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Трехквазичастичные возбуждения в ядре ^{205}At

В реакции $^{197}Au(^{12}C, 4n)^{205}At$ было обнаружено изомерное состояние с периодом полураспада $T_{1/2}$ = 110±25 нсек. Оно было приписано уровню $21/2^-$ из мультиплета конфигурации $p(h_{9/2})^3$. По сравнению с состояниями ядра ^{211}At мультиплет в ядре ^{205}At выражен слабее, так как наличие незаполненной нейтронной оболочки приводит к примесям от двухнейтронных состояний.

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Three-Quasiparticle Excitations in ^{205}At

In the reaction $^{197}Au(^{12}C,4n)^{205}At$ an isomeric state with a half-life $T_{1/2}$ = 110±25 ns was observed, which is ascribed to the $21/2^-$ state of the $p(h_{9/2})^3$ multiplet. Compared to the corresponding nucleus ^{211}At this multiplet is not well developed, because the unfilled neutron shell causes a configuration mixing with the two-neutron states.

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1. Introduction

Shell-model calculations for three identical particles, added to closed shells, predict the following features of the three-particle multiplet:

i) the level scheme contains levels with spin values $J_{min} = 3/2$ up to $J_{max} = 3j-3$

ii) the level with $J = J_{max} - 1$ is always absent

iii) in every case the level with $J = J_{max}$ has the highest excitation energy, and the lowest lying level of the $(j)^3$ multiplet is characterized by the spin value $J = j$ and the seniority $s = 1$. In this picture a stretched $E2$ cascade $J_{max} \to J_{max}-2 \to J_{max}-4 \dots$ deexcites the highest spin state of the $(j)^3$ configuration. It was observed that the energy difference between the excited levels decreases with increasing spin values in agreement with theoretical calculations. For the $J_{max} \to J_{max}-2$ transition a considerable lifetime is, therefore, to be expected. Going away from closed shell nuclei we find an increasing collective character of the lower lying levels of the multiplet, whereas the highly excited levels with high spin values remain nearly pure quasiparticle states. Recently, the $(h_{9/2})^3$ multiplet of three protons outside the closed proton $(Z = 82)$ and closed neutron $(N = 126)$ shells has been found in ^{211}At /1/. The aim of our investigation was to look whether or not the character of this multiplet remains unchanged if we go away from the closed neutron shell. At the heavy ion cyclotron U-300 of the Laboratory for Nuclear Reactions, JINR Dubna, we started, therefore, pulsed beam experiments in order to investigate isomeric states of the neutron deficient astatine nuclei.

2. Experimental Method

2.1. Gamma-ray investigations

For our studies we made use of the natural nanosecond beam bunching of the cyclotron. For ^{12}C and ^{18}O the heavy ion cyclotron U-300 works with a period duration of 237 ns. The experimental arrangement has already been described elsewhere /2/. Fig. 1 shows typical gamma-ray spectra, measured with a Ge(Li) planar detector (1.4 cm^2 x 1.1 cm) by bombarding an 8.5mg/cm^2 metallic gold foil with 81 MeV ^{12}C ions. In each part of Fig. 1 the upper (prompt) spectrum was measured with the time gate set on the beam burst, whereas the lower (delayed) spectrum includes the delayed gamma rays measured within the time region 30-200 ns after the beam pulse. Eight prominent delayed gamma transitions were found in this time interval. Furthermore, in a special run with a 43 cm^3 Ge(Li) coaxial detector we also have searched for high energy gamma transitions up to 2.5 MeV. Besides of some weak background lines no further delayed gamma rays could be found. The energies and relative intensities of the gamma lines in the delayed spectra are given in Table 1. Some typical time spectra, which are calculated from the two-dimensional energy-time spectrum, are given in Fig. 2a. Fig. 2b shows a multichannel time spectrum measured by selection of the 332 keV transition. For the gamma rays listed in Table 1, within the experimental error the same lifetime was found. Calculated from several runs, the average half-life amounts to $T_{1/2} = 110 \pm 25$ ns. It should, however, be noted, that the 125 keV and the 191 keV transitions tend to a somewhat shorter half-life.

