-deficient caesium isotopes studied in this work were produced by spallation reactions in a 20 cm thick (122 g/cm^2) target of molten lanthanum metal, kept at a temperature of $\sim$ 1300° C, and bombarded with a 1 μA beam of 600 MeV protons from the CERN Synchro-cyclotron. Of the elements formed in high yields by the spallation of La, only Ba, Cs, Xe and I are sufficiently volatile to be released from the target melt. A Ta transfer tube between the target and the extraction electrode of the ISOLDE isotope separator, was kept at a temperature of $\sim$ 1000°C, and acted as a selective surface ionization source for caesium atoms (for details see Ref. 7). Magnetic analysis in the isotope separator resulted in chemically pure beams of mass-separated caesium ions. A beam of any selected mass could then be directed by a pair of electrostatic deflector plates [8] into a beam-line that connected the separator with the experimental set-up.

The following four set-ups were used in the experiments to be described here:

A) An 80 mm diameter × 50 mm plastic scintillator (NE110) was used for the detection of high-energy beta particles. To reduce the background of gamma and beta radiations, this detector was operated in coincidence with energy signals from a 100 mm^2, 1 mm thick ΔE plastic scintillator. The two detectors, acting as a beta telescope, had an over-all efficiency of 20% for 3.5 MeV betas. By means of deflector plates the ion beam could be directed periodically onto a stationary collector of aluminized mylar placed directly in front of this telescope.

B) A ΔE-E detector telescope equipped with surface barrier detectors (ΔE; 25 μm, 100 mm^2; and E: 500 μm, 450 mm^2) was used for the identification of protons and alpha particles. The solid angle for this telescope was 11% of 4π sr.

C) Half-lives of delayed particle precursors were determined with a position-sensitive Si surface-barrier detector (500 μm thickness, 7 × 45 mm^2 area). In these experiments the radioactive beam was collected on a continuously moving tape, which subsequently passed in front of the detector. Energy and position signals, the latter corresponding to time, yielded both energy spectra and half-life of the delayed particle activity.

D) A Si surface-barrier detector (100 μm, 100 mm^2) together with a 40 cm^3 Ge(Li) detector was used for measurements of high-resolution particle spectra and coincidence measurements between beta-delayed particles and gamma-rays.

3. EXPERIMENTAL RESULTS

The main findings in this work are presented below and in Table 1.

^{118}Cs: Measurements with a detector telescope showed that the energy regions covered by beta-delayed protons and beta-delayed alphas from ^{118}Cs do not overlap. A simultaneous measurement of both protons and alpha particles is therefore possible

with a single detector offering the advantage of high resolution (20 keV FWHM). Figures 1 and 2 illustrate the observed proton and alpha spectra, respectively. The ratio of protons to alphas (P_p/P_α) obtained was 17.2 ± 0.3, in close agreement with an earlier result [6].

The half-life of ^{118}Cs has been determined [1] by positon counting to be 16.4 ± 1.2 sec. A half-life measurement based on counting of delayed protons (set-up C) yielded $T_{\frac{1}{2}}$ = 17 ± 2 sec, confirming the common origin of both activities.

The population of excited final states after delayed particle emission was determined in coincidence experiments using set-up D. The spectrum of γ-rays observed in coincidence with protons is shown in the lower part of Fig. 3. The three strongest coincident lines are attributed to transitions [10, 11] in ^{117}I with energies 117, 160, and 221 keV, respectively. Coincidences with annihilation radiation showed that (2.1 ± 0.5)% of the ^{118}Cs delayed protons followed positon decay. The resultant ratio of positon decay to electron capture decay can then be used, with the method outlined in Ref. 12, to determine the energy available for beta-delayed proton emission, the $Q_{EC} - B_p$ value. The result is 4.7 ± 0.3 MeV.

The excited states in ^{114}Te that can be reached after delayed alpha emission are the 709 keV (2^+) and the 1484 keV (4^+) states [13]. In a 24-hour experiment with a 3 in. × 3 in. NaI detector, a total of 45 gamma events of energy 709 keV were observed to be in coincidence with alpha particles (Fig. 4). These correspond to a feeding of (29 ± 6)% for the 2^+ state in ^{114}Te. The branch to the 4^+ state, which would yield coincidences with 775 keV ($4^+ \rightarrow 2^+$) gamma-rays, was found to be ≤ 4%.

<u>^{117}*Cs:*</u> As no beta-delayed particles could be observed from ^{117}Cs, its half-life was determined solely from counting of high-energy positons with set-up A. The ion beam was collected on an aluminium foil in front of the beta telescope for 0.2 sec. The beam was then interrupted and the subsequent radioactive decay was followed both in a multiscaling and a multispectrum mode. Analysis of the region above 7 MeV in the beta spectrum, after subtraction of a contribution from ^{117}Xe, ($T_{\frac{1}{2}}$ = 65 sec, Ref. 10), yielded a half-life for ^{117}Cs of (6.5 ± 0.4) sec, in agreement with the earlier result [1], 8 ± 2 sec.

^{116}*Cs:* A number of different half-life measurements for ^{116}Cs were performed in order to identify possible isomers. In one experiment, similar to the one described by Hagberg et al. [14], delayed protons were detected in a nuclear emulsion and the half-life was found to be 3.5 ± 0.2 sec (Fig. 5). This value was confirmed with both set-ups C and D and is also in perfect agreement with the value given by Bogdanov et al. [15]. No other half-life component could be extracted from the delayed proton decay in these experiments. However, the positon spectrum detected with set-up A showed in addition to the 3.5 sec half-life, a second component [9] with a decay period of 0.7 ± 0.2 sec. This isomer has recently been confirmed in similar positon counting experiments [16, 17]. The highest energy part of the positon spectrum showed only the short-lived component (Fig. 6), which indicates that this mainly feeds the ground state of ^{116}Xe. The end-point energy was measured to be 10.5 ± 1.5 MeV. Energy calibration of the beta telescope was achieved using a ^{106}Ru source, and ^{74}Rb produced [18] on-line. The production ratio of the two isomers was found to be 3:1, favouring the longer-lived component. Gamma spectra from ^{116}Cs were measured in coincidence with signals from a 4π beta scintillation detector in order to reduce the room background. Several lines appeared (Fig. 7) with 3.5 sec half-lives, but only the annihilation radiation signals showed both the 0.7 sec and 3.5 sec components. In a recent, more detailed, spectroscopic investigation, Knipper et al. [17] have found that there are weak gamma transitions with energies $\sim$ 322 keV and $\sim$ 458 keV (see Fig. 7) that belong to the short-lived isomer.

The delayed proton and delayed alpha spectra from ^{116}Cs were measured with a detector telescope (set-up B), placed behind a 20 $\mu g/cm^2$ carbon foil, which acted as a collector for the ion beam from the separator. The delayed proton spectrum is shown in Fig. 8. The ratio P_p/P_α was found to be 47 ± 2. The in-beam measurement gives a mixture of possible particle emission from the two isomeric states and we have, therefore, carried out an experiment where protons and alphas were detected in a multispectrum mode. We find the P_p/P_α ratio to be 50 for the 3.5 sec component and no indication of either protons or alphas from the short-lived isomer.

This result is, in fact, expected if the main feeding of the 0.7 sec state goes to the ^{116}Xe ground state. We have thus not been able to reproduce either the strong alpha branch for the 0.7 sec isomer or the different P_p/P_α ratios given in Ref. 16.

The delayed proton- and alpha-branching ratios were independently measured to be $(3.6 \pm 0.8) \times 10^{-3}$ and $(8 \pm 2) \times 10^{-5}$, respectively. The total number of ^{116}Cs ions was deduced from the count rate of the 93.3 keV gamma transition in the decay of ^{116}Te.

