Observation of the new Isomer ^{32m}Al

(August 1, 1995)

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Abstract

A new isomer in the neutron-rich isotope ^{32}Al has been identified among the fragmentation products of a 61 A·MeV $^{40}Ar^{16+}$ beam using the LISE spectrometer at GANIL. The population of the isomeric state was inferred from the detection of γ-radiation following its decay in coincidence with its respective heavy-ion implantation signal. The half-life of ^{32m}Al was determined to be 240$\pm$30 ns. Shell model calculations using the interaction of Warburton *et al.* do in fact provide two long-lifetime states in the relevant energy range, although the calculated decay scheme suggests that the structure of the detected isomer is not yet understood.

29.30.Kv,21.10.Pc,21.10.Tg,21.60.Cs

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The existence of isomers in nuclei gives important information for studies in nuclear structure. For instance, if the long lifetime is due to the common fast electromagnetic processes M1 and E2 being forbidden, there exists a rare opportunity to study other processes. The region around N=20 is of particular interest since, as the shell closure is crossed, the approximate degeneracy of the various configurations leads to the possibility of low energy isomers. Thus, as part of an extended program at GANIL to search for nuclear isomers, an experiment was set up to detect $\sim$ μs lifetimes in neutron-rich nuclei in the region. In a previous experiment [1] the existence of the remnant of an ^{32}Al isomer population was deduced, however this was too small to allow the extraction of any decay properties.

A 61 A·MeV $^{40}Ar^{16+}$ beam of average intensity 3 pnA from the GANIL cyclotron complex was directed on to a ^{9}Be target of thickness 120 mg/cm^2 placed at the entrance to the LISE spectrometer [2]. Reaction products were transported over a 18m long flight path in about 0.2μs and were isotopically separated by means of the LISE spectrometer magnetic field, the magnetic rigidity (Bρ) of which was set to 2.4681 Tm with the momentum acceptance (Δp/p) set to 0.58%. The nuclei were then implanted into a detection set-up at the first achromatic focal point of LISE. This consisted of three silicon detectors of thicknesses 300μm, 1000μm, and 5000μm, the first providing information on the energy loss (ΔE) for atomic number identification (Z). The time of flight which served for A/q (mass over atomic charge) determination, was measured using a start signal from the first Si detector with a stop signal derived from the radiofrequency of the second cyclotron. On the basis of the total kinetic energy measurement from the sum of energy losses in the Si detectors, it was deduced that all ions transmitted through the LISE spectrometer with Z<14 were fully stripped (i.e q=Z).

The γ-radiation from the implanted ions were measured by a large volume (70%) germanium detector placed in close proximity ($\sim$3cm) to the silicon telescope. For each implanted heavy-ion, the time difference between implantation signal and detected γ-ray was measured. This served towards the construction of the time distribution of decay for the observed isomers.

The observation of the γ-radiation in a slow ($\sim$16μs) correlation with the identified implanted ions, allowed the enhancement of photon detection following the μs-isomer decay against the laboratory background, the prompt γ-rays emitted in the secondary reactions within the silicon detectors, and the γ-rays following the β-decay of transmitted nuclei. Details on the present experimental method are presented fully in [3]. Identification of ions was based on the observation of the charge states of the primary beam and the characteristic γ-decays of the known short lived isomers ^{16}N ($T_{1/2}$=5.25μs, Eγ=120 keV) and ^{26}Na ($T_{1/2}$=9.2μs, Eγ=82.5 keV) transmitted through the spectrometer simultaneously with the ^{32}Al ions.

Evidence for the ^{32m}Al isomer is given in Fig.1. The mass distribution of observed Al ions is shown in Fig.1a, with the same spectrum however measured within a slow $\sim$1.7μs coincidence with γ-radiation (prompt and background γ's included) displayed in Fig.1b. For Fig.1c, the background and prompt contributions were removed using a ratio obtained by dividing the number of counts from Fig.1b by the number of counts from Fig.1a for each Al isotope, excluding ^{32}Al. After this background subtraction, the 160 counts attributed to the peak of the ^{32m}Al isomer are clearly visible.

The corresponding 'heavy-ion correlated' γ-spectrum for ^{32m}Al is given in Fig.2, showing clearly two γ-lines at 231$\pm$2 keV and 734$\pm$2 keV. The time decay spectrum for ^{32m}Al is given in Fig.3. A χ^2 fit to the decay curve gave a half-life of 240$\pm$30 ns. From the number of counts 30$\pm$5 and 20$\pm$4 in the 231 and 734 keV γ-lines, and absolute γ-detection efficiencies of 0.87% and 0.48%, it was concluded that most probably both γ-lines belong to the same cascade in the decay of ^{32m}Al. This was comfirmed by the comparison between the total number of heavy-ion (HI)-γ coincident events (Compton gammas included), to those deduced from the two γ-lines and photopeak efficiencies at 231 and 734 keV.

