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NEW NEUTRON-RICH ISOTOPES OF ASTATINE AND BISMUTH

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ABSTRACT

Neutron-rich isotopes of astatine have been produced through spallation reactions with 600 MeV protons on a ^{232}Th target and identified by spectroscopic techniques combined with on-line mass separation at the ISOLDE facility. The half-lives of ^{218}At and ^{219}At have been remeasured to be 1.5(3) s and 57(4) s, respectively. Four new isotopes of astatine, $^{220-223}$At, have been observed for the first time, and their half-lives were found to be 3.73(13) min, 2.3(2) min, 54(10) s, and 50(7) s, respectively. Another nuclide, ^{216}Bi, has been observed for the first time as the daughter product of the ^{220}At alpha decay, and its half-life has been measured to be 6.6(21) min.

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1. INTRODUCTION

Recently, extensive studies [1–3] on heavy radium isotopes (A = 224–228, 230) have shown evidence of the occurrence of stable octupole deformation around A = 225 (for a review see, for example, Ref. [4]). The present study was initiated to investigate the limits of the 'island of octupole deformation' in this mass region. It is expected [5, 6] that the heavy radon isotopes are situated on the border of this region. The identification of the isotopes $^{220-223}$At and the determination of their primary decay properties is the first step in the investigation of heavy radon isotopes produced in beta decays of astatine nuclei.

2. EXPERIMENTAL METHODS AND RESULTS

The astatine activities were produced by spallation of ^{232}Th, induced by 600 MeV protons from the CERN Synchro-cyclotron. The thorium/tantalum metal-foil target [7] was prepared by rolling 15 μm foils of thorium metal between two 20 μm foils of tantalum metal.

In this way, thin layers of molten thorium metal are sandwiched between the tantalum foils so that a target thickness of 10 g/cm^2 is obtained. A negative surface ionizer consisting of a LaB_6 pellet placed at the opening of the transfer line served as the ion source [8]. The nuclides were obtained as mass-separated ion beams from the ISOLDE II on-line separator [9]. A selected beam, collimated through a 3 mm slit to reduce contamination from adjacent masses, was deflected onto an aluminized Mylar tape. With a tape system working in a Start–Stop mode, the activity was transported from the collection point to the detectors. The beta activity was measured using a 4π plastic scintillator, and the half-lives of the new isotopes were obtained by means of a multiscaling analysis.

In addition, for mass 220, a second tape station was used, equipped with a plastic scintillator, a Ge detector, and an alpha detector. The half-life values were determined by means of a multispectrum analysis.

The results obtained for each mass number are given in the following subsections.

2.1 Mass number A = 218

The half-life was determined to be 1.5(3) s, in agreement with the previously adopted value of 1.6(4) s for ^{218}At (Ref. [10]).

2.2 Mass number A = 219

For the half-life of ^{219}At, the value of 57(4) s obtained in the present study is in agreement with the earlier observation of 54(6) s (Ref. [11]). A half-life of 7.5(4) min was observed for the daughter product ^{215}Bi, also in agreement with the previous value of 7.4(6) min [12].

2.3 Mass number A = 220

The X- and γ-rays following the decay of ^{220}At were detected with a 75 cm^3 high-purity Ge detector (energy resolution 1.8 keV at 1332 keV). To suppress γ-rays from background activities, the spectra were gated with signals from a thin plastic scintillator β-detector. Figure 1 shows the low-energy part of a β-gated γ-ray spectrum from the decay of ^{220}At. Alpha spectra were recorded with a surface-barrier Si detector of 100 μm thickness and an energy resolution of 19 keV for the 5486 keV ^{241}Am-line. Figure 2 shows an alpha spectrum obtained from the decay of mass 220. The precise energies of alpha-lines from the daughter products ^{220}Rn and ^{216}Po [13], together with those from $^{208-210}$Po (background impurities) were used for internal energy calibration.

The observation of Rn K X-rays confirms the element assignment, and known γ-transitions [14] with energies of 241.0, 292.7, 404.2, 422.0, and 645.5 keV de-exciting states in ^{220}Rn unambiguously

assign the mother activity to ^{220}At (Fig. 1). The measured half-life for the beta activity is in agreement with the half-life values obtained from the γ-lines (see Fig. 3) and from the alpha-line. Taking the weighted average, a half-life of 3.73(13) min is obtained for the decay of ^{220}At. The observed decay properties of ^{220}At are summarized in Table 1.