The spectrum of gamma-rays in coincidence with delayed protons, counted over a 10-hour period is displayed in the upper part of Fig. 3. Coincident gamma-rays are seen at the energies 55 ± 5, 107 ± 5, 318 ± 5, 580 ± 5, and 590 ± 5 keV. The intensities are given in Table 1. From the coincidences with annihilation radiation it was found that (40 ± 8)% of the protons were emitted after positon decay. This yields a value of 6.45 ± 0.30 MeV for the energy $Q_{EC} - B_p$, which is in good agreement with the value given by Bogdanov et al. [19].

<u>^{115}*Cs:*</u> Initial indications of this isotope were obtained in the emulsion experiment (Fig. 5). A search for delayed-particle activity (set-up B) at mass position 115 gave a rate of 200 protons/h. However, the beta-decay daughter, ^{115}Xe, is itself a well-known [20] delayed-proton precursor and, in order to get a result for the ^{115}Cs delayed-proton branching ratio, a measurement with the position-sensitive detector was performed (set-up C). From the complex decay curve obtained for proton events at mass 115 and knowing the ^{115}Xe delayed-proton branch (3.4×10^{-3}, Ref. 20) the value of P_p for ^{115}Cs was determined to be 7×10^{-4}. The delayed-proton activity exhibited a half-life of about 1 sec for ^{115}Cs, but the much stronger proton branch of the daughter made a precise determination difficult. An experiment with set-up A gave a more accurate value: 1.4 ± 0.8 sec.

<u>^{114}*Cs:*</u> Both delayed-proton and delayed-alpha activities were observed (set-up B) at the A = 114 mass position. Since the daughter, ^{114}Xe, has been shown [14] not to be a delayed-particle emitter, the observed activity is attributed to ^{114}Cs. The ratio P_p/P_α was measured to be 33 ± 12.

The production yield of ^{114}Cs is estimated to be around 5 atoms/sec from the calculated proton branching ratio. A half-life measurement, based on particle counting (set-up C), gave in a 6-hour experiment a value of $T_{\frac{1}{2}}$ = 0.7 ± 0.2 sec.

^{113}*Cs:* Most calculations [21] of nuclear masses predict the ground state of ^{113}Cs to be unstable towards proton emission. With the present high production rates at ISOLDE there should have been a fair chance to observe this type of radioactivity had the Q value for proton emission been favourable.

A search for ^{113}Cs was performed with a detector telescope equipped with a 20 μm thick front detector. The counting with the telescope was done in two different ways: (i) the coincident summed $\Delta E + E$ signals were recorded in order to observe possible beta-delayed particle events from ^{113}Cs and its daughter ^{113}Xe; (ii) a single spectrum from the ΔE detector was recorded in anticoincidence with the E detector. The latter mode allows low-energy (directly emitted) protons to be recorded, while suppressing the background signals from beta particles and delayed particles which pass through the telescope. ^{113}Cs lies in the region where several new alpha emitters recently have been identified [22]. With an estimated [21] Q_α value of about 3 MeV, this isotope would also be a candidate for alpha emission. The anticoincidence spectrum from the ΔE detector would also register such possible alpha events from ^{113}Cs.

A 32-hour experiment was performed on the ^{113}Cs mass position and the following observations were made:

i) No beta-delayed particle events were registered in the telescope detector.

ii) No peak from a possible direct proton or alpha branch was observed in the anticoincidence spectrum from the ΔE detector.

From this we may estimate an upper limit for the production yield which depends on the proton and beta partial half-lives. If $t_p \gg t_\beta$ the ground-state proton branch would be weak and the ^{113}Cs decay would be dominated by beta decay with an estimated [23] half-life of 0.2 sec. The calculated delayed proton branch from ^{113}Cs is 5% and based on this value result (i) then gives an estimated upper limit for the yield to be 13 atoms/hour. If $t_p \approx t_\beta$ the non-observation of a peak in the ΔE counter would give a limit of the production of less than 10 atoms/hour.

We thus find a drop of more than three orders of magnitude between the ^{114}Cs and the ^{113}Cs yields (see Table 1). This is much more than expected from the empirical spallation yield formula [24]. A possible explanation of this result is a very short half-life ($t_p << t_\beta$) for ^{113}Cs, which would result in sufficiently high delay losses in the target and ion source as to preclude detection of the activity.

4. DISCUSSION

Beta-delayed proton emission from heavier elements is well understood. The present study adds to this knowledge, but is special in the sense that it represents the first systematic study of a family of odd-Z precursors. For such nuclei many final states may be reached after proton emission and this fact together with the high level densities characteristic of emitters relatively far from closed shells, results in proton spectra showing almost no fine structure, with the present experimental resolution (Fig. 1).

Here will be given a few examples of statistical model calculations for the delayed-particle spectra. The present calculations follow the ideas outlined earlier [25, 26] with an assumed constant beta-strength function, constant alpha-strength function [9] and standard optical model parameters [27] for determining the proton widths. Level densities were calculated from the formulae of Gilbert and Cameron [28]. The average alpha widths were obtained from the formula [9]

$$\langle \Gamma_\alpha \rangle = \frac{\gamma_W^2 \, P_\ell}{\hbar\omega \cdot \rho_i} , \qquad (1)$$

where γ_W^2 is the Wigner sum rule limit and P_ℓ the barrier penetrability for angular momentum ℓ (calculated with Igo's potential [29] and with $\hbar\omega = 41\ A^{-1/3}$. The transition intensity for proton or alpha decay to one final level was then calculated from the expression

$$I_x^{if}(E_x) = \omega(I,I_i) \cdot b(E) \cdot \frac{\Gamma_x^{if}(E_x)}{\Gamma_{tot}^{i}} , \qquad (2)$$

where b(E) is the beta intensity, $\omega(I,I_i)$ a spin weight factor, and $\Gamma_x^{if}(E_x)$ the particle width connecting the intermediate state i with a final state f (for details see Ref. 25). Since we treat both proton and alpha emission the total width is

$$\Gamma_{tot}^{i} = \Gamma_{\gamma}^{i} + \sum_{f'} \Gamma_{p}^{if'}(E_p') + \sum_{f''} \Gamma_{\alpha}^{if''}(E_\alpha'') , \qquad (3)$$

where f′ and f″ are the final states populated by delayed proton and delayed alpha emission, respectively. The absolute values of the proton- and alpha-branching ratios as well as their ratio are reproduced remarkably well in this type of calculation, as has been demonstrated earlier [9]. Examples of the calculated envelopes for alpha and proton spectra are shown in Figs. 2 and 8, respectively. In Table 2 we show the results of a calculation for the population of the 2^+ and 4^+ states in ^{114}Te after delayed alpha emission from ^{118}Cs. Different assumptions about the spin and parity for the ^{118}Cs ground state have been made and the best agreement between the calculations and the experiment is found for $I^\pi = 2^+$ or 3^+. It should be noted that the P_p/P_α ratio also points to these two possibilities.

The observation of isomerism in ^{116}Cs is not surprising in view of similar observations [5] in the neighbouring even-A caesium isotopes. Based on our results it is however not easy to explain the results given by Bogdanov et al. [16]. They find a P_p/P_α ratio of 4.7 for the short-lived isomer and ≥ 200 for the long-lived one. Further, the relative production of the short-lived isomer is twice as strong in their experiment as in ours. In spite of this fact the in-beam result given in Ref. 16 is 50 ± 1, which is in perfect agreement with our value 47 ± 2. Our measurements give a P_p/P_α ratio of 50 for the 3.5 sec isomer and there is no indication of a short-lived component in the decay curves based on proton counting (even with our lower production it should certainly have been seen in these measurements).

