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PROPERTIES OF 15/2$^-$ STATES IN ^{215}Ra AND ^{217}Th; EVALUATION OF THE 15/2$^-$ TO 9/2$^+$ E3 STRENGTH IN N=127 ISOTONES

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Abstract: The lifetime of the yrast 15/2$^-$ state in ^{215}Ra was measured using pulsed beams and γ-ray and electron techniques. Transition multipolarities were established from measured conversion coefficients. The B(E3) of the 15/2$^-$→9/2$^+$ transition is found to be considerably larger than previously reported. A candidate for the corresponding transition in ^{217}Th was also observed. The E3 strength of the 15/2$^-$→9/2$^+$ transition in the N=127 isotones is evaluated in the light of these and other recent results. Interpretation in the framework of particle-octupole vibration coupling requires a systematic lowering of the core 3$^-$ vibration as proton pairs are added to ^{208}Pb.

NUCLEAR REACTIONS ^{208}Pb(^{12}C,5n) 80 MeV; ^{206}Pb(^{13}C,4n) 78 MeV; ^{204}Pb(^{16}O,3n) 84 MeV. Measured E_γ, $I_\gamma(t)$ E_e, $I_e(t)$. ^{215}Ra, ^{217}Th deduced ICC, levels, $T_{1/2}$ B(E3) values. Enriched Targets, pulsed beams, Ge, Si(Li), Compton suppressed detector.

NUCLEAR STRUCTURE N=127 isotones particle-octupole vibration coupling, B(E3), 3$^-$ energies.

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1. Introduction

Enhanced E3 transitions occur in nuclei near ^{208}Pb because of particle-vibration coupling to the 3^- octupole-vibration[1]. Previous measurements of the $15/2^-$ to $9/2^+$ ($j_{15/2} \rightarrow g_{9/2}$) transition in the odd-A, N=127 nuclei ^{209}Pb (ref.[2]), ^{211}Po (ref.[3]), ^{213}Rn (ref.[4]) and ^{215}Ra (ref.[4]) yielded a relatively constant E3 strength of about 22 single particle units. This implied[4] a constant core octupole-vibration energy close to the ^{208}Pb value of 2.614 MeV.

However, our recent results[5] for the $15/2^-$ state lifetime in ^{213}Rn disagree with the earlier value[4], and give a much larger E3 strength, incompatible with a core 3^- energy of 2.6 MeV. Consequently, we have remeasured the $15/2^-$ state lifetimes in ^{215}Ra. Since spectroscopic assignments in that nucleus were tentative, conversion coefficients were also measured to substantiate the multipolarity assignment. To extend the systematics to as large a number of valence protons as possible, a search was made for the corresponding transition in ^{217}Th. Identification of this nucleus is problematic because of the severe fission competition in fusion-evaporation reactions leading to the light actinides. The results are not extensive but a candidate for the $15/2^- \rightarrow 9/2^+$ transition in ^{217}Th has been observed.

The B(E3) of the $15/2^- \rightarrow 9/2^+$ transition in the N=127 odd-A isotones is interpreted in terms of particle-vibration coupling, taking into account, in a simplified manner, the effect of the additional proton-neutron interaction which acts as successive pairs of protons are added to the ^{208}Pb core. The results of the analysis imply a substantial fall in the excitation energy of the 3^- core of nuclei heavier than ^{208}Pb.

2. Experimental Procedure

2.1 ^{215}Ra

Information on ^{215}Ra was obtained from three measurements. In the first, a 2.5 mg/cm^2 ^{208}Pb foil (enriched to 99%) was bombarded with a ^{12}C beam at 80 MeV, an energy at which 4n evaporation leading to ^{216}Ra dominates, and the weaker 5n channel leads to ^{215}Ra. The beam from the ANU 14UD pelletron accelerator was pulsed to have a width (FWHM) of about 1 ns, and a pulse separation of 1 μs. Gamma rays were measured in either of two detectors, a small volume planar Ge detector, or a large Ge detector (24% efficient) at ±55° to the beam axis. The γ-ray energies and times with respect to the beam pulse were recorded in event-by-event format, as were all experimental data described here.

The second (separate) experiment used the ^{206}Pb(^{13}C,4n)^{215}Ra reaction at 78 MeV with a 2.5 mg/cm^2 thick metal target enriched to 92% in ^{206}Pb. The beam pulse-width was ~3 ns, with a pulse separation of 1 μs. Gamma-rays were detected at 55° to the beam axis in a 24% efficient Ge detector, surrounded by a NaI(Tl) Compton-suppression shield. Concurrently, conversion electrons were directed by a"mini-orange" system to a cooled Si(Li) detector at 125° to the beam axis. Both electrons and γ-rays were timed with respect to the beam pulse. A measurement was also performed using the reaction ^{208}Pb(^{12}C,4n)^{216}Ra to provide information on possible contaminant γ-rays and internal calibrations for the combined electron and γ-ray efficiencies. In-beam calibrations were also provided by the various ^{206}Pb and ^{208}Pb transitions excited in the targets. Electrons and γ-ray efficiency calibrations were carried out with a ^{152}Eu source at the target position.