In the time spectrum of the 125 keV transition no prompt component is to be seen (Fig. 2a). This fact suggests the conclusion, that this transition deexcites the isomeric level. From the energy and intensity balance it may be concluded that also the 191 keV transition comes from the isomeric state, but this transition contains a significant prompt component. A careful remeasurement with high energy resolution showed, that this prompt component is probably caused by the not resolved admixture of the Coulomb excited 191.5 keV transition in ^{197}Au. This assumption is confirmed by the fact that the 191 keV line was also obtained in the delayed spectrum of the crossing reaction $Ir + {}^{18}O$ but without prompt component.

2.2 Identification of the reaction products

Heavy ions reactions with heavy weight nuclei demand a careful determination of the reaction type. For a given target-ion combination the fission cross section increases rapidly with increasing bombarding energy and completes with the *(HI,xn)* process. The isomeric gamma transitions of Table 1 were observed, when the gold was bombarded with ^{12}C ions at incident energies above the Coulomb barrier up to 81 MeV. The same characteristic lines were found in a cross-bombardment, namely by irradiation of a metallic iridium foil (18 mg/cm^2) with 110 MeV ^{18}O ions. With this energy we expect the maximum yield of the $^{193}Ir(^{18}O,6n)^{205}At$ reaction. The yield is, however, lower than with the $^{197}Au(^{12}C,4n)\,^{205}At$ reaction, which is in rough agreement with the tendency of the cross-sections of fission and neutron evaporation processes. Our identification is further confirmed by an estimation of the cross section for the formation of the isomeric state. From the intensity ratio of the delayed 566 keV transition and the 718 keV transition in ^{205}Po we obtain the ratio σ (i.st.) / σ(g.st. ^{205}At) = 0.4 ± 0.1 For this estimation the measured decay constant, the timing conditions of our measurement and the branching ratios of the delayed gamma transitions (Tab. 1) and the α - decay of the ^{205}At ground state /3/ I_α / I_{tot} = 0.18 have been taken into account. From the known value /4/ for the ^{205}At ground state formation σ (g.st.)= 90± 10 mb at 70 MeV we obtain σ (i.st.) = 36 ± 10 mb, i.e. the same order of magnitude. On the other hand for fission products of the reaction $^{197}Au + {}^{12}C$ at 81 MeV the maximum cross section values /5/ are below 15 mb, and spontaneous fissioning At isomers within the time range 2 ns...2000 s should have cross section values /6/

$\sigma <$ 0.1μb. We, therefore, conclude, that the found isomeric state is formed by the (HI, xn) compound nuclear reaction, whereas the charged particle evaporation is improbable because of the low bombarding energy and the high Coulomb barrier in this mass region.

In order to determine the number x of the evaporated neutrons we draw the relative intensities of characteristic gamma lines of the ^{204}At, ^{205}At and ^{206}At decay together with the prominent delayed 332 keV line versus the heavy ion energy. If we set the intensity of the 718 keV line of the ^{205}At decay equal to unity we obtain the behaviour shown in Fig. 3. The 332 keV transition shows the same dependence of the H.I. energy as the 718 keV transition, which allows the conclusion that the 110 ns isomeric state belongs to the nucleus ^{205}At. In Fig. 4 the relative excitation functions of other delayed and prompt gamma lines are shown, which belong to other reaction products.

3. Decay Scheme and Discussion

The decay scheme shown in Fig. 5 is based on the intensity ratios of corresponding gamma lines in the prompt and delayed spectra as well as on the energy and intensity balance of the delayed gamma transitions. This intensity balance can only be fulfilled if we assume an $E2$ multipole order of both the 125 keV and 191 keV transitions, which is also to be expected from the measured half-life. Furthermore, with an $M1$ character of the 332 keV transition we obtain a better intensity balance than with an $E2$ multipole order.

In Fig. 6 our level scheme is compared with those of the neighbouring even isotones $N = 120$, namely ^{202}Pb /7/ and ^{204}Po /8/. A similar but clearer comparison is possible /1/ for the closed neutron shell isotones ^{210}Po and ^{211}At with $N = 126$, which is also drawn in Fig. 6. The level schemes of ^{210}Po and ^{211}At can be described by the pure $p(h_{9/2})^2$ and $p(h_{9/2})^3$ configurations.