A 735 keV photon was also observed by Klotz *et al.* [4] in cascade with one of 2467 keV following the β-decay of ^{32}Mg, where only rapid decays could be detected. Thus the most likely interpretation of our results is that the isomer makes a 231 keV transition to an intermediate state which then rapidly decays, possibly [4] to the ground state.

On comparing the 6700$\pm$900 ^{32m}Al isomeric yield at the target resulting from γ-

measurements and corrected for in-flight decay losses, with the number 8000±90 of implanted ^{32}Al ions detected (Fig.1), the isomeric to total ratio F was estimated to be 84±11%. This agrees with the value of F estimated in the previous experiment [1], when corrected for decay losses using our measured lifetime.

It must now be asked whether current nuclear structure models allow a reasonable description of the measured photon energies and isomer lifetime. Extensive shell model studies in this region have been carried out in an sdpf valence space using the interaction of Warburton, Becker, Millener, and Brown [5] which has been phenomenologically fitted (from an initial G-matrix form) for calculations in separate n-$\hbar\omega$ subspaces. We choose to follow this approach for a first treatment by virtue of the work already invested in it. A previous investigation for ^{32}Al [5] compared estimates of the lowest 1-$\hbar\omega$ and 2-$\hbar\omega$ energies (the full calculations being deemed impracticable) with those of the energetically favoured 0-$\hbar\omega$ configuration, giving excitation energies of 959 and 2214 keV respectively, and further estimated the 3-$\hbar\omega$ energies in the region to be significantly higher. Thus, within the context of such separate n-$\hbar\omega$ calculations, plausible candidates for a low-energy isomer in the region of 1 MeV could arise for n=0 and n=1 (even and odd parity respectively). Here we present full calculations for both n=0 and the previously intractable n=1, performed with a version of the Glasgow shell model code [6], and use the eigenfunctions to obtain the theoretical decay scheme.

The resulting excitation spectrum is shown in Table 1, together with that obtained with a further restriction, suggested [5] in the context of 2-$\hbar\omega$ calculations, where only neutron excitations to the $f_{7/2}$ and $p_{3/2}$ orbits are allowed. For comparison, a full calculation for the more-studied nucleus ^{36}Cl is shown in Table 2, along with the data [7,8], indicating that a shift of ~300-500 keV in the odd-parity levels might be expected, but that relative energies within each space are probably better determined. It can be noted that the truncation has a significant effect (~200 keV) partially compensating for the probable overbinding manifested in the full calculations.

The electromagnetic decay properties of the lowest even-parity levels are presented in

Table 3 for charges and g-factors taking both free-nucleon and renormalised values, where the latter for M1 and E2 are typical of those in common use, and for M3 are those suggested by calculations for the $1^+ \rightarrow 4^+$ decays in the nearby mirror nuclei ^{24}Na and ^{24}Al. The calculated lifetime of the 4^+ state places it outside the reach of the present experiment; its observation would provide useful information as noted in the introduction. In contrast, the 2^+ decay could readily provide the 734 keV photon believed to follow the initial decay of the detected isomer. If this scenario is correct, then the deduced energy of the isomer would be 965 keV, matching well that estimated for the calculated 1-$\hbar\omega$ states on inclusion of the shift found for ^{36}Cl.

Table 4 shows the electromagnetic decay properties of the 4^- and 5^- states, in the case that each is in turn placed as the lowest odd-parity level giving a photon of the measured energy 231 keV. (The decays to the 2^+ would only be significant if the branching to the 4^+ were reduced dramatically from its current calculated value). The trial effective charges for E1 and E3 were chosen from analysis of decays in ^{36}Cl and the Ar isotopes, while effective g-factors for M2 and M4 were chosen to be those used for M1, in the absence of strong evidence to the contrary. Thus, although the 4^- is calculated to be reasonably long-lived for a placing close to its calculated energy, the lifetime is shorter than that measured by a factor of 10^3, and there is no sequential decay. Placing the 4^- near the expected energy of 965 keV leads to an even faster decay to the 4^+. (In contrast, the electromagnetic decays calculated for the case of ^{36}Cl noted above, and in trials for the Ar isotopes, are largely in qualitative agreement with the data).