The 393.8, 524.2 and 614.8 keV lines observed in the decay of ^{116}Cs (Fig. 7) may be assigned to the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions of the ground-state quasi-rotational band in ^{116}Xe. The energies of the two first transitions agree with those found by Batch et al. [30], while there is no indication of a 596 keV line, earlier assigned [30] as the $6^+ \rightarrow 4^+$ transition, in our spectrum. The energy assigned to the 2^+ state in ^{116}Xe is higher than that for ^{118}Xe and reflects that the 2^+ energy in the light even xenon isotopes exhibits a minimum for N = 66. This corresponds to the mid-point between closed shells. The analogous behaviour is observed in, for example, the platinum and osmium region [31].

Our search for ^{113}Cs, although unsuccessful, leads to one important conclusion: it appears that at mass 113 one has reached the proton drip line for caesium. The heaviest element for which this line has been reached previously is rubidium, where it was proposed [18] that the lightest particle stable isotope has mass number 74.

To make a rough estimate for the experimental possibility of observing proton radioactivity we consider first a nuclear ground state decaying by a combination of beta and proton emission. Experimental limits on the possible observation of proton decay follow from a consideration of the partial half-lives, t_β and t_p, for the two processes, if

$$t_p \ll t_\beta : T_{\frac{1}{2}} \sim t_p$$

and if

$$t_p \gg t_\beta : P_p \sim \frac{t_\beta}{t_p} \ll 1 ,$$

where $T_{\frac{1}{2}}$ is the total half-life and P_p is the proton branching ratio. Thus any given experiment will have an "observation window" [32] covering a range of possible t_p values, limited on one side by the minimum observable lifetime and on the other by the minimum observable proton yield.

In order to determine the window available to our ^{113}Cs experiment, we take $t_\beta \sim 0.2$ sec from the calculations by Takahashi et al. [23] and calculate t_p from the relationship

$$t_p \sim 10^{-22} \left[P_\ell(E_p)\right]^{-1} \text{ sec} , \qquad (5)$$

where $P_\ell(E_p)$ is the barrier penetrability for protons of energy E_p. Thus $T_{\frac{1}{2}}$ and P_p may be calculated as a function of E_p. In the present experiment we assess that, to be observed as a Coulomb-delayed proton emitter, ^{113}Cs must have the properties $T_{\frac{1}{2}} > 5$ msec and $P_p > 10\%$, which correspond to the requirement: 540 keV $< E_p <$ 650 keV. Equivalent calculations were performed for ^{111}Cs, ^{112}Cs, and ^{114}Cs, and the E_p "windows" for these nuclei are shown in Fig. 9 together with the predicted E_p values from various mass formulae [21]. The approximate nature of the calculation precludes specific conclusions, but it does indicate that for any given element in this region of Z there is less than a 20% chance that a proton emitter can be observed.

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Table 1

Production and decay characteristics of neutron-deficient caesium isotopes

Isotope	Production yield a) (atoms/sec)	$T_{1/2}$ (sec)	β-delayed proton branch P_p	P_p/P_α	γ-rays in coinc. with delayed prot. (MeV) (%) b)	Final excited levels after delayed α emission c) (MeV) (%)	Exp. determined $Q_{EC} - B_p$ (MeV)
^{118}Cs	3.2×10^6	16.4 ± 1.2	$(4.2 \pm 0.6) \times 10^{-4}$ d)	17.2 ± 0.3	0.117 (14 ± 2) 0.160 (8 ± 1) 0.221 (13 ± 2)	0.709 (29 ± 6) 1.484 (≤ 4)	4.7 ± 0.3
^{117}Cs	1.9×10^5	6.5 ± 0.4	-	-	-	-	-
^{116}Cs	4.3×10^3	3.5 ± 0.2 e) 0.7 ± 0.2 e)	$(3.6 \pm 0.8) \times 10^{-3}$ -	47 ± 2 -	0.055 (6 ± 2) 0.107 (7 ± 2) 0.318 (16 ± 4) 0.580 (26 ± 7) 0.590 (15 ± 5)	-	6.45 ± 0.30
^{115}Cs	120	1.4 ± 0.8	$\sim 7 \times 10^{-4}$	-	-	-	-
^{114}Cs	5	0.7 ± 0.2	-	33 ± 12	-	-	-
^{113}Cs	$< 3.5 \times 10^{-3}$	-	-	-	-	-	-

a) Production yield in a 122 g/cm^2 target of molten La irradiated with a 1 μA beam of 600 MeV protons.

b) The three gamma transitions in ^{117}I have been reported in Refs. 10 and 11. The gamma transitions following delayed proton emission from ^{116}Cs, and thus assigned to gamma transitions in ^{115}I, have energy uncertainties of ±5 keV.

c) Gamma energies from Ref. 13.

d) Ref. 9.

e) Two isomers are observed in ^{116}Cs. From the present experimental data we cannot decide which of them is the ground state.

Table 2

Calculated populations of excited final states in ^{114}Te after beta-delayed alpha emission from ^{118}Cs

I^{π} (^{118}Cs)	% feeding to 709 keV (2^+)	% feeding to 1484 keV (4^+)	P_p/P_α
1^+	13	0.2	6.8
2^+	30	0.9	20.0
3^+	27	1.7	18.5
4^+	43	5.3	31.0
Exp.	29 ± 6	≤ 4	17.2 ± 0.3

Figure captions

Fig. 1 : Beta-delayed proton spectrum from ^{118}Cs measured with a single surface-barrier detector. The experimental resolution was 20 keV FWMH and the spectrum was obtained in a 12-hour experiment. The stability of the counting equipment was controlled with a precision pulse generator.

Fig. 2 : Beta-delayed alpha spectrum from ^{118}Cs measured simultaneously with the delayed-proton spectrum shown in Fig. 1. The full drawn curve shows the result of a statistical model calculation of the spectral envelope. The decline of the calculated shape towards lower energies is slower than the experimental one, which may be ascribed to our assumptions about the alpha width and the distribution of the alpha strength and the energy dependence of Γ_γ.

Fig. 3 : Spectra of gamma-rays in coincidence with delayed protons from ^{116}Cs and ^{118}Cs. The gamma-rays were detected in a 40 cm^3 Ge(Li) detector. Besides peaks from coincidences with annihilation radiation originating from positons feeding the proton emitting states, peaks from coincident gamma transitions in ^{115}I and ^{117}I are seen. The energies and intensities of the strongest of these are given in Table 1.

Fig. 4 : Spectrum of gamma-rays in coincidence with delayed alpha particles from ^{118}Cs. Coincidences with annihilation radiation and with 709 keV gamma-rays, from the $2^+ \rightarrow 0^+$ transition in ^{114}Te, are observed. A NaI detector shielded with lead, cadmium and copper (4 mm + 0.5 mm + 0.5 mm) was used for the detection of gamma-rays. The full drawn curve shows the expected detector response function for the two strongest lines.

Fig. 5 : Radial distribution of proton tracks in an ILFORD K2 nuclear emulsion registered in a time interval 0-4 sec after a 4 sec collection time and repeated for 1100 cycles. The experimental technique used was

practically identical to the one described in detail earlier [14], the only modification was that the disc collector moved in steps of 30° instead of a continuous rotation. A strong peak of delayed protons from ^{116}Cs is seen, while only a weak indication of particle activity is found at mass position 115. The increase of the track density on the heavy mass side of ^{117}Cs is due to delayed protons and delayed alphas from ^{118}Cs. The decay curve for ^{116}Cs determined from the number of tracks at five consecutive points, each exposed for 4 sec per cycle, is shown in the inset.