The measured energy of 5943(6) keV for the new alpha-line gives an alpha decay Q-value of 6053(6) keV for ^{220}At, assuming that the observed transition populates the ground state of ^{216}Bi. This agrees well with the value of 5910(140) keV predicted by Wapstra et al. [15].

An alpha branching ratio of 8(2)% has been determined from a comparison of the intensities of parent and daughter alpha-lines. The 8% alpha branch of ^{220}At feeds the daughter nucleus ^{216}Bi, the half-life of which has been determined to be 6.6(21) min.

2.4 Mass number A = 221

Multiscaling of the 4π plastic scintillator signal gave a half-life of 2.3(2) min. This can be assigned to ^{221}At. Only one daughter activity with a known half-life of 25(2) min (Ref. [6]), ^{221}Rn, is observed, showing that ^{221}At disintegrates predominantly through β-decay (see Fig. 4).

2.5 Mass number A = 222

At mass A = 222, an activity with a half-life of 54(10) s has been observed and assigned to ^{222}At. The activity after background subtraction is shown in Fig. 5 (empty circles).

2.6 Mass number A = 223

The most neutron-rich astatine isotope seen in the present experiment was ^{223}At. Its half-life was measured to be 50(7) s (see Fig. 6). There was concern that this result could be due to a cross-contamination from mass A = 222, which has a similar half-life. Thus great care was taken to show that an activity maximum existed at mass number 223. Since a clear maximum was found in the mass spectrum and significant cross-contamination was not observed at the other masses, it is concluded that the observed half-life belongs to ^{223}At.

Contamination from molecular ions of the type $^{223}(^{137}\text{Ba}\ ^{86}\text{Br})$, often encountered in target/ion-source combinations with plasma discharge sources, can also be excluded. In fact, they are unlikely to be produced as negative ions on the LaB_6 surface, and were also not observed in the γ-spectra of mass 220 decay.

2.7 Production rates of astatine isotopes

The yields of astatine isotopes produced in this work are listed in Table 2. The values have been normalized in the customary way to the numbers of atoms per second for 1 μA of proton beam current, although up to 4 μA proton beam is available.

3. CONCLUSION

The half-lives of $^{218,\ 219}$At have been remeasured and confirmed. The new neutron-rich isotopes $^{220-223}$At and ^{216}Bi have been identified. The measured half-lives are summarized in Table 3. Theoretical predictions of half-lives, based on the gross theory of beta decay by Takahashi et al. [17] and on the microscopic model by Klapdor et al. [18], are given in the third and fourth columns, respectively. Both models predict, within a factor of 3, the measured values, except for ^{216}Bi where the Klapdor et al. [18] prediction is too low by a factor of 18. Contrary to other target/ion-source combinations, a negative ionizer provides chemically pure beams of halogen elements. In this work, pure mass-separated sources of astatine isotopes were studied. It is found that the LaB_6 surface is a

much less efficient ionizer for astatine than for the other halogens, in agreement with its lower electron affinity [7, 8]. Therefore, the production yields for astatine isotopes are not as high as can be obtained in combination with the non-selective plasma-discharge ion source [7]. Nevertheless, the high purity of the produced isotopes allowed both identification and half-life determinations. If materials with lower work function than LaB_6 could be used in the ion source, increased astatine yields may be anticipated.

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Table 1

Decay properties of ^{220}At

Energy (keV)	Relative I_γ	Half-life (s)	
		Separate measurements	Average
Rn K_α X-rays	8.3(8)	200(33)	
γ-rays:			
241.0(5)	≡ 100	220(9)	
292.7(5)	39(2)	255(20)	
404.2(5)	3(1)	–	224(8)
422.0(5)	23(2)	229(31)	
645.5(5)	6(1)	–	
Betas	–	222(30)	
Alpha:			
5943(6)	–	223(53)	

Table 2

Production rates of astatine isotopes normalized to a beam current of 1 μA

Nuclide	Atoms per second
^{218}At	870(120)
^{219}At	840(20)
^{220}At	350(5)
^{221}At	204(8)
^{222}At	110(9)
^{223}At	32(3)

Table 3

A summary of the observed half-lives
and their comparison with the theoretical predictions

Nuclide	$T_{1/2}$ measured	$T_{1/2}$ predicted	
		Ref. [17]	Ref. [18]
^{218}At	1.5(3) s	–	–
^{219}At	57(4) s	–	–
^{220}At	3.73(13) min	4.0 min	1.5 min
^{221}At	2.3(2) min	8.0 min	5.0 min
^{222}At	54(10) s	1.5 min	21.5 s
^{223}At	50(7) s	2.0 min	48.9 s
^{216}Bi	6.6(21) min	2.0 min	21.7 s

Figure captions

Fig. 1: Low-energy part of the beta-gated γ-ray spectrum from the decay of ^{220}At.