Hence, it appears that, while the attempted approach gives a satisfactory description of energies throughout the region, including the favoured interpretation of the ^{32m}Al data described here, and of elecromagnetic properties in other systems, it does not adequately describe the decay of the 240 ns isomer detected in this work. It could be speculated that this is due to the lower energies of the higher-n-$\hbar\omega$ states for ^{32}Al leading to atypically large mixing, that is not accounted for by these unmixed calculations which involved renormalisation effects appropriate for the more usual situation. Alternatively, it may be that the isomer is dominated by 2-$\hbar\omega$ or 3-$\hbar\omega$ states lying at a lower energy than currently expected. Another possibility is that the isomer is at an energy >1 MeV, with the γ-cascade leading to a long-lived excited state.

Calculations to explore these possibilities are under consideration. Experimentally, it would be of great interest to observe the 4^+ isomer predicted here, and to search for the decays predicted, in particular that of the 4^-. Moreover, the observation of analogous isomers in neighbouring nuclei would allow a more systematic consideration of their structure.

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FIGURE CAPTIONS

1 Mass distribution of Z=13 ions observed in the final focus of the LISE spectrometer: (a) implanted Al isotopes, (b) ions observed in a slow ($\sim 1.7\mu s$) coincidence with γ-rays, (c) as (b) however with background and prompt contributions subtracted. (See text for details).

2 Heavy-ion correlated energy spectrum obtained for ^{32m}Al. The γ-lines from the isomeric transition are indicated by their energies in keV.

3 Time spectrum of ^{32m}Al decay.

TABLES

TABLE I. Lowest energy levels in the 0-$\hbar\omega$ and 1-$\hbar\omega$ calculations for ^{32}Al (binding energy in parentheses). The truncated 1-$\hbar\omega$ calculation only allows promotion of a neutron to the $f_{7/2}$ and $p_{3/2}$ orbits.

J^π	E (MeV)		
	Full	Trunc.	Expt.
1^+	(259.193)		(259.170)
4^+	0.425		
2^+	0.687		
3^+	1.679		
4^-	0.622	0.813	
5^-	0.791	0.996	
3^-	1.152	1.323	
6^-	1.531	1.763	

TABLE II. Lowest energy levels in the 0-$\hbar\omega$ and 1-$\hbar\omega$ calculations for ^{36}Cl.

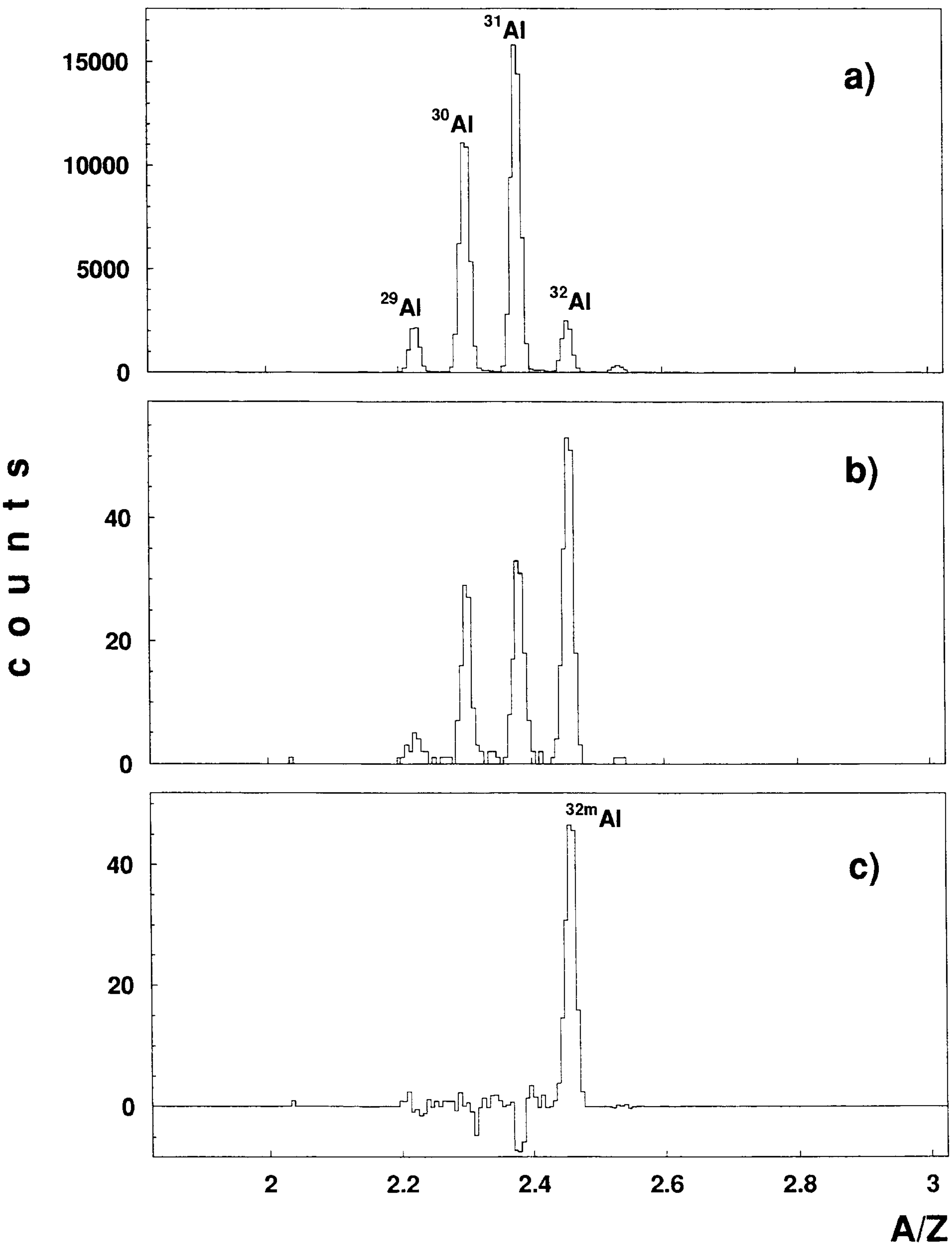
J^π	E (MeV)	
	Calc.	Expt.
2^+	(306.788)	(306.790)
3^+	0.805	0.788
1^+	1.202	1.165
1^+	1.536	1.601
2^+	2.005	1.959
2^-	1.453	1.951
5^-	2.020	2.518
3^-	2.134	2.468
4^-	2.450	2.811
3^-	2.659	2.896