Fig. 6 : Decay curve for beta particles from ^{116}Cs with energies greater than 7 MeV counted in a beta telescope (set-up A). The collection time was 1 sec and the decay was followed in a series of 16 successive subgroups for a counting period of 0.5 sec subgroup. The measuring cycle was repeated 420 times. No 3.5 sec component can be observed with this bias setting and the half-life was calculated with the assumption of a constant background.

Fig. 7 : Part of the resultant gamma-ray spectrum in coincidence with betas from the decay of ^{116}Cs. The energies of gamma rays assigned to the 3.5 sec isomer in ^{116}Cs are indicated. The energy uncertainties amounts to ±1 keV in this experiment. The weak line at about 458 keV (indicated with an arrow) has been found [17] to belong to the 0.7 sec isomer.

Fig. 8 : Beta-delayed proton spectrum from ^{116}Cs measured with a detector telescope (set-up B). The curve shows the result of a statistical model calculation (Section 4), where the experimental value for the $Q_{EC} - B_p$ value was used. Besides the good agreement with the main shape the proton branching ratio and the P_p/P_α value are well reproduced (Table 2) by the calculation.

Fig. 9 : Proton separation energies for caesium isotopes as calculated from different mass formulae [21]:

I. Myers (open circles),

II. Groote, Hilf, Takahashi (filled triangles),

III. Janecke, Garvey, Kelson (open squares),

IV. Comay, Kelson (black dots),

V. Janecke, Eynon (open triangles).

The shadowed area represents the calculated "observation window", which covers the range of possible partial proton half-lives, limited on one side by the minimum observable half-life and on the other by the minimum observable proton branching ratio, here taken to be 5 msec and 10%, respectively.