Fig. 2: Alpha spectrum obtained for mass A = 220.

Fig. 3: Decay curve of the 241.0 keV γ-line of ^{220}At. Cycles of 250 s collection time followed by 6 $\times$ 30 s plus 10 $\times$ 60 s measuring time were used.

Fig. 4: Beta count rate, as a function of time after collection, for the ^{221}At activity and its ^{221}Rn daughter. The ^{221}At activity (open circles) is found by subtracting the background and the 25 min ^{221}Rn activity from the original data points (filled circles).

Fig. 5: Beta count rate, as a function of time after collection, for the ^{222}At activity. The data points indicated by empty circles show the difference between the original data points and the dashed line for the background.

Fig. 6: Beta count rate, as a function of time after collection, for the ^{223}At activity. The data points indicated by empty circles show the difference between the original data points and the dashed line for the background.

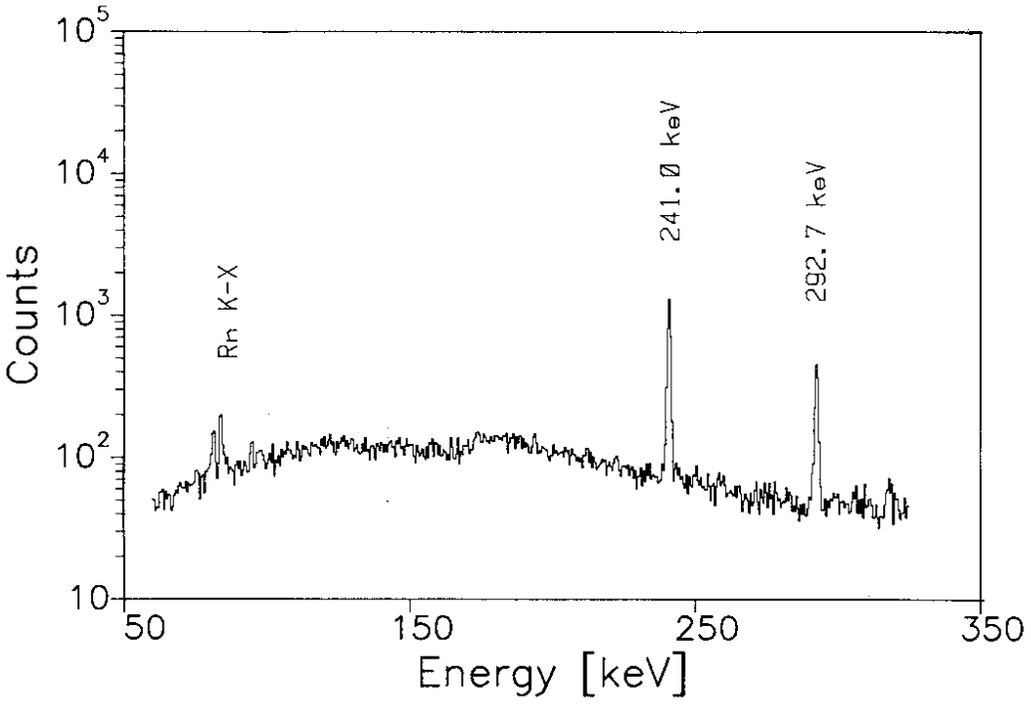
Counts
Energy [keV]
Rn K-X
241.Ø keV
292.7 keV