The third experiment was a γ-γ –time coincidence measurement using two Ge detectors at ±135° to the beam axis, each surrounded by a Bismuth Germanate (BGO) Compton Suppression shield, and the (^{13}C,4n) reaction described above.

This measurement is part of a more comprehensive study in progress and only the lifetime of the $15/2^-$ state obtained from the γ-γ-time data will be reported here.

All time spectra were calibrated using a commercial module[a].

2.2 ^{217}Th

The measurements on ^{217}Th were carried out with the second arrangement described above for ^{215}Ra. A target of ^{204}Pb 2.8 mg/cm^2 thick (composition: ^{204}Pb, 67%; ^{206}Pb, 16%; ^{207}Pb, 7%; ^{208}Pb, 10%) with its surface at 35° to the beam axis was bombarded by a pulsed 84 MeV ^{16}O beam whose pulse separation was 2μs.

The target projectile combination and beam energy, which is close to the Coulomb barrier, were chosen on the basis of fusion-evaporation calculations. These predicted that fission would dominate over the ^{204}Pb(^{16}O,3n)^{217}Th reaction, the main fusion-evaporation channel. Corresponding calculations for ^{16}O bombardment of ^{206}Pb were in qualitative agreement with the measurements of Häusser et al.[6]) in which ^{219}Th is produced in the (^{16}O,3n) reaction, the measured yield peaking near 85 MeV. Although the predicted cross section for the reaction leading to ^{217}Th is small, it was expected that the $15/2^- \rightarrow 9/2^+$ transition would be delayed and therefore identifiable in the more sensitive out-of-beam time region, where γ-rays from fission channels are reduced. Further, electron background from fission is less of a problem since fission products have relatively low Z.

[a] ORTEC Time Calibrator model 462.

3. Experimental Results

3.1 ^{215}Ra

Partial spectra of delayed γ-rays and delayed electrons following the ^{206}Pb(^{13}C,4n) reaction are shown in figure 1a and 1b. The 773 keV transition in ^{215}Ra is evident in these spectra. Its multipolarity is assigned as E3 on the basis of the measured conversion coefficients given in table 1.

The lifetime of the $15/2^-$ yrast state was deduced initially from analyses of the time spectra obtained for γ-rays and electrons in the various measurements (which have different proportions of feeding from high–lying states including the long-lived yrast $25/2^+$ state [4]) using a multi-level analysis to take account of the decay paths. The decay curve for the 773 keV γ–ray obtained in the pulsed beam, ^{206}Pb + ^{13}C bombardment is shown in figure 1c. The lifetime of 110(8) ns deduced for the $15/2^-$ state is considerably shorter than the previous value of 173(14) ns of Lonnröth and Baktash[4]), the discrepancy being comparable with that between their value for ^{213}Rn (measured in the same experiment), and our recent measurement[5]).

A more accurate value for the $15/2^-$ state lifetime in ^{215}Ra is obtained from the time spectrum measured in the γ–γ–time coincidence experiment with individual gates on the 852 keV γ–ray which directly feeds the $15/2^-$ state and the 773 keV γ-ray which depopulates it. This time spectrum, which yields a value of 99 (3) ns is shown in figure 2. Since the γ-γ technique avoids any systematic errors caused by the long-lived feeding in the pulsed-beam measurement, this lifetime is adopted. The corresponding transition strength is given in table 2.

3.2 ^{217}Th

An example of part of a delayed γ-ray spectrum from the ^{16}O bombardment of ^{204}Pb is shown in figure 3a. Most of the delayed γ-rays observed can be attributed to nuclei excited by neutron interactions in the NaI(Tl) crystal of the Compton suppressor, and in surrounding material. After evaluation of the γ-ray and electron data the 674 keV transition emerges as the only candidate which satisfies the criteria:

(i) corresponding γ-ray and electron energies for a transition in thorium (K-binding energy of 110 keV)

(ii) equivalent γ-ray and electron decay curves.

The region of the spectrum covering the L- and M-conversion lines for the 674 transition is contaminated but can be partly corrected by subtraction of the spectrum obtained for a later time regime (>450 ns). Corresponding γ-ray and electron spectra treated in this way are shown in figure 3. The K- and L-lines from the 674 keV transition appear to be clear, however both are contaminated by the K and M lines from the 660 keV ^{208}Po transition. After correction for this contaminant (a known E2 transition with essentially the same intensity as the 687 keV, ^{208}Po transition), the K-conversion coefficient given in table 1 is obtained. The statistics of the time spectrum obtained with a gate on the 674 keV, K electron line, shown in figure 3c, are marginal but sufficient to obtain an estimate of the lifetime. The mean life and transition strength are given in table 2.

The conversion coefficients (K and K/L ratio) support an E3 assignment and the electron energies suggest assignment to a thorium nucleus, presumably ^{217}Th. Production of ^{216}Th (the 4n channel) is severely restricted by fission while production of ^{218}Th (the 2n channel) is unlikely because of suppression by the Coulomb barrier.

The 674 keV transition is therefore suggested as a candidate for the $15/2^-$ to $9/2^+$ transition in ^{217}Th.

The observed yield, approximately 0.3% of that observed for the ^{215}Ra case, corresponds to a cross section of about 0.9 mb which is compatible with the predicted proportion of evaporation products to fission and measured fission cross-sections[7].