TABLE III. Electromagnetic decays of the lowest 0-$\hbar\omega$ states. The renormalisations used are: (M1) g_s=0.7 $g_{s,\text{free}-N}$; (E2) δe=0.5; (M3) g_s=0.63 $g_{s,\text{free}-N}$. The lifetimes obtained on shifting the 2^+ so as to provide a photon of the measured energy 734 keV are also shown.

J_i^π	E (keV)	J_f^π	E/M λ	Half-life	
				Free-N	Renorm.
4^+	425	1^+	M3	3.9s	7.8s
2^+	687	1^+	M1(+E2)	0.31ps	0.38ps
	734			0.25ps	0.31ps

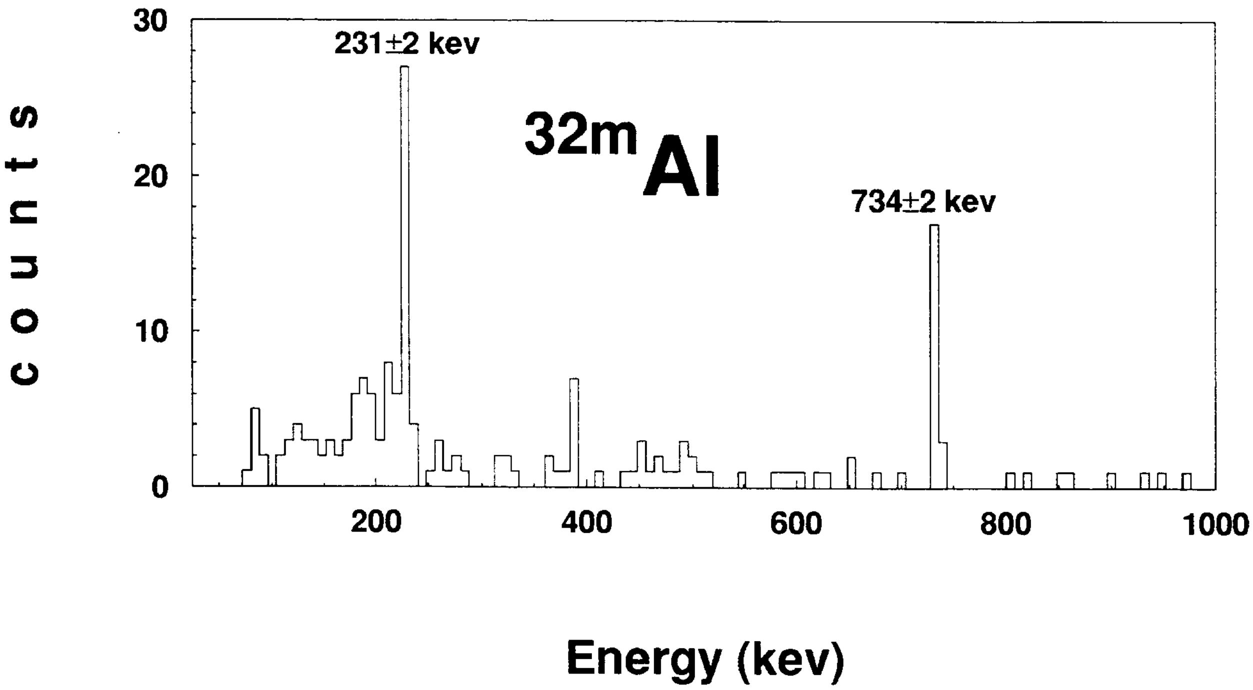
TABLE IV. Electromagnetic decays of the lowest 1-$\hbar\omega$ states, placed at energies such that the decay yields a photon of the energy observed in the experiment. The renormalisations used are: (E1) e_1=1.6, $e_{1,\text{free}-N}$; (E3) δe=1.0; (M2 and M4) g_s=0.7 $g_{s,\text{free}-N}$.