For the $N = 120$ isotones ^{204}Po and ^{205}At the situation is somewhat different. Going away from the closed neutron shell we find an increasingly collective character of the first low-spin levels $I^{\pi} = 2^+$ and 4^+ in ^{204}Po, for the two-neutron quasiparticle states are increasingly admixed. For example, the 2^+ and 4^+ states of the $(f_{5/2})^2$ neutron configuration in ^{202}Pb are placed at 960 keV and 1384 keV, respectively /7/. On the other hand, the $I^{\pi} = 6^+$ and 8^+ levels in ^{204}Po remain fairly pure proton states of the $p(h_{9/2})^2$ configuration, because the corresponding neutron configurations in ^{202}Pb which give such high spin values, have considerably higher excitation energies and should, therefore, be of little influence.

It seems to us, that the isomeric level with $I^{\pi} = 21/2^-$ in ^{205}At corresponds to the $I^{\pi} = 6^+$ level in ^{204}Po and may be regarded as the highest-spin state with $I = I_{max}$ of the $(h_{9/2})^3$ proton configuration, similar to the situation in ^{211}At. The excitation energies of the $I^{\pi} = 21/2^-$ levels in ^{205}At and ^{211}At are nearly the same (1492 and 1416 keV, respectively) and somewhat lower than the $I^{\pi} = 6^+$ levels in ^{204}Po and ^{210}Po (1624 and 1472 keV, respectively). Deviating from the ^{211}At deexcitation we observed two γ-ray transitions of 125keV and 191keV of nearly equal intensity, deexciting the isomeric $21/2^-$ level. The $B(E2)$ value of the 125 keV transition (Table 1) does not deviate much from the theoretical value $B(E2) = 61\ e^2fm^4$ of the $(h_{9/2})^3_{21/2^-} \longrightarrow (h_{9/2})^3_{17/2^-}$ transition /9/, whereas the 191 keV transition gives a very low $B(E2)$ value. We, therefore, assume the existence of a second $17/2^-$ level not belonging to the $(h_{9/2})^3$ configuration. Corresponding to the coupling rules /10/ such a $17/2^-$ state may be formed by coupling the $(h_{9/2})^3_{9/2}$ proton state to the second 4^+ state in ^{202}Pb with the structure $n_1(f_{5/2})n_2(p_{3/2})$. The 191 keV transition from the $21/2^-$ level to this $17/2^-$ level at 1301 keV probably goes via an $(h_{9/2})^3$ admixture of the $17/2^-$ state. From the comparison of the decay schemes of the odd A Rn isotopes has been concluded /11/ that the ground state of ^{205}At also has the value $I^\pi = 9/2^-$. For the levels at 566, 663, 1035 and 1301 keV the observed γ-transitions suggest the values $11/2^-$, $13/2^-$, $15/2^-$ and $17/2^-$, respectively. These levels correspond to the 2^+ and 4^+ states in ^{202}Pb and ^{204}Po. The assumption, that in ^{205}At the lower lying states are not pure proton states is supported by the facts that no $E2$ transition from the $17/2^-$ level at 1367 keV to the $13/2^-$ level at 663 keV could be found, and that the 332 keV γ-ray transition to the $15/2^-$ level is of mainly $M1$ character.

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Table 1

Delayed gamma transitions in ^{205}At

E_γ (keV)	I_γ (relative)	assumed multipolarity	α_{tot}	I_{tot}	$B(E2)$ ($e^2\ fm^4$)
125	31	E2	2.78	117	31 ± 9
191	28	E2	0.58	44	3.4 ± 1.4
332	93	M1	0.43	133	
372	67	M1	0.31	88	
469	55	E2	0.04	57	
566	56	M1	0.10	61	
638	42	E2	0.02	43	
663	100	E2	0.03	103	