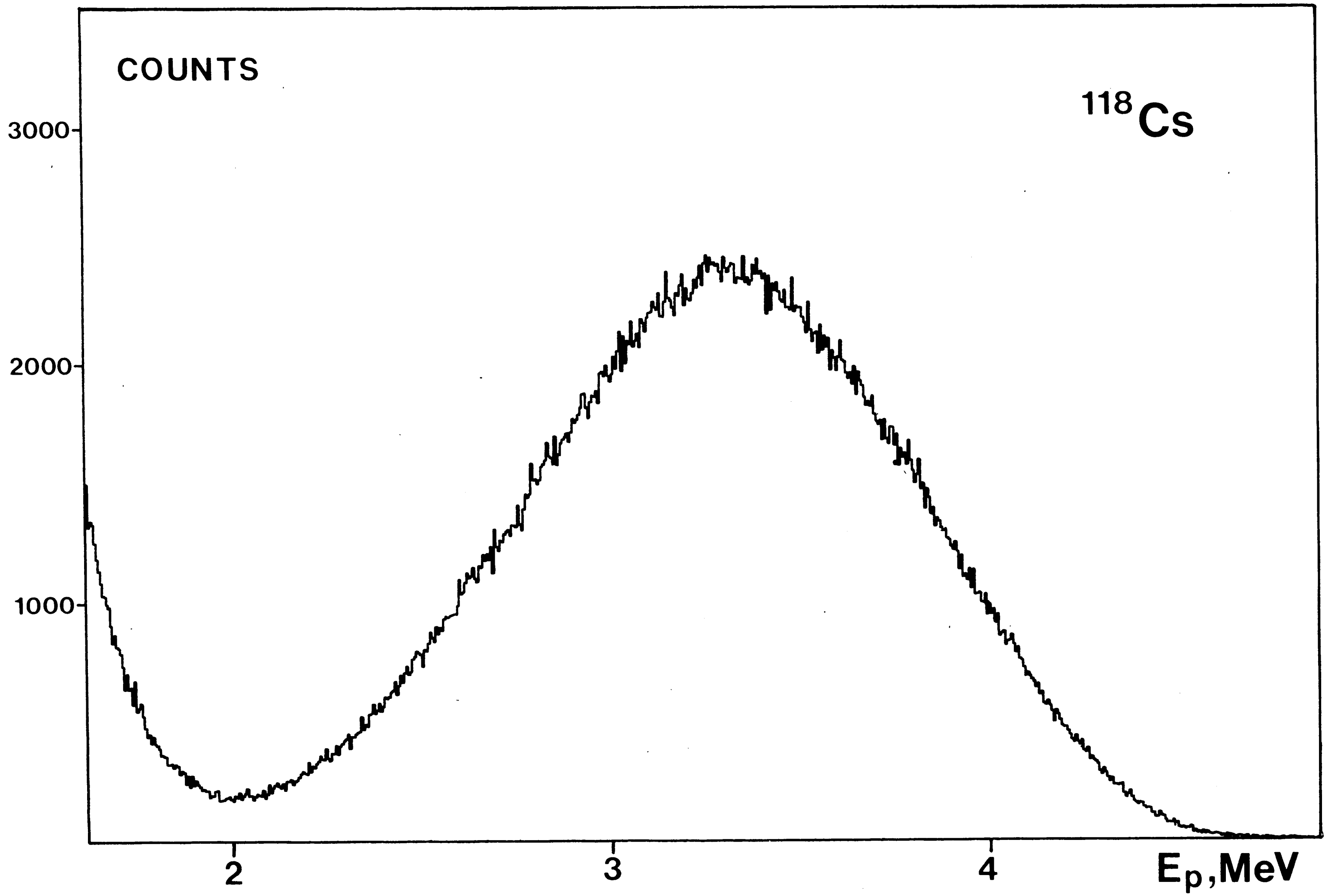


Fig. 1

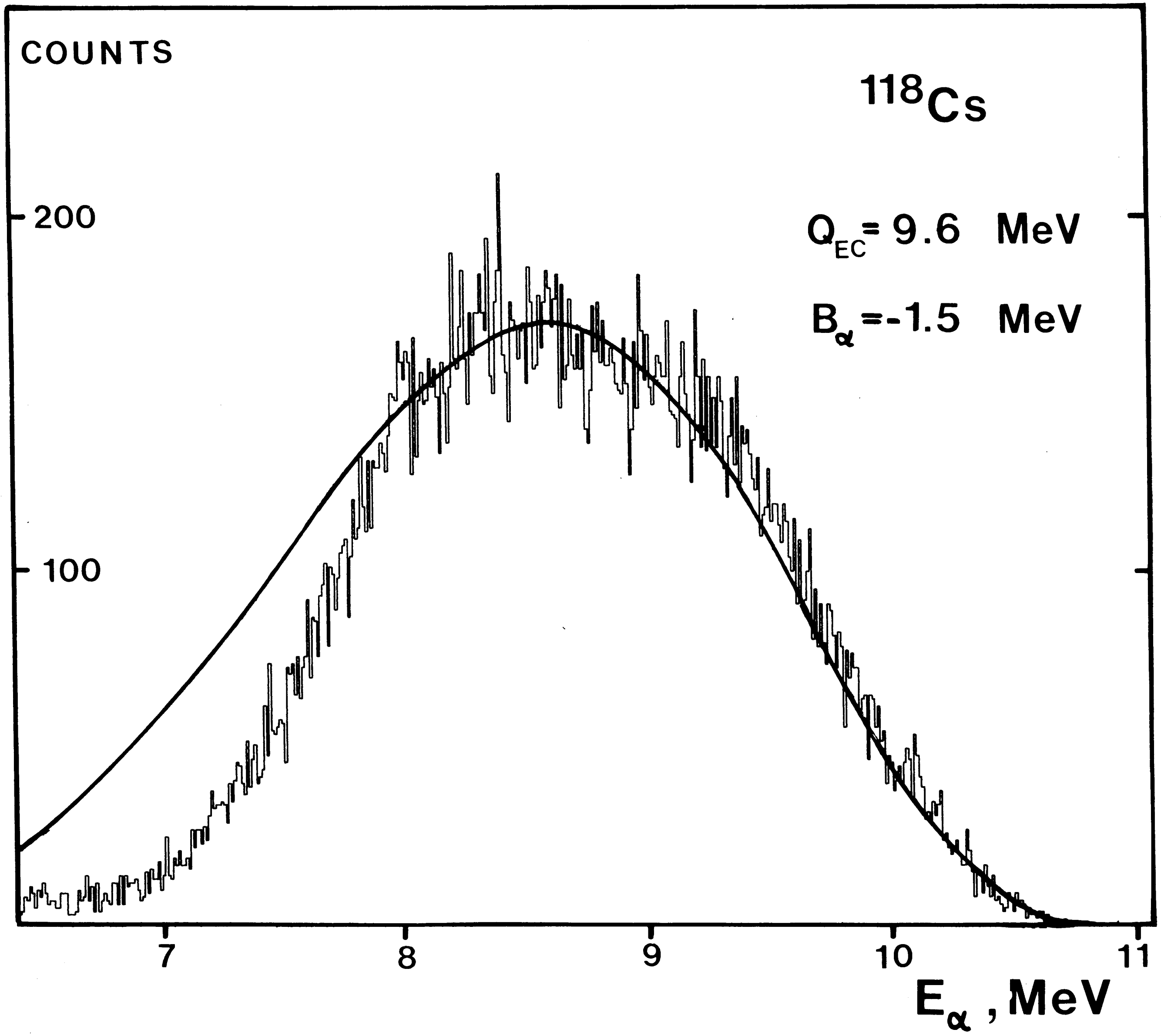


Fig. 2

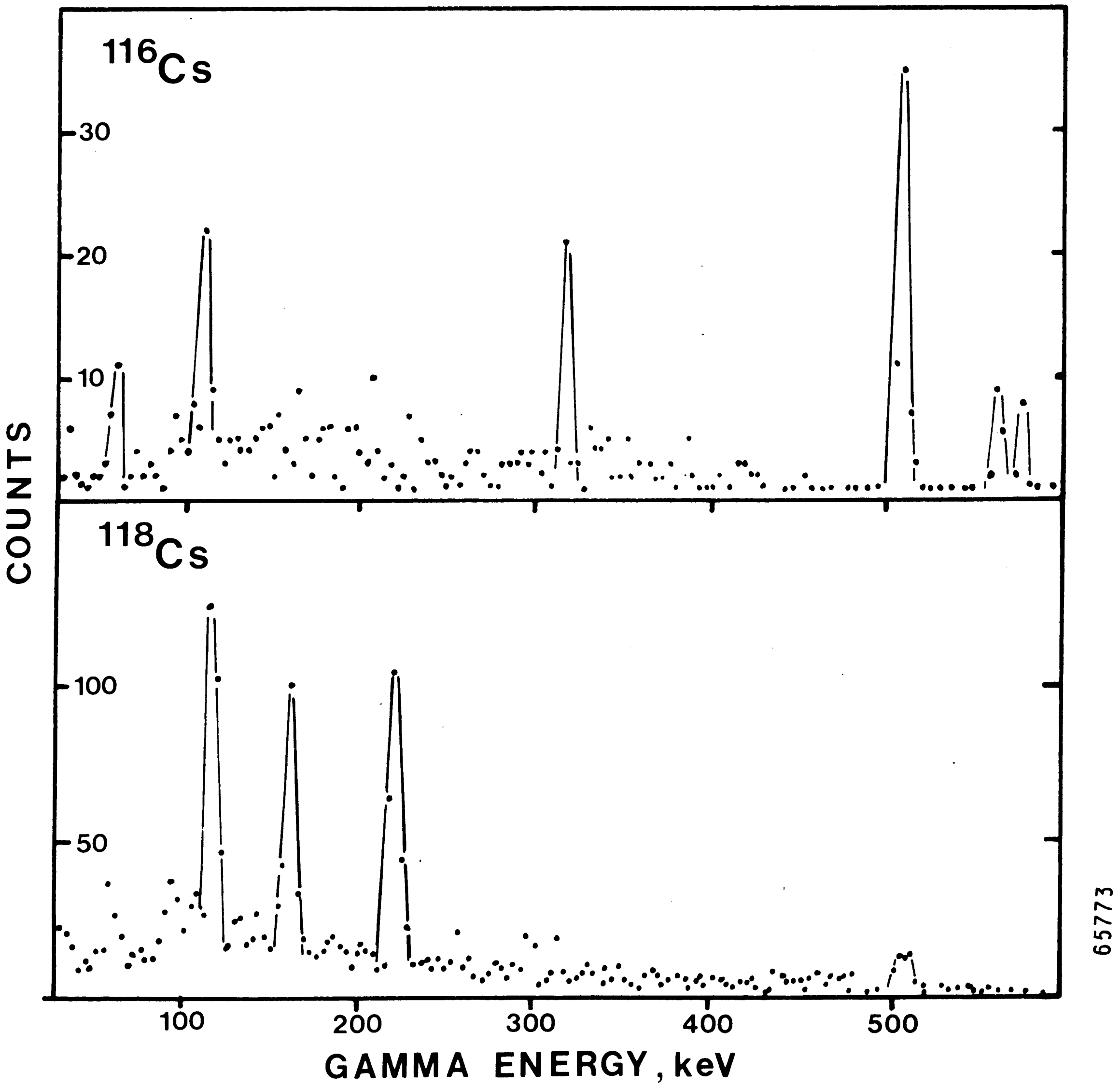

116Cs
118Cs
COUNTS
30
20
10
100
50
100
200
300
400
500
GAMMA ENERGY, keV