4. Interpretation

The $15/2^- \rightarrow 9/2^+$ transition strengths in the N=127 isotones are collected in table 2. Errors for the γ-ray intensities in the ^{211}Po case were not given in ref.[3]), so no errors have been assumed in evaluating the branching ratio. The results for ^{209}Pb are from ref[2]), those for ^{213}Rn from our recent study[5]) and the remainder from the present work.

Contrary to the previously accepted trend[4,8]), the E3 strength rises with increasing proton number.

4.1 PARTICLE-OCTUPOLE VIBRATION COUPLING

A simple approach has been taken in analysing the observed E3 strengths within the framework of the particle-vibration coupling model. Although a number of assumptions are implicit in this approach, the consequences of which will be discussed briefly below, it should serve to reveal, at least semi-quantitatively, the behaviour of the octupole vibration of the core.

As is well known[1,9]), the enhanced E3 strength of the $15/2^- \rightarrow 9/2^+$ transition in ^{209}Pb can be explained by admixtures of octupole-coupled states in the $15/2^-$ state. Its wave function can be written

$$|15/2^-\rangle = \alpha\,|j_{15/2}\rangle + \beta\,|g_{9/2} \otimes 3^-\rangle_{15/2^-}$$

and similarly for the $9/2^+$ state,

$$|9/2^+\rangle = \gamma\,|g_{9/2}\rangle + \delta\,|j_{15/2} \otimes 3^-\rangle_{9/2^+}$$

The amplitudes α,β,γ and δ which, with the single-particle $\nu j_{15/2} \rightarrow \nu g_{9/2}$ and octupole $3^- \rightarrow 0^+$ strengths, determine the value of $B(E3{:}15/2^- \rightarrow 9/2^+)$ (see the equation in section 4.5 of ref.[10])), depend on the energy separation of the pairs of unperturbed $15/2^-$ and $9/2^+$ states and on the coupling matrix element.

The unperturbed energies will not be the same in ^{211}Po, ^{213}Rn ... etc., as in ^{209}Pb, primarily because of the interaction between the odd neutron and the valence protons. For simplicity we have calculated this interaction $V_{pn}^{(n)}$ using the Kuo and Herling interactions[11]) for the restricted configuration $\pi(h^n_{9/2})_0 - \nu j$ where the protons are coupled to spin zero. The unperturbed energies $E_c + V^{(n)}_{pn}$ are given in table 3. For the $h_{9/2}$ shell the n=6 (Ra) and n=8 (Th) cases are equivalent to n=2 (Po) and n=4 (Rn) respectively.

The particle-vibration coupling matrix element H_{PV} is determined by the amplitude of the octupole oscillation which is proportional to the $\sqrt{B(E3)}$ of the core $3^- \rightarrow 0^+$ transition. In ^{208}Pb, $\hbar\omega_3$ = 2.614 MeV and B(E3:$3^- \rightarrow 0^+$) = 87(2) x 10^3 e^2fm^6 (ref.12). The corresponding matrix elements are given in table A.1 of ref.[5]). To allow for a change in the core octupole vibration we have assumed a sum rule form, B(E3:$3^- \rightarrow 0^+$)• $\hbar\omega_3$ = constant, implying an increased collectivity for lower energies. The other E3 strength required is the single particle value given in table A.2 of ref.[5]).

Diagonalisation of the 2 x 2 matrices for the $15/2^-$ and $9/2^+$ states yields the amplitudes and therefore the B(E3:$15/2^- \rightarrow 9/2^+$) for each odd-A nucleus, as a function of the energy of the 3^- state of each respective core.

The results are compared with experiment in figure 4. The upper panel shows the experimental B(E3) values, the lower panel the energies of the 3^- excitations. The dashed line in the upper panel shows the $15/2^- \rightarrow 9/2^+$ B(E3) calculated for a 3^- energy of 2.614 MeV for the ^{208}Pb, ^{210}Po, ^{212}Rn, ^{214}Ra and ^{216}Th cores. It reproduces the ^{209}Pb and ^{211}Po values but is predicted to vary only slightly with increasing proton number, in agreement with the earlier results and interpretation but in contrast to the new experimental results. The vertical bars in the lower panel represent the energy of the 3^- excitation required to reproduce the new experimental B(E3) values. As foreshadowed above a drop in energy to ~2.0 MeV in ^{214}Ra, and much lower in ^{216}Th, is required to explain experiment.

Several comments on the assumptions are appropriate. The assumed correlation between the 3^- energy and the core B(E3:$3^- \rightarrow 0^+$) value leads, in the above analysis, to a 3^- energy higher than would be required if the strength (which affects both the coupling matrix element and the component B(E3) values) were assumed to be constant. Related assumptions are contained in the neglect of mixed proton configurations and of blocking of components of the 3^- wave function by the added protons. These would have the effect of reducing the octupole correlations thus increasing the core 3^- energy and reducing its collectivity.

A lower 3^- energy was suggested as the likely cause of the remaining discrepancy between experimental and theoretical B(E3) values between (octupole-vibration mixed) multi-particle high-spin states in the Rn and At isotopes [5,13,14]).