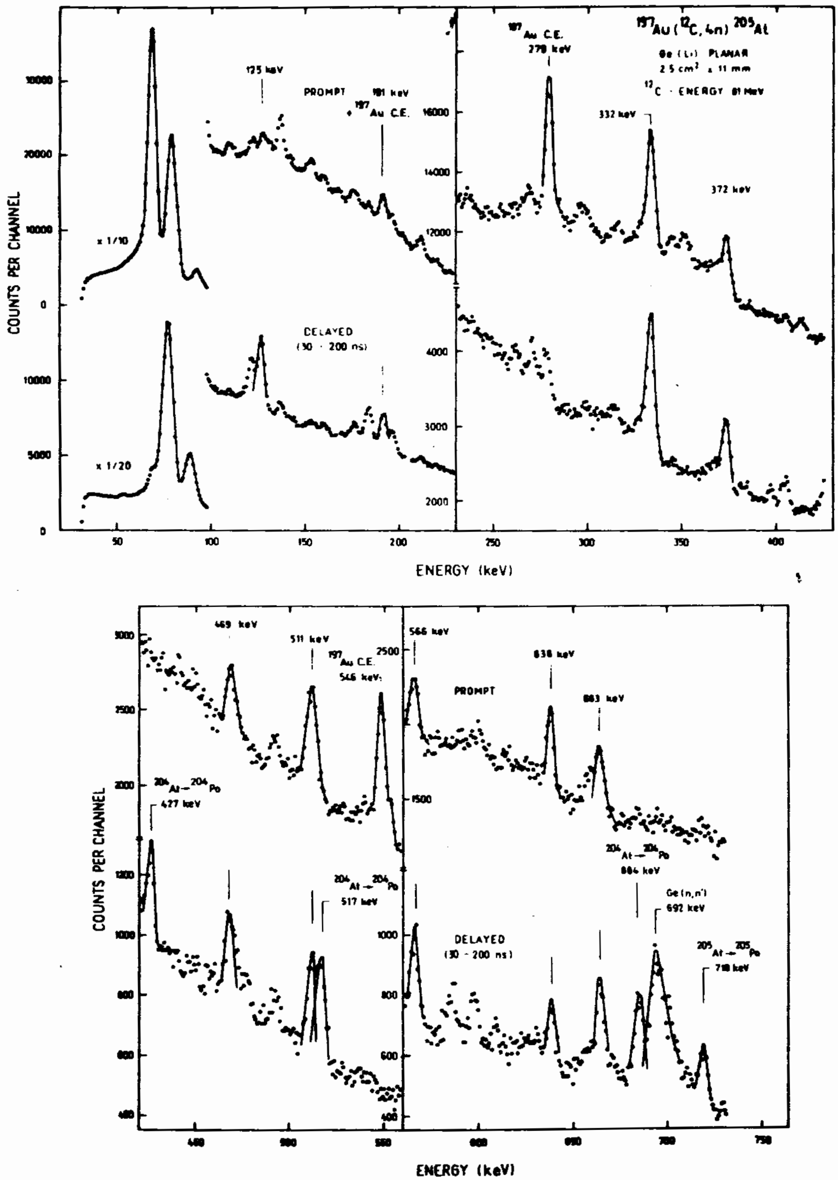

Fig. 1. Prompt and delayed gamma-ray spectra of the reaction $^{197}Au+^{12}C$. Coulomb excited gamma transitions in ^{197}Au are denoted by C.E.

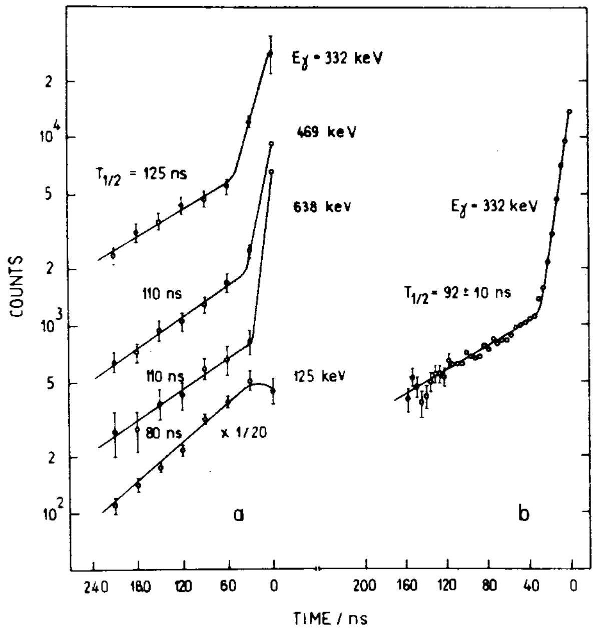

Fig. 2. Time spectra of some delayed gamma transitions in ^{205}At
a) calculated from the two-dimensional energy-time spectrum;
b) measured directly by selection of the 332 keV line.