65773

Fig. 3

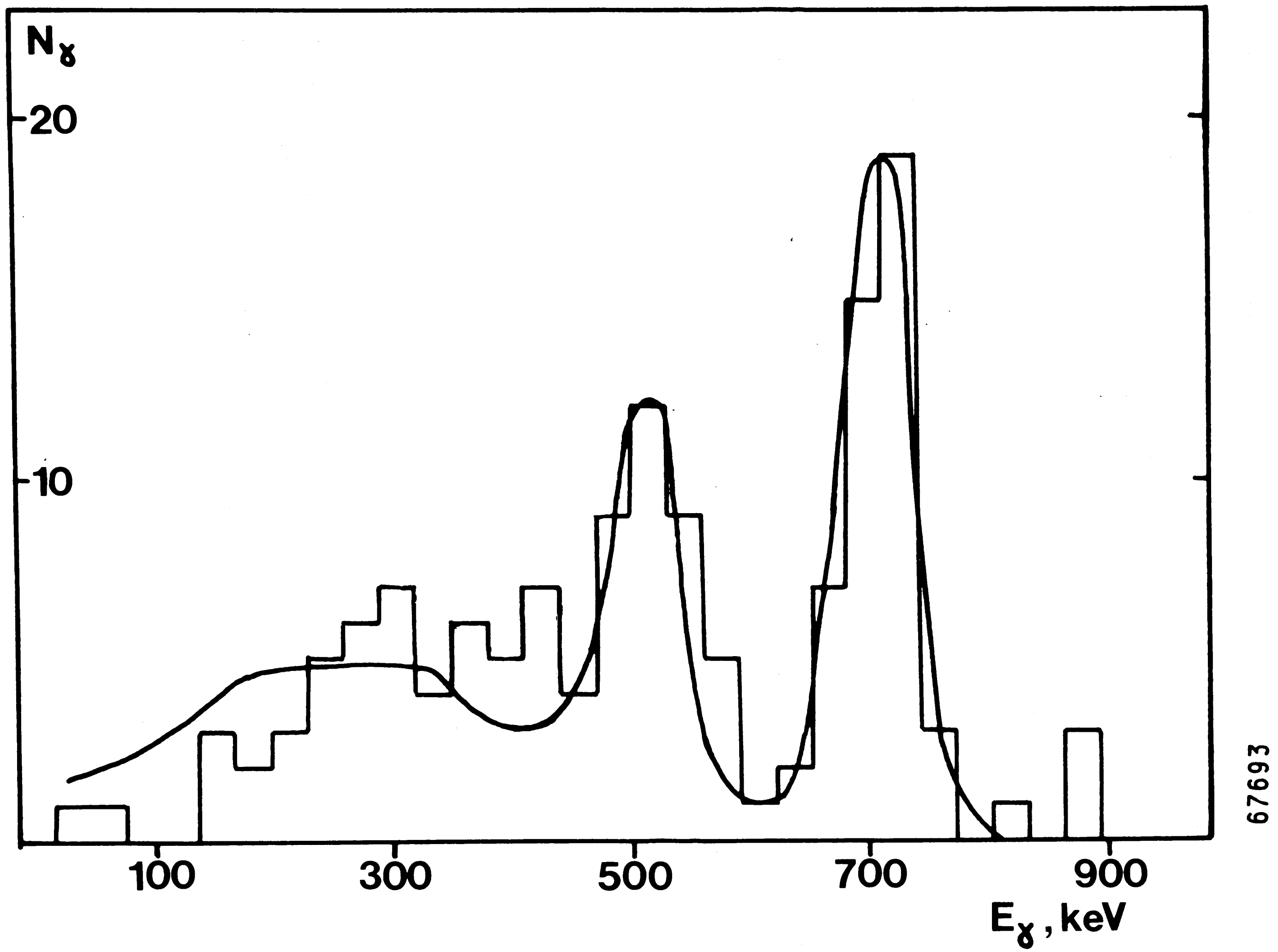
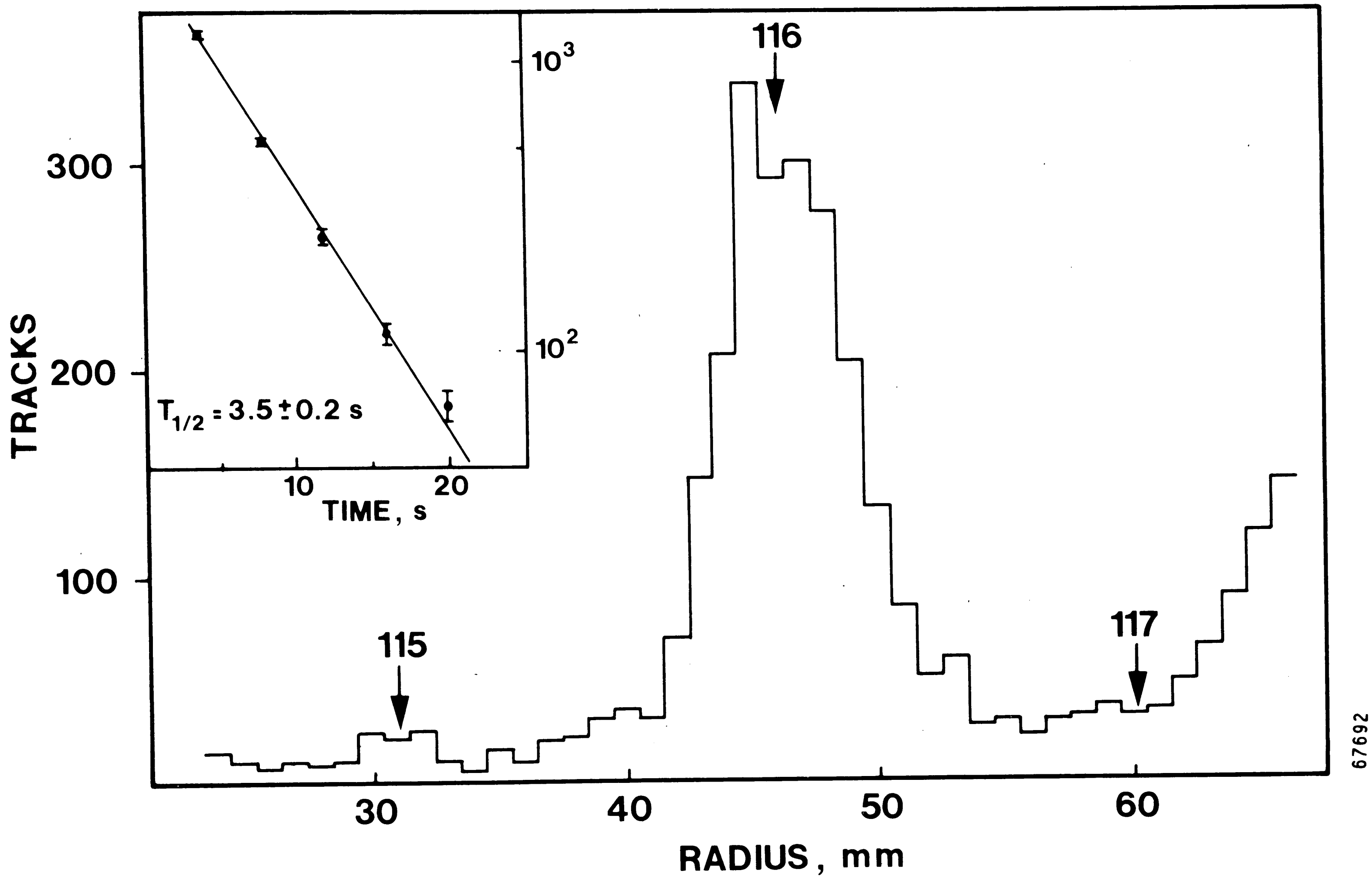


Fig. 4



TRACKS
300
200
100
30
40
50
60
RADIUS, mm
115
116
117
10
20
TIME, s
10^3
10^2
$T_{1/2} = 3.5 \pm 0.2$ s
67692