4.2 3^- STATE SYSTEMATICS

The transition from spherical Pb nuclei, which have vibrational 3^- states, to the suggested octupole-deformed nuclei, where collective octupole bands may be observed, is understood[15,16]) to be related to the availability of pairs of orbitals with $\Delta l=3$ such as $g_{9/2}$ and $j_{15/2}$ for the neutrons and $f_{7/2}$ and $i_{13/2}$ for the protons. The mapping of such a transition, involving the spectroscopy of nuclei with an increasing number of protons and neutrons added to ^{208}Pb, is difficult experimentally because of the inaccessibility of many of the nuclei, and in some cases the non-yrast nature of the states of interest. Cottle and Bromley[17]) have recently collected results for the Z=82-90 nuclei and suggested a parametrization in terms of the occupation probabilities of specific orbitals, in particular the $\Delta l=3$ pairs mentioned above. The same systematics are reproduced with the addition of the present deduced values as a function of neutron number in figure 5(a) and as a function of the occupation parameters B_n and B_p, quantities defined by Cottle and Bromley[17]), in figure 5(b). The large scatter observed as a function of neutron number is largely removed by their parametrization, the present results following reasonably well the experimental trend. (Some caution is necessary in such a compilation, which contains only the lowest experimental 3^- state, since the experimental octupole strength may be fragmented through mixing with particular particle configurations. That is probably the case in ^{210}Po[18]) and in ^{210}Pb - see for example ref.[19]).

As well as the pairs of Δl=3 configurations the spin-flip combinations $g_{9/2}$ and $i_{11/2}$(neutrons) and $h_{9/2}$ and $i_{13/2}$ (protons) contribute to octupole mixing, the protons being more important. Figure 5(c) shows the effect of including 20% of the occupation probability of the proton $h_{9/2}$ orbital in the calculation of B_p. A somewhat smoother trend results. Formal treatment of these and other effects such as the blocking of components of the 3^- vibration as particles are added, is outside the scope of the present work. RPA calculations which include blocking effects are being pursued by other authors[20]).

5. Conclusions

Analysis of new measurements of the B(E3) values of the $15/2^- \rightarrow 9/2^+$ transition in the N=127 isotones suggests a lowering of the energy of the 3^- vibration of the core as protons are added to ^{208}Pb.

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TABLE 1 Conversion coefficients in ^{215}Ra and ^{217}Th

Nuclide	Transition Energy (keV)	Conversion Coefficient x10^{-2}	Mλ	Theory x10^{-2}
^{215}Ra	772.8	K 2.57(11)	E3	2.58
		L 0.96(6)		1.13
		M 0.027(5)		0.03
^{217}Th	673.8	K 5.1(14)	(E3)	3.8
		L ≤3.0(11)		2.1

TABLE 2. $15/2^- \rightarrow 9/2^+$ state lifetimes and $15/2^- \rightarrow 9/2^+$ transition strengths in N=127 isotones

Nuclide	Energy (keV)	Meanlife (ns)	γ-ray Branch (%)	B(E3) $10^3\ e^2fm^6$	$\lvert M \rvert^2$ s.p.u.	Ref.
^{209}Pb	1422	2.0(4)	90(1)	67(14)	26(6)	[2]
^{211}Po	1065	20.2(14)	96[a]	51.0(37)	19.3(14)	[3]
^{213}Rn	896	38(1)	99.6(1)	85.6(24)	31.8(9)	[5]
^{215}Ra	773	99(3)	100	103.1(32)	37.5(11)	
^{217}Th	(674)	203(72)	100	128(45)	46(16)	

a) Uncertainty in branching ratio is not known.

TABLE 3. Unperturbed energies and proton–neutron interactions

State	E_0 [a] (keV)	$V_{pn}^{(2)}$ (keV)	$V_{pn}^{(4)}$ (keV)
$\|15/2^-\rangle_1$	1848	-634	-1268
$\|15/2^-\rangle_2$	$213 + \hbar\omega_3$	-634	-1268
$\|9/2^+\rangle_1$	213	-373	-745
$\|9/2^+\rangle_2$	$1848 + \hbar\omega_3$	-373	-745

a) $\hbar\omega_3 \equiv 3^-$ excitation energy.

Figure Captions

Figure 1. Delayed γ-ray (panel (a)) and electron (panel (b)) spectra in the ^{13}C + ^{206}Pb bombardment. The 773 keV γ-ray time spectrum is shown in (c). The prompt component is from a small contaminant γ-ray of the same energy.

Figure 2. Time spectrum obtained in the ^{215}Ra γ-γ coincidence experiment with gates on individual γ-rays.

Figure 3. Delayed γ-ray (a) and electron (b) spectra (with the long time regime subtracted), and the 674 keV K-electron, time spectrum from the ^{16}O + ^{204}Pb bombardment. The time spectrum (panel (c)) has been corrected for the ^{208}Po contaminant and is offset by 100 counts.

Figure 4. E3 strengths of $15/2^- \rightarrow 9/2^+$ transitions in the N=127 isotones. The 3^- energies required to reproduce the experimental data are shown in the lower panel.

Figure 5. Systematics of 3^- state energies a) vs. neutron number N, b) vs. B_n+ B_p, occupation probabilities as defined in ref.[17]), c) with B_p modified to include the $h_{9/2}$ orbital. Filled (open) symbols represent firm (tentative) assignments. Symbols with error bars are the values <u>deduced</u> from the present evaluations.