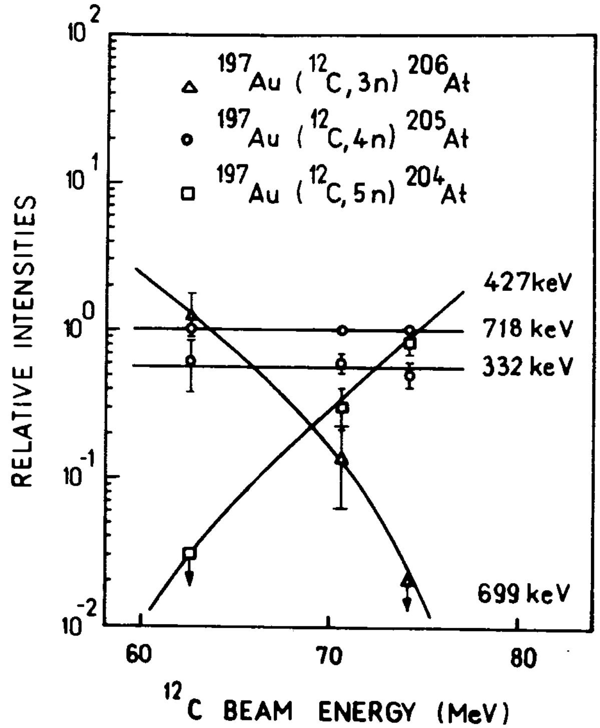

Fig. 3. Excitation functions of the $^{197}Au(^{12}C,xn)^{209-x}At$ reaction for x = 3,4, and 5.

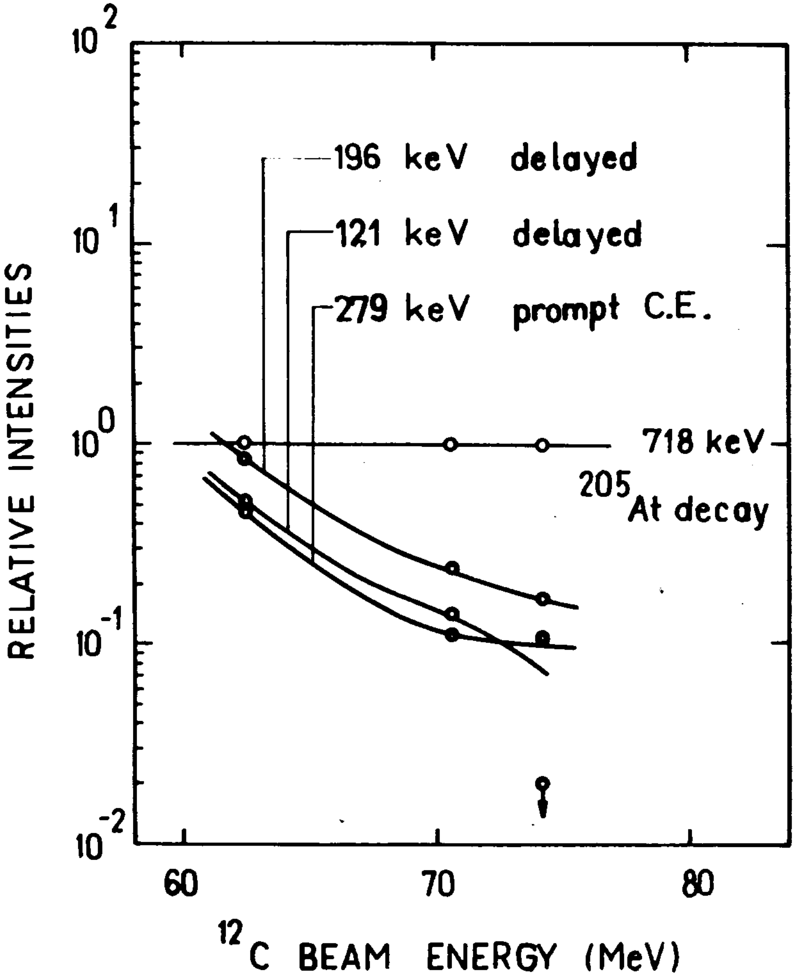

Fig. 4. Excitation functions of some gamma transitions not belonging to ^{205}At .