Fig. 1

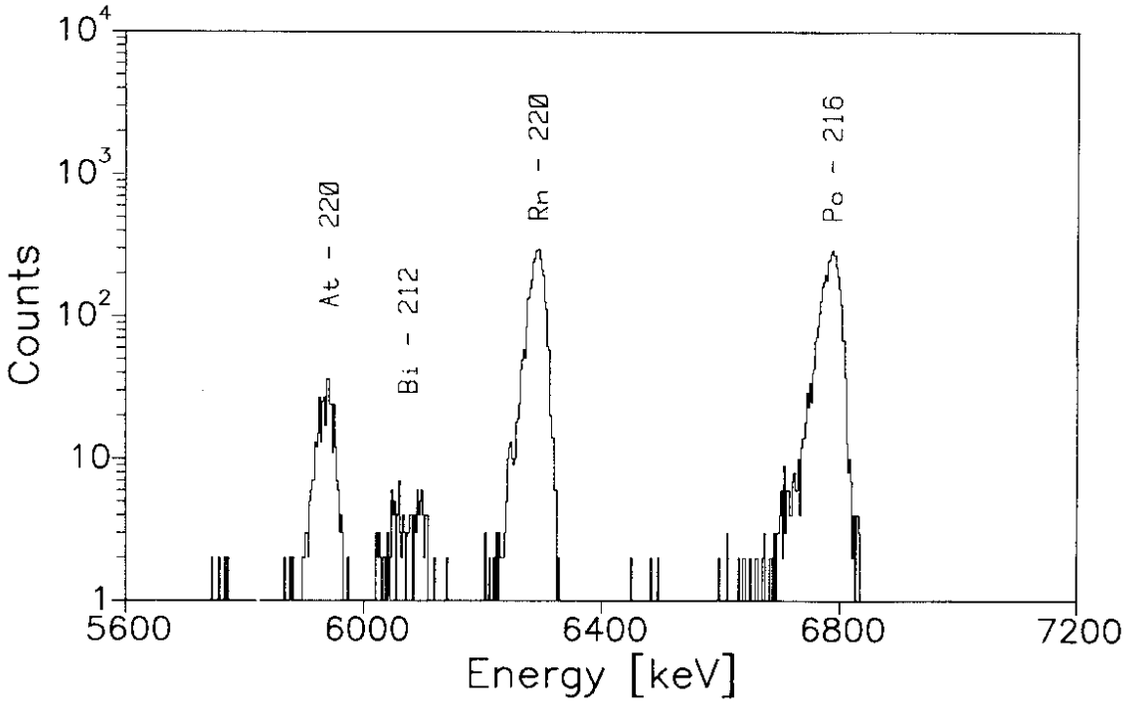
Counts
Energy [keV]
At - 220
Bi - 212
Rn - 220
Po - 216

Fig. 2

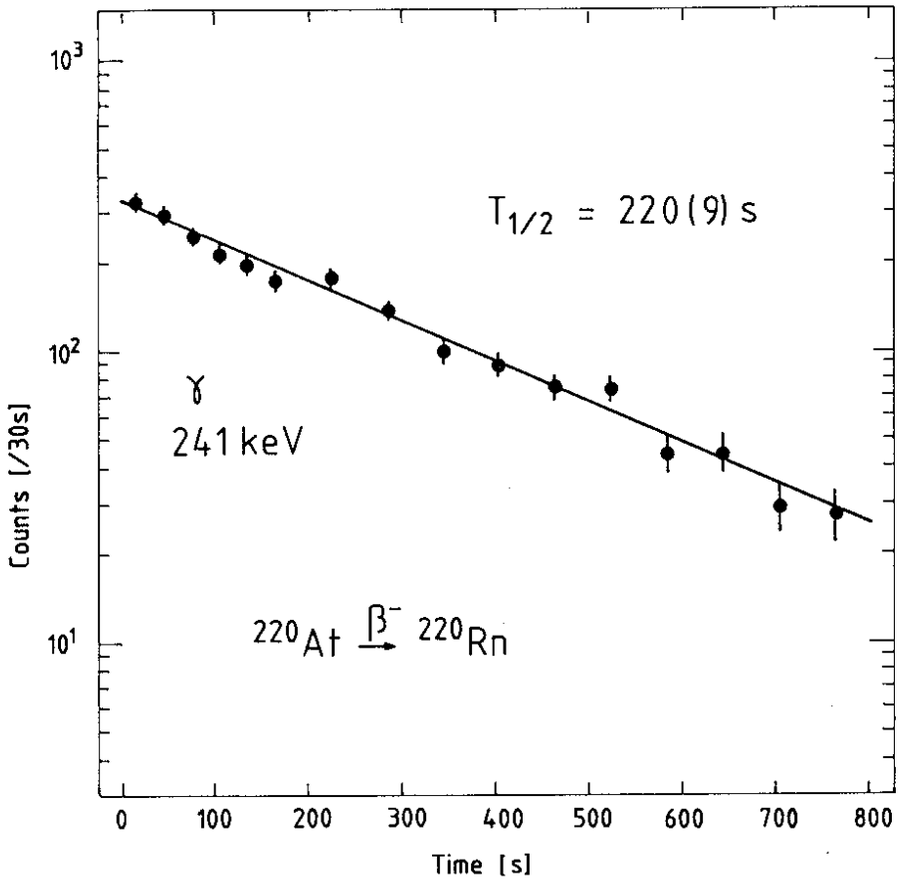
10^3
10^2
10^1
Counts [/30s]
$T_{1/2}$ = 220(9) s
γ
241 keV
^{220}At $\xrightarrow{\beta^-}$ ^{220}Rn
0
100
200
300
400
500
600
700
800
Time [s]

