Investigation of the $[\pi h_{9/2} \nu i_{13/2}^{-1}]10^-$ Isomer in ^{206}At*

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Abstract The high-spin states of ^{206}At have been studied in the ^{197}Au (^{12}C,3n) ^{206}At reaction at ^{12}C energies from 60 to 80 MeV using technique of in-beam γ-ray spectroscopy. Measurements of γ-ray excitation functions, γ-γ-t coincidences, and γ-ray angular distributions were performed. A level scheme for ^{206}At, including a 10^- isomer with a measured half-life of 908 ± 400 ns, was established for the first time. The characteristics of the 10 isomers in doubly odd ^{206}At nuclei were stressed.

Key words isomer, half-life, two-body interaction

Isomers with $J^\pi = 10^-$ were observed systematically in the $Z = 83$, 85 doubly odd nuclei[1,2,4]. Configuration of $[\pi h_{9/2} \nu i_{13/2}^{-1}]10^-$, involving the $i_{13/2}$ neutron intruder state, was suggested to these isomers. The goal of the present investigation is to search for the corresponding isomer in ^{206}At. Before the pressent work, no excited states in ^{206}At were known.

The excited states in ^{206}At were populated via the reaction ^{197}Au (^{12}C, 3n)^{206}At. The ^{12}C beam was delivered from the 13 MV tandem accelerator at the China Institute of Atomic Energy in Beijing. In order to determine the optimum beam energy and to identify the transitions in ^{206}At, the excitation functions for producing γ rays were measured in the energy range 60—80 MeV using a 1 mg/cm^2 ^{197}Au target. Then the beam energy of 63 MeV, at which the yield of ^{206}At was a maximum, was chosen to populate the high-spin states in ^{206}At. In the later measurements, the 1 mg/cm^2 ^{197}Au target was replaced by a 10 mg/cm^2 ^{197}Au target to increase the production of ^{206}At. γ-γ-t coincidence measurement was performed at this optimum beam energy with seven BGO (AC) HPGe detectors and one intrinsic-Ge planar detector, the latter of which was used to detect low energy photons. Here, t refers to the relative time difference between any two coincident γ rays detected within ± 470 ns. A total of 78×10^6 coincidence events were recorded event by event for off-line analysis. After accurate gain matching, the γ-γ coincidence data were sorted off-line according to the energies of the two γ rays into three 4096×4096 matrixes with a prompt ($-51\text{ns} < t < 51\text{ns}$), a prior-prompt ($-470\text{ns} < t < -51\text{ns}$), and a post-prompt ($51\text{ns} < t < 470\text{ns}$) time condition, respectively. In order to obtain information on the transition multipolarities, the γ-

Received 27 October 1999
* Supported by NSFC (19575059 19635030), '100 Persons Project' of CAS, and '95' Significant Project for Basic Research of CAS (KJ95T-03)

ray angular distributions were measured at six laboratory angles between 29° and 145° relative to the beam direction. The angular distribution coefficients, as well as the relative γ- ray intensities, were extracted from least-squares fits to the normalized photopeak areas.

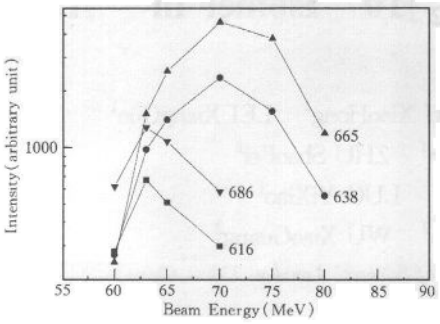

Fig. 1 Excitation functions for γ rays from the products of the reaction $^{12}C + ^{197}Au$. ▲ ^{205}At, ● ^{205}At, ▼ ^{206}At, ■ ^{206}At.

Assignment of the observed γ rays to ^{206}At was based on the γ- ray excitation functions and on the observation of γ- X and γ- γ coincidences. The excitation functions for some of the observed γ rays are shown in Fig. 1. The excitation functions for the 616 and 686 keV γ rays showa maximum at about 63 MeV ^{12}C beam energy, shifting significantly from the peaks for the γ rays of ^{205}At[3]. This along with the fact that the 616 and 686 keV γ rays were in coincidence with At K X rays measured with the planar detector, allows unambiguous assignments of these transitions to ^{206}At. Based on coincidences with these intensive γ rays of ^{206}At, some weak γ rays could also be assigned to ^{206}At.