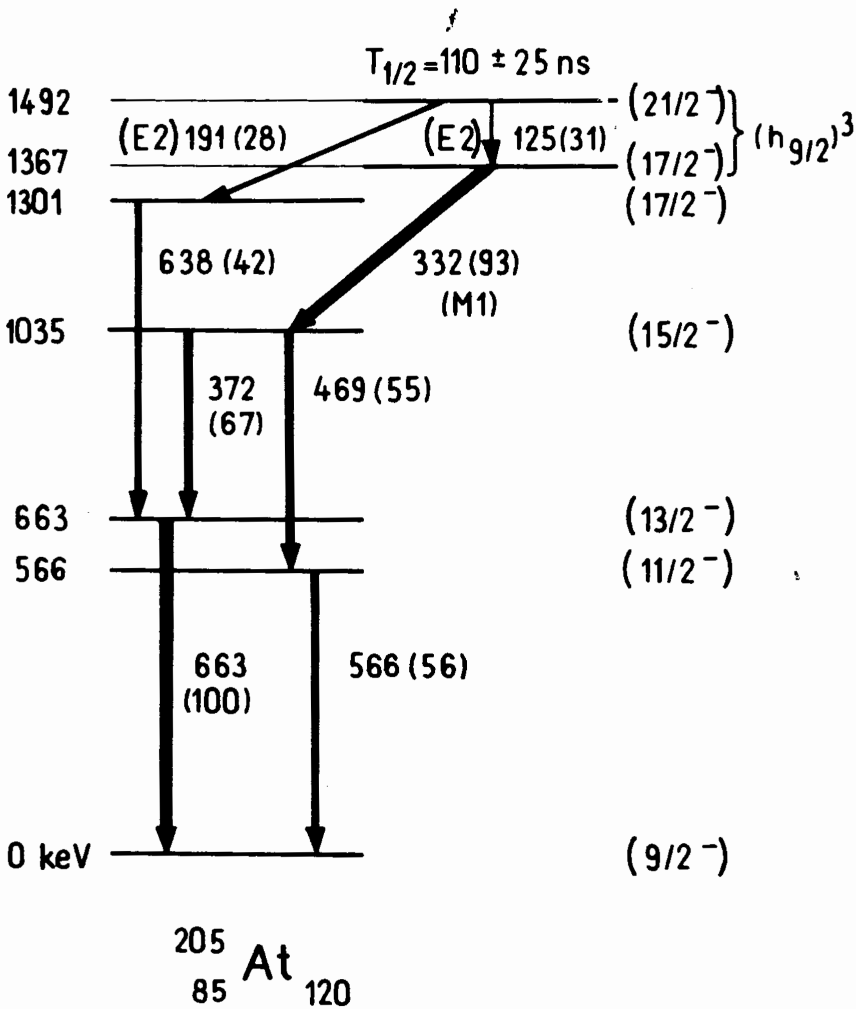

Fig. 5. Decay scheme of the isomeric state in ^{205}At . The relative γ -ray intensities are given in brackets.

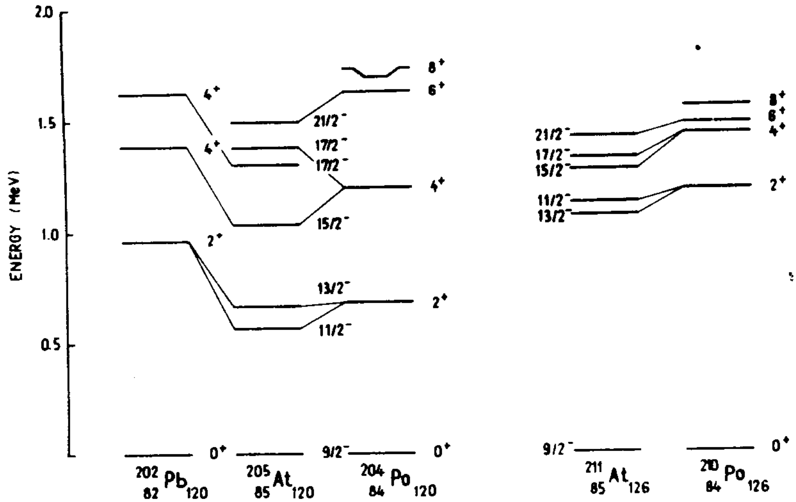

Fig. 6. Comparison of many-particle levels in the $N = 120$ and 126 isotones.