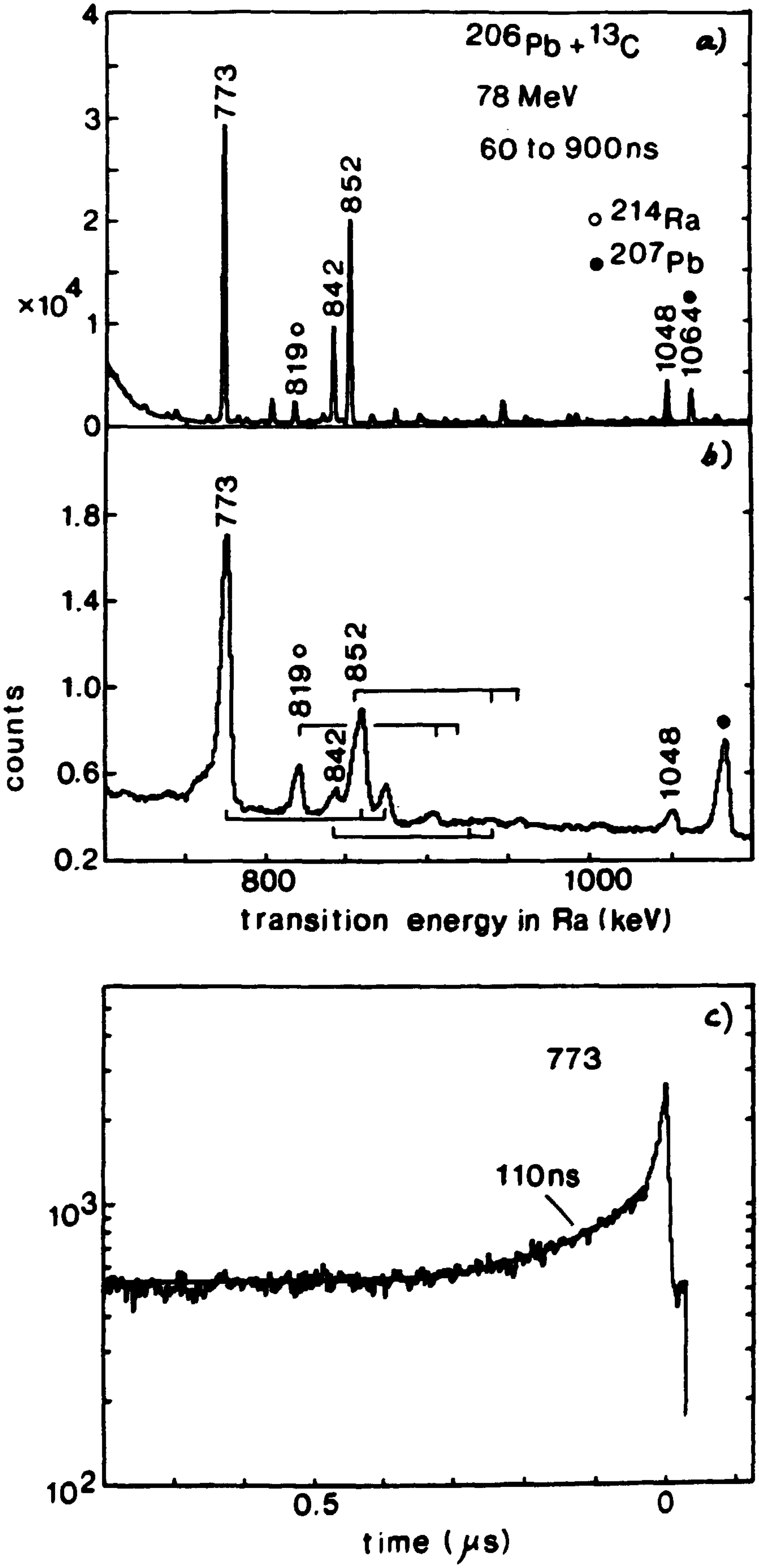
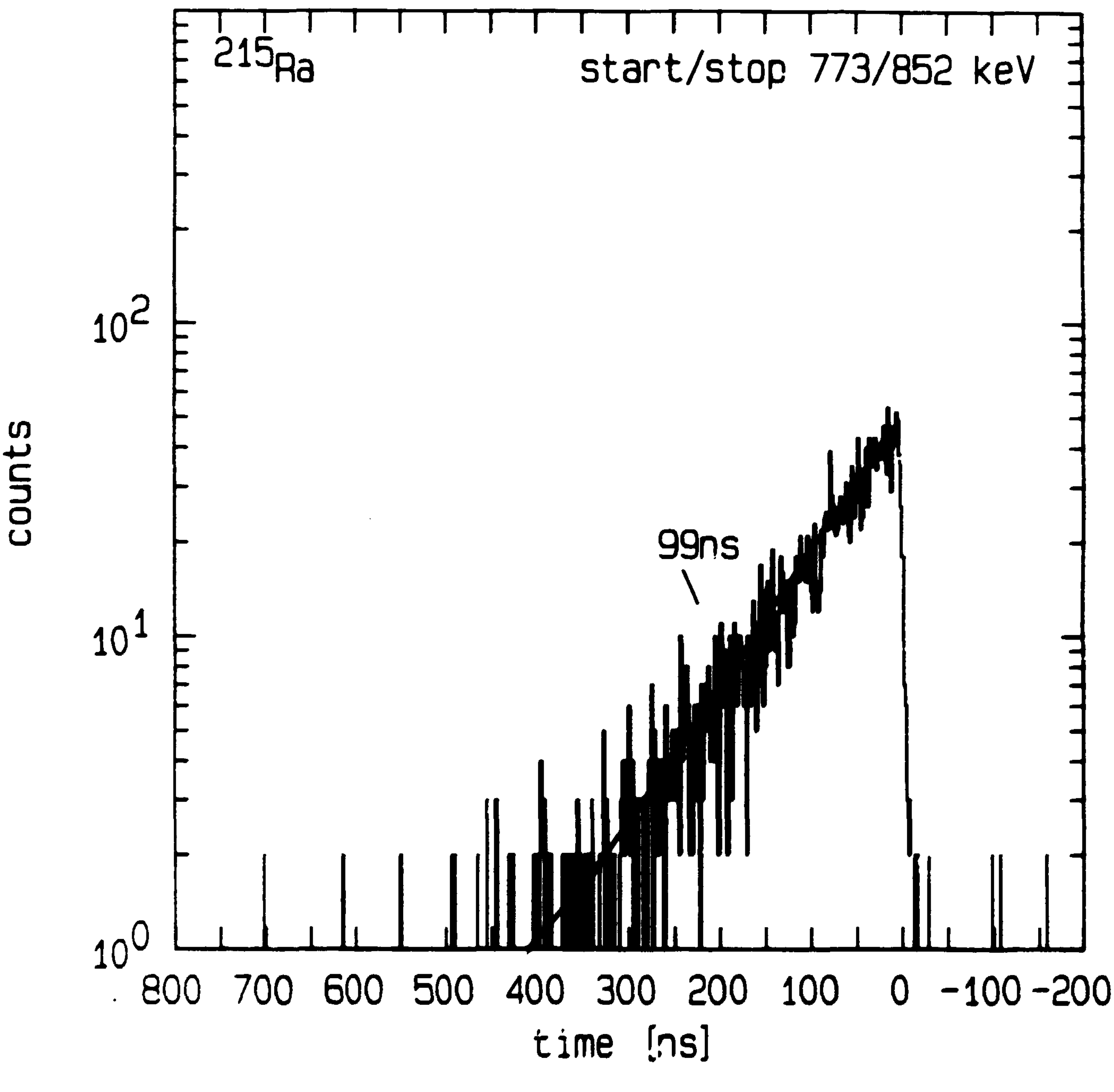