Fig. 5

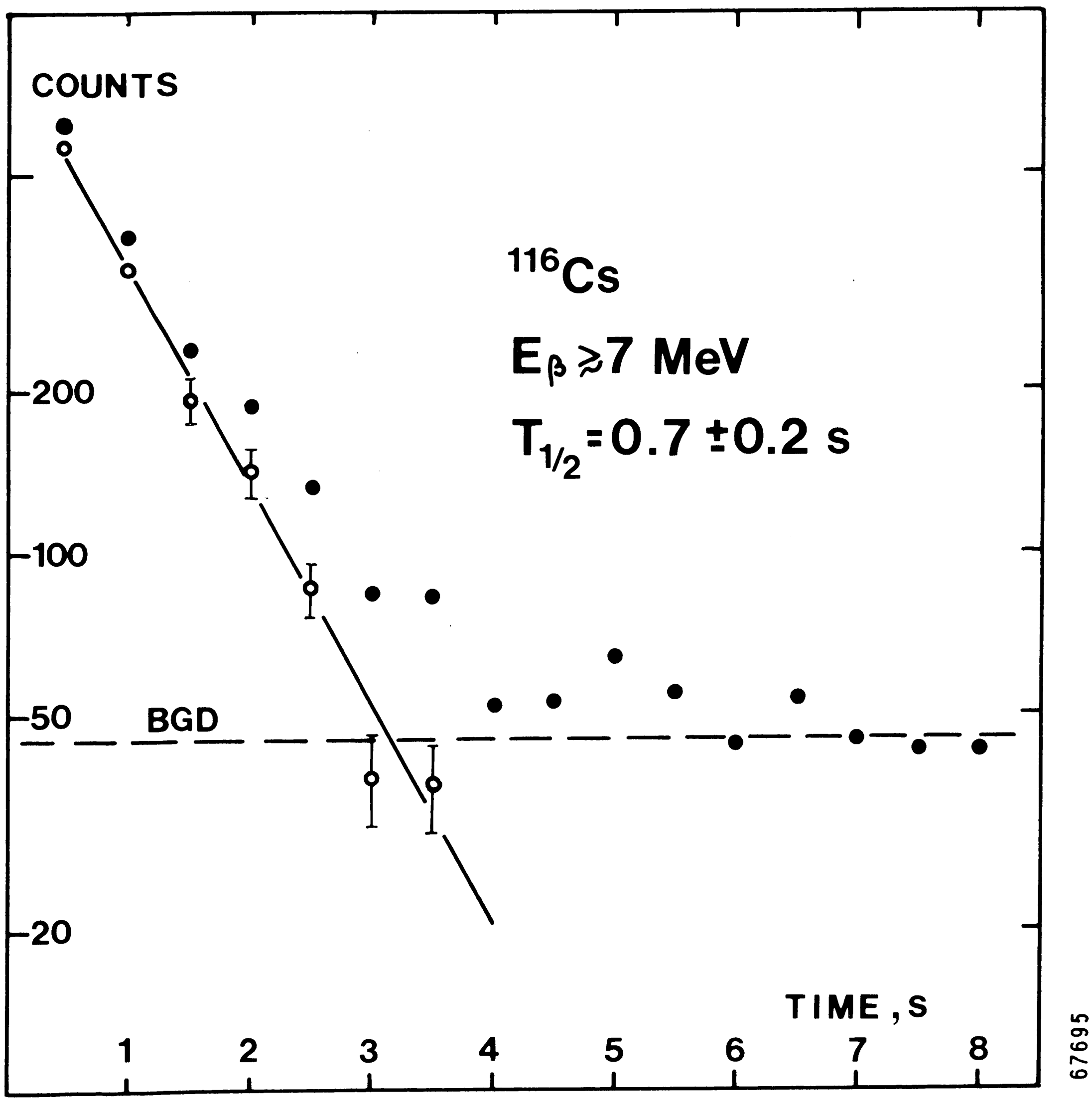
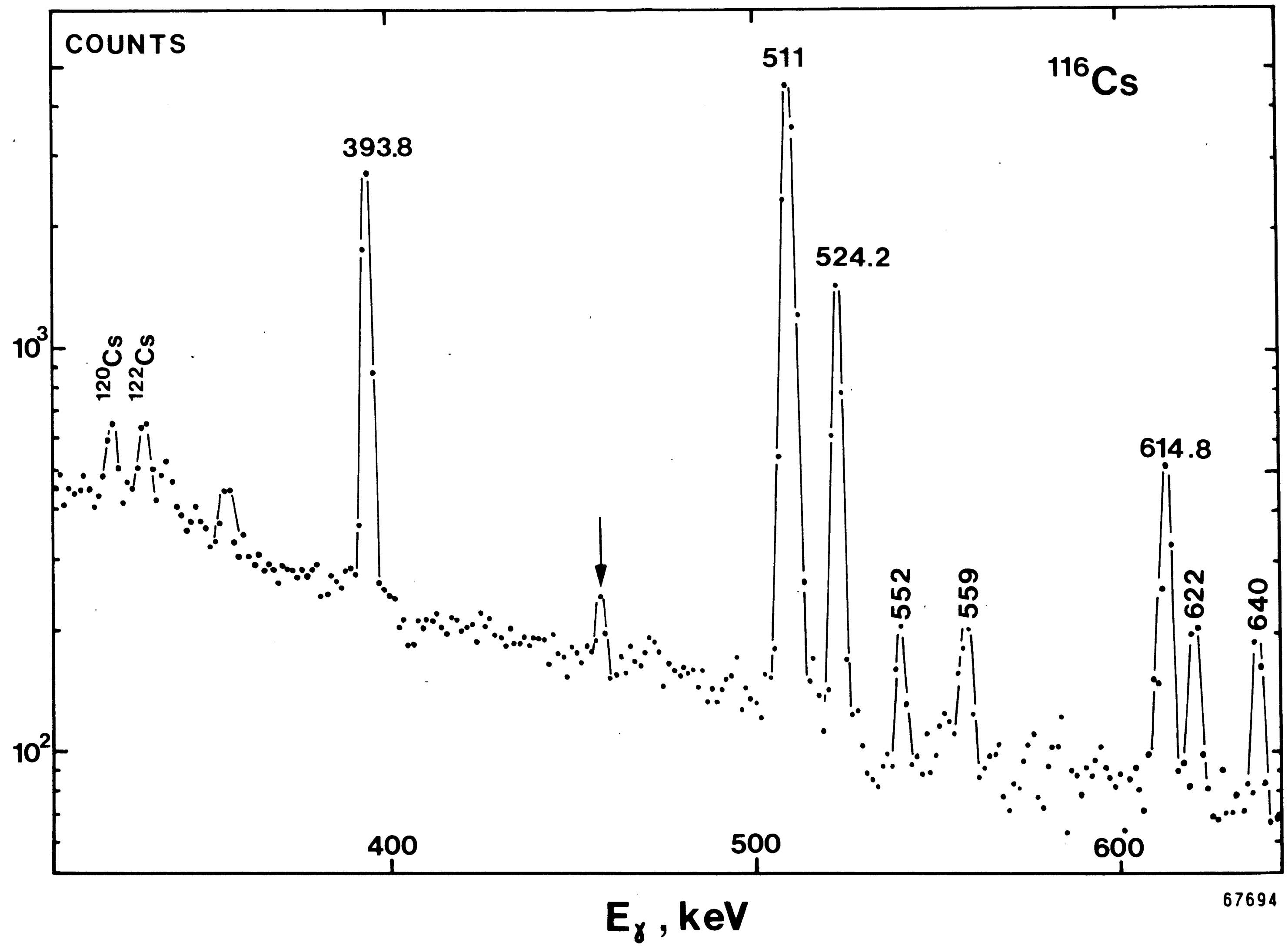

COUNTS
^{116}Cs
$E_\beta \gtrsim 7$ MeV
$T_{1/2} = 0.7 \pm 0.2$ s
200
100
50
BGD
20
TIME, s
1
2
3
4
5
6
7
8
67695

Fig. 6



COUNTS
116Cs
393.8
511
524.2
552
559
614.8
622
640
120Cs
122Cs
10³
10²
400
500
600
67694
Eγ , keV