J_i^π	E (keV)	J_f^π	E/M λ	Half-life	
				Free-N	Renorm.
4^-	231	1^+	E3	3540s	6.1s
5^-	231	1^+	M4	1×10^8s	2×10^8s
4^-	231	4^+	E1	161ps	63ps
5^-	231	4^+	E1	364ps	140ps
4^-	231	2^+	M2	286μs	630μs
5^-	231	2^+	E3	505s	6.6s



counts
a)
b)
c)
^{29}Al
^{30}Al
^{31}Al
^{32}Al
^{32m}Al
15000
10000
5000
0
40
20
0
40
20
0
2
2.2
2.4
2.6
2.8
3
A/Z

Fig.1



30
20
10
0
counts
231±2 kev
32mAl
734±2 kev
200
400
600
800
1000
Energy (kev)

Fig.2

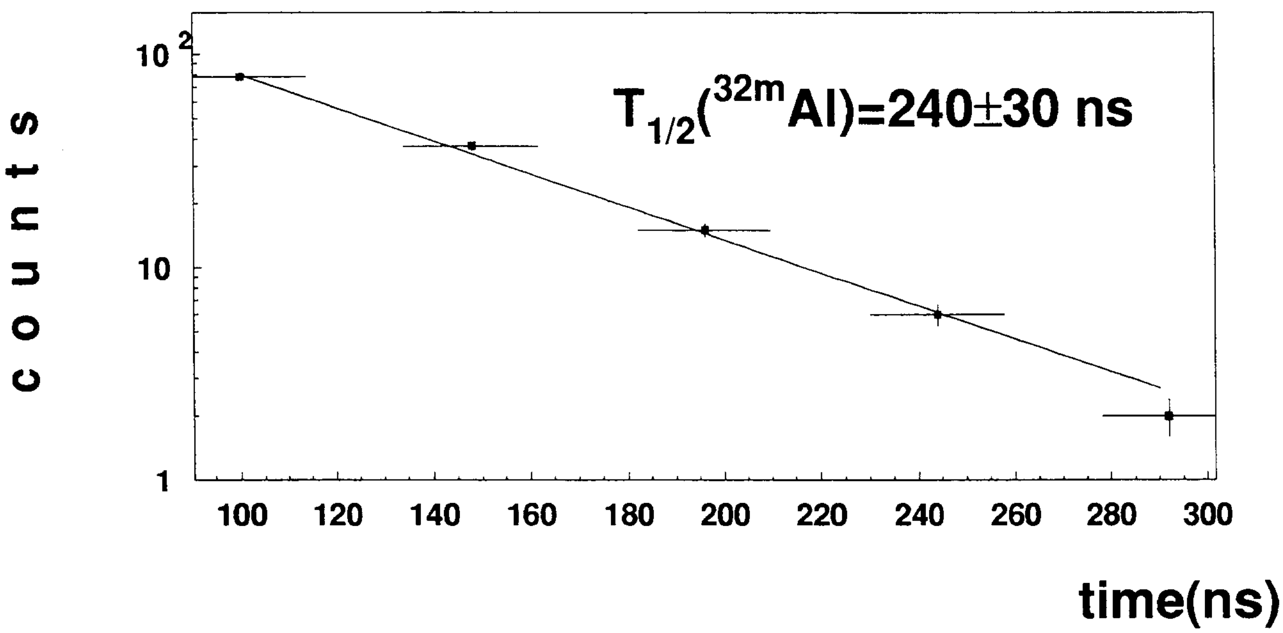

$T_{1/2}(^{32m}Al)=240\pm30$ ns
counts
10^2
10
1
100
120
140
160
180
200
220
240
260
280
300
time(ns)

Fig.3