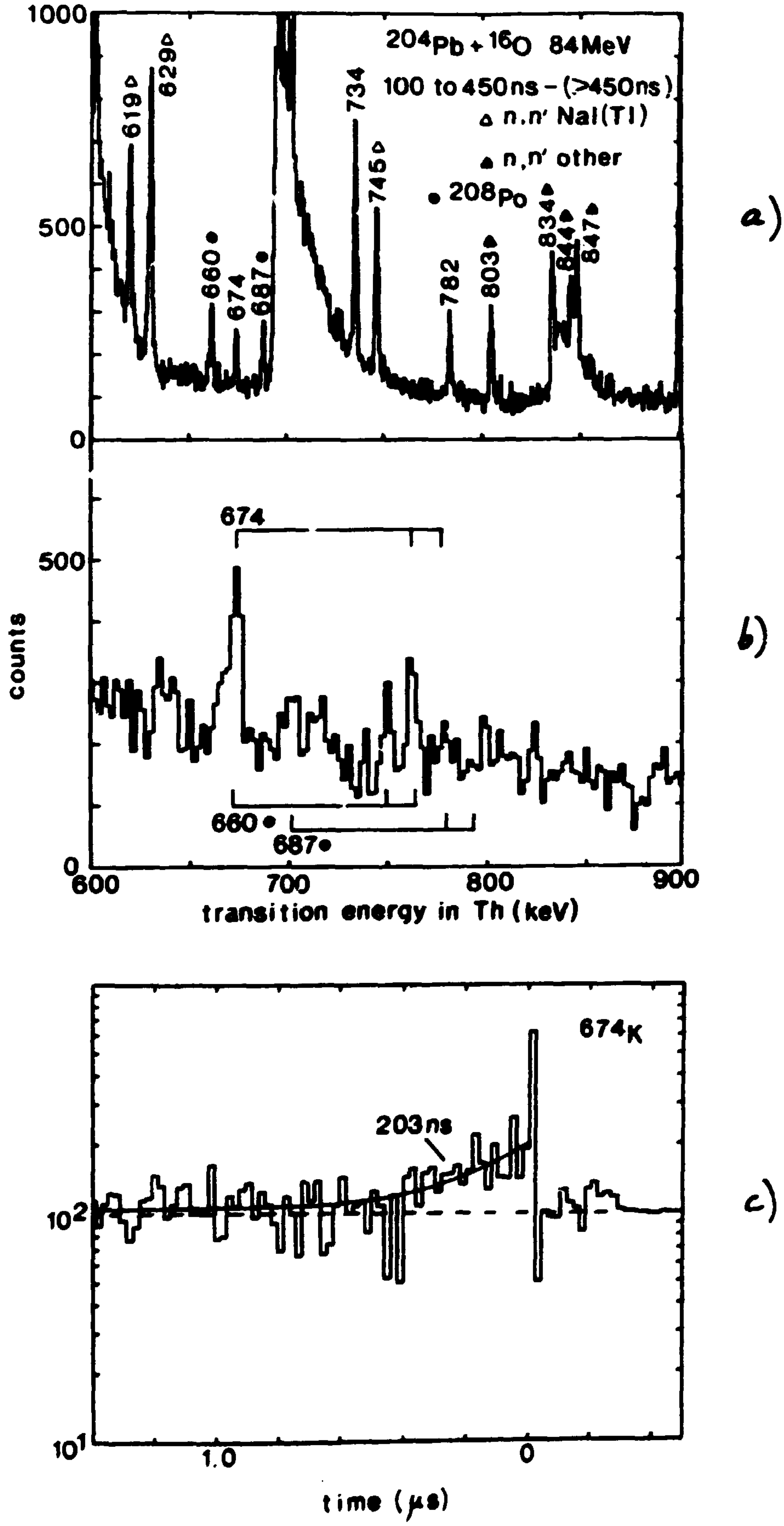