Fig. 3

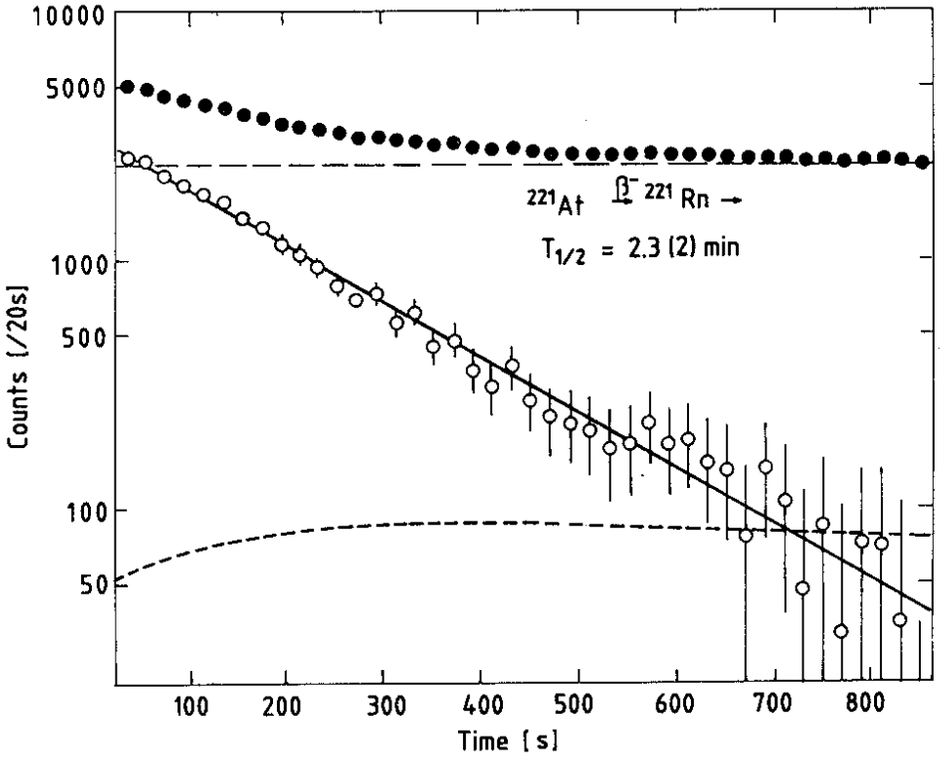
10000
5000
1000
500
100
50
Counts [/20s]
^{221}At $\xrightarrow{\beta^-}$ ^{221}Rn →
$T_{1/2}$ = 2.3 (2) min
100
200
300
400
500
600
700
800
Time [s]