Fig. 7

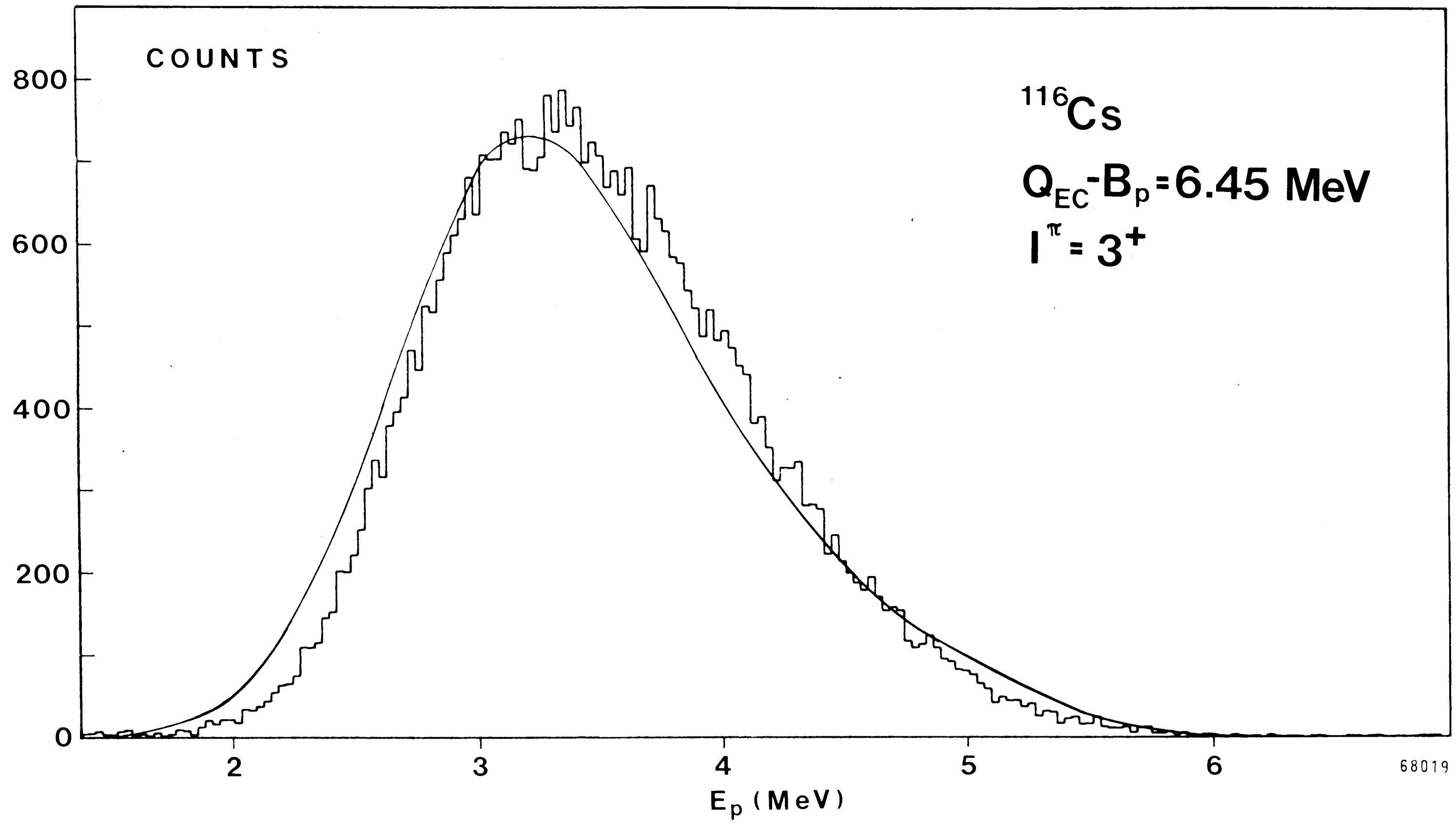
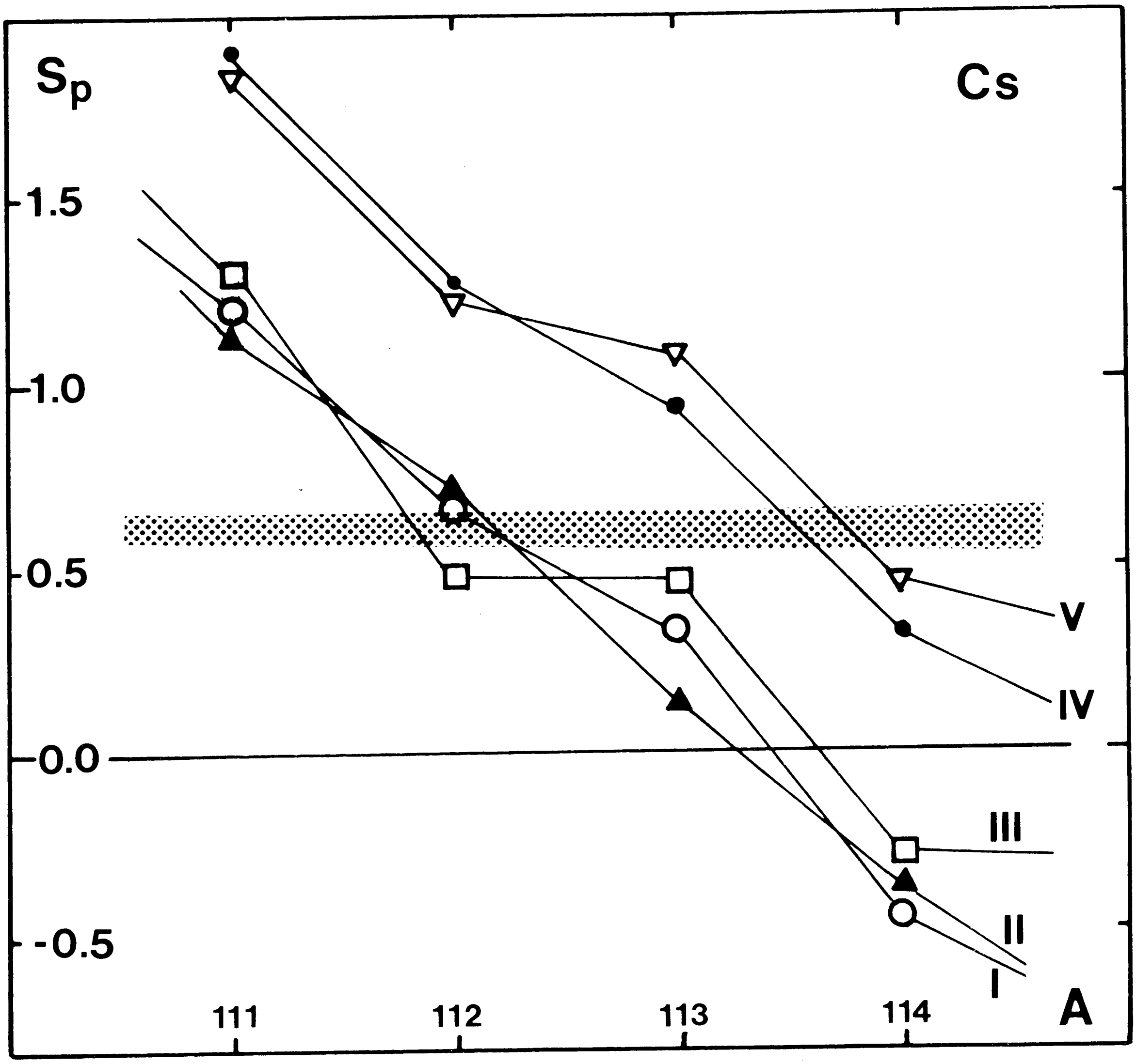

COUNTS
800
600
400
200
0
116Cs
QEC-Bp=6.45 MeV
Iπ= 3+
2
3
4
5
6
Ep (MeV)
68019

Fig. 8



67696

Fig. 9