206Pb + 13C
a)
78 MeV
60 to 900ns
773
852
842
819o
o 214Ra
• 207Pb
1048
1064•
×10^4
4
3
2
1
0
b)
1.8
1.4
1.0
0.6
0.2
counts
800
1000
transition energy in Ra (keV)
c)
773
110ns
10^3
10^2
0.5
0
time (μs)

Fig. 1



215Ra
start/stop 773/852 keV
99ns
counts
10^2
10^1
10^0
800 700 600 500 400 300 200 100 0 -100 -200
time [ns]

Fig. 2



204Pb + 16O 84MeV
100 to 450ns - (>450ns)
n.n' NaI(Tl)
n.n' other
208Po
619
629
660
674
687
734
745
782
803
834
844
847
1000
500
0
a)
674
660
687
500
0
600
700
800
900
counts
transition energy in Th (keV)
b)
674K
203ns
10^2
10^1
1.0
0
time (μs)
c)

Fig. 3

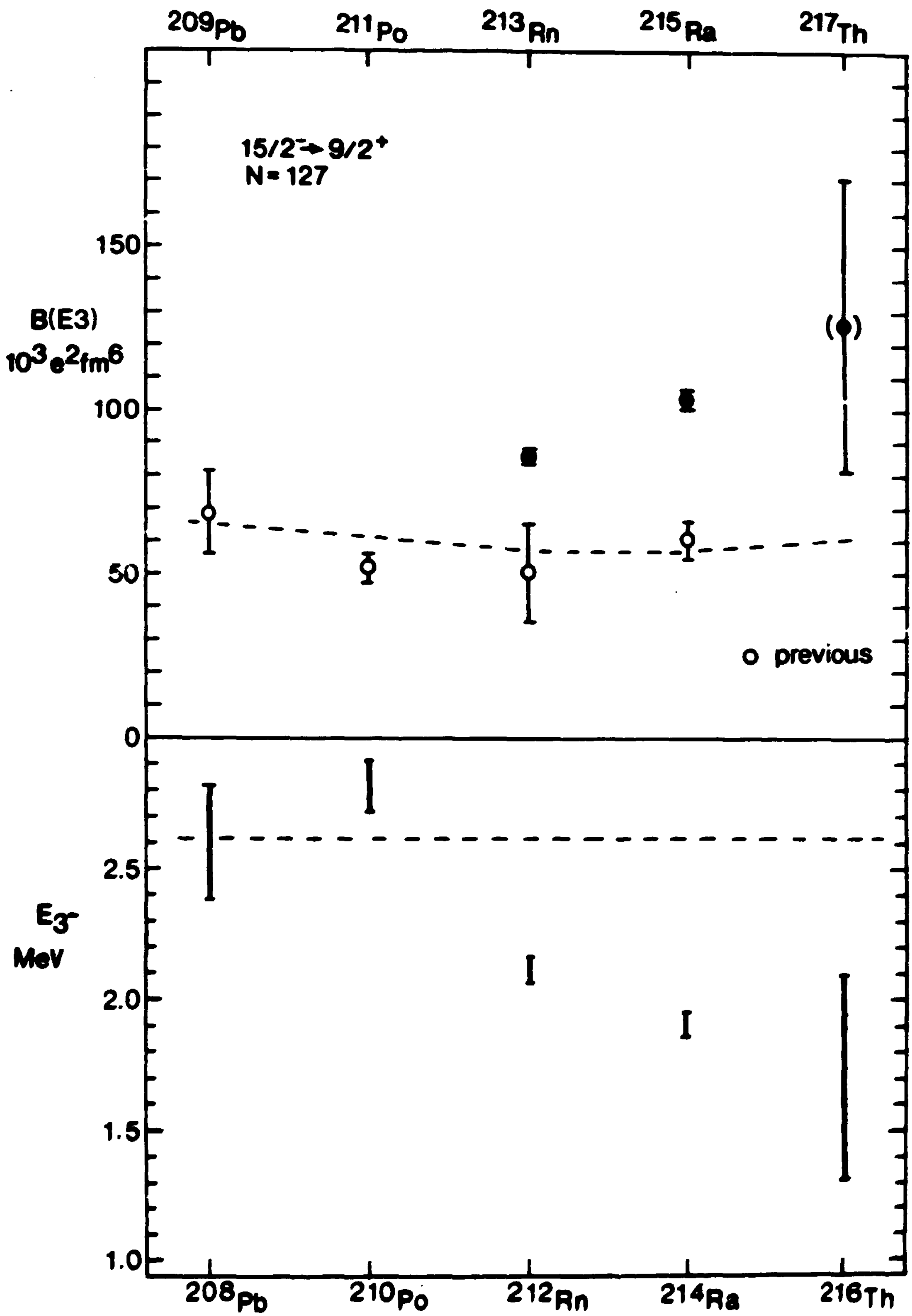

209Pb
211Po
213Rn
215Ra
217Th
15/2⁻→9/2⁺
N=127
B(E3)
10³e²fm⁶
150
100
50
0
o previous
E3⁻
MeV
2.5
2.0
1.5
1.0
208Pb
210Po
212Rn
214Ra
216Th

Fig. 4

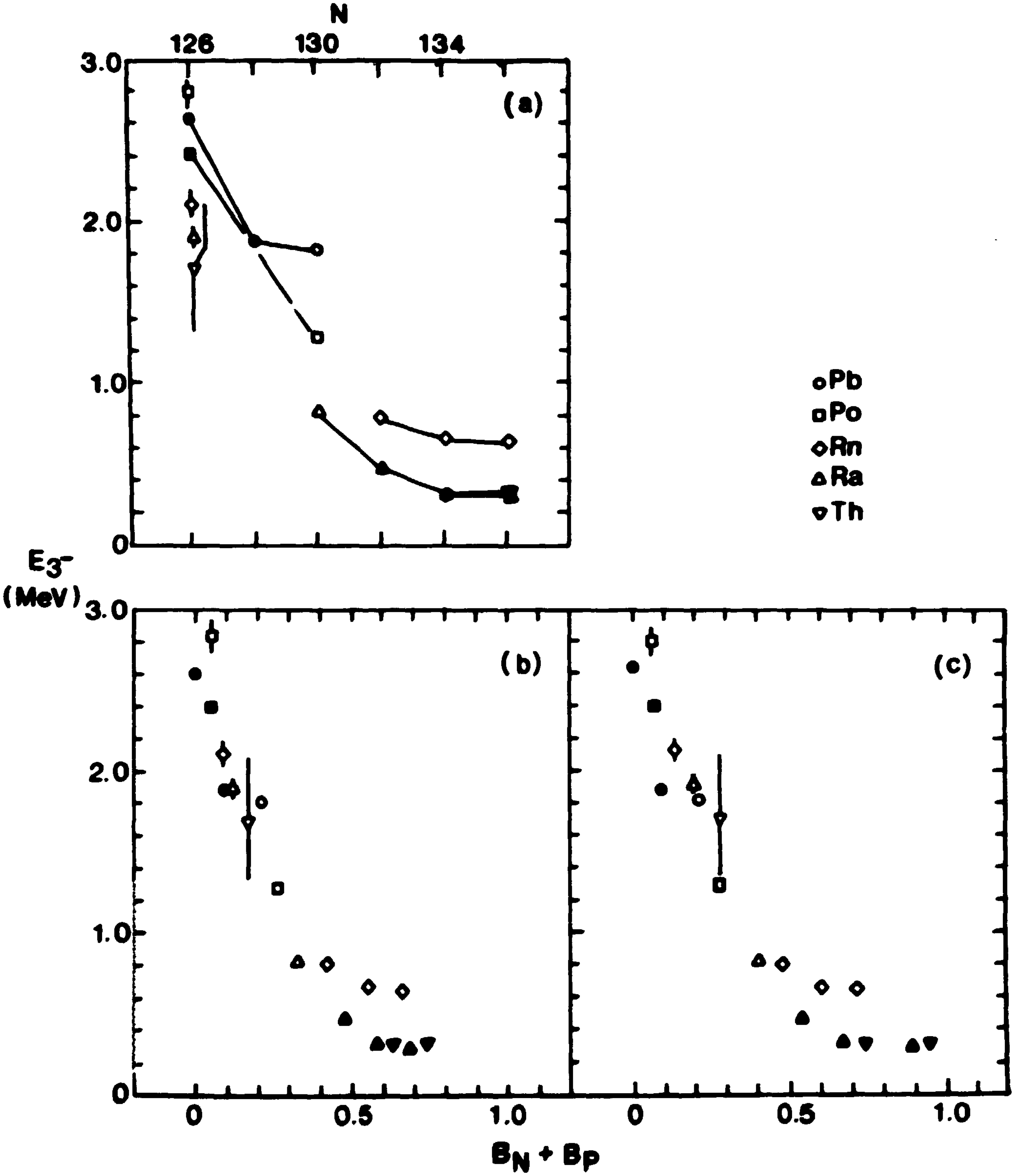


Fig. 5