Fig. 4

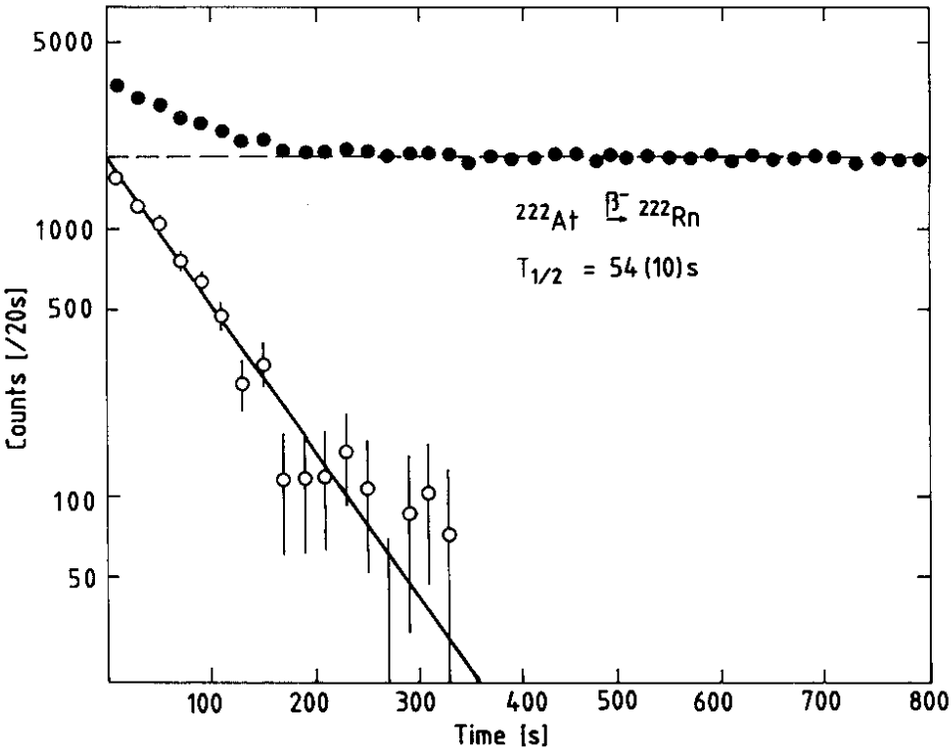
5000
1000
500
100
50
Counts [/20s]
^{222}At β^- ^{222}Rn
$T_{1/2}$ = 54 (10) s
100
200
300
400
500
600
700
800
Time [s]

Fig. 5

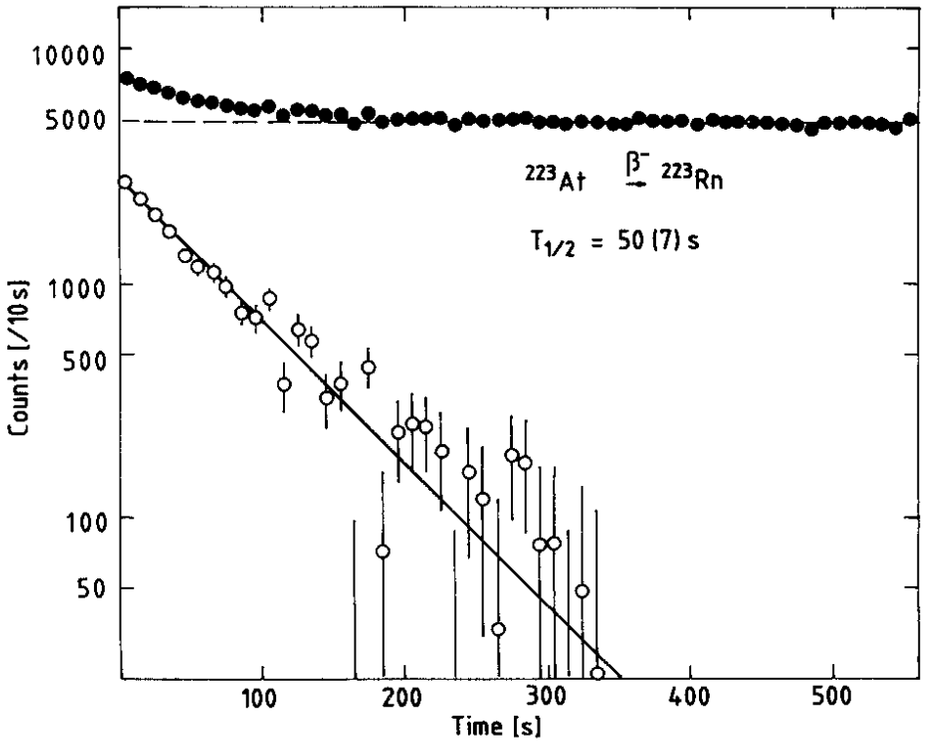
10000
5000
1000
500
100
50
Counts [/10s]
^{223}At β^- ^{223}Rn
$T_{1/2}$ = 50 (7) s
100
200
300
400
500
Time [s]

Fig. 6