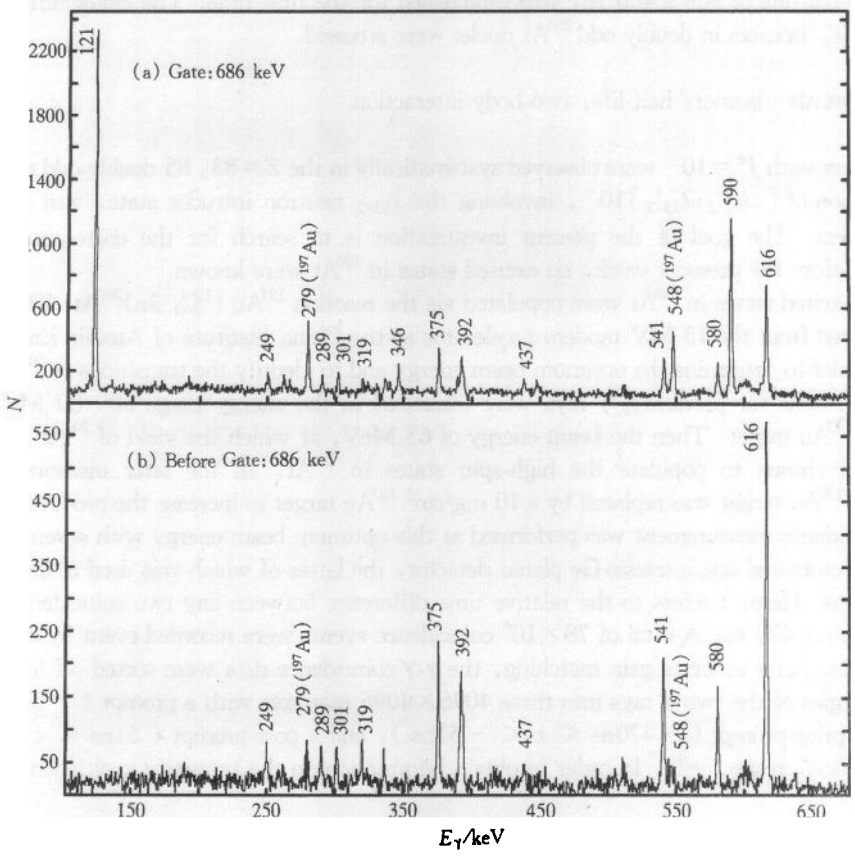

Fig. 2 γ-ray coincidence spectra gated on the 686 keV transition (a) all the γ rays in coincidence with the 686 keV transition, (b) the γ rays preceding the 686 keV transition by at least 51ns

Three gated spectra were obtained for each of the γ rays studied, under prompt, prior-

prompt, and post-prompt coincidence time condition, respectively. These spectra greatly helped to identify and locate the isomer of ^{206}At, and to place transitions into a level scheme for ^{206}At. In Fig. 2, coincidence spectra are shown as typical examples useful in the construction of the ^{206}At level scheme. Fig. 2(a) shows the spectrum for γ rays within $\pm$470 ns of the gating 686 keV γ-ray, while Fig. 2 (b) shows the spectrum for γ rays preceding the 686 keV transition by at least 51 ns. The time delay between the γ rays in Fig. 2(b) and the 686 keV transition indicated the presence of an isomeric level. A level scheme for ^{206}At, including an isomer at 807 keV, is proposed as shown in Fig. 3.

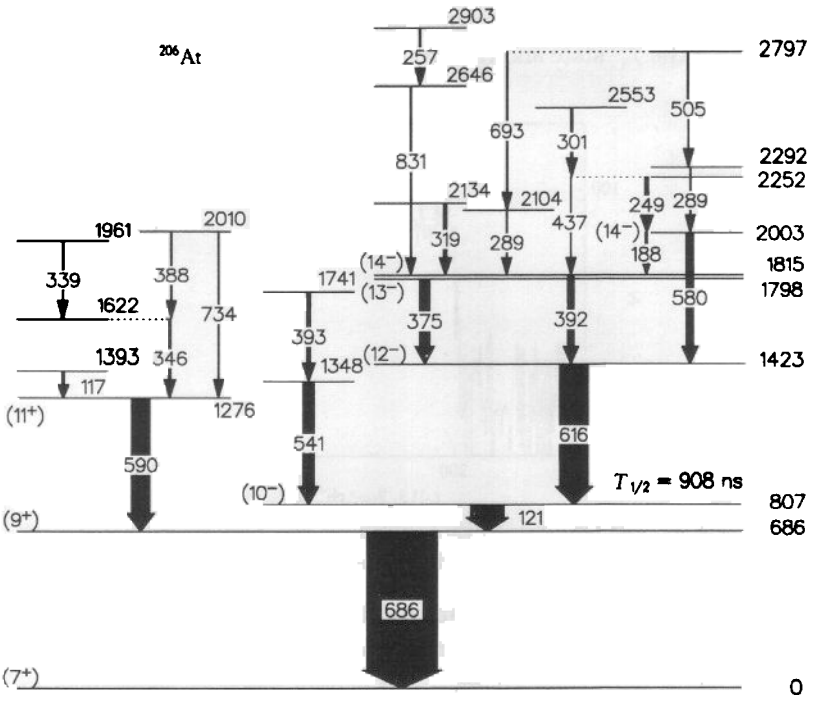

Fig. 3　The proposed level scheme for ^{206}At

The half-life of the 807 keV isomer was extracted from the γ-γ-t data. Fig. 4 shows the time distribution between the two γ-ray groups, which lie above and below the isomer, respectively. A half-life of 908 $\pm$ 400 ns was obtained for the isomer at 807 keV from an exponential fit to the curve in Fig. 4.

Two-quasiparticle excitations are expected at low-lying states in ^{206}At, namely those arising from the configurations of $\pi h_{9/2}\nu f_{5/2}^{-1}$, $\pi h_{9/2}\nu i_{13/2}^{-1}$ and so on. The $[\pi h_{9/2}\nu i_{13/2}^{-1}]$ 10^{-} isomeric states were observed systematically in the odd-odd Bi and At nuclei[1,4]. From the systematics of the 10^{-} isomers in doubly-odd At nuclei, the isomer at 807 keV in ^{206}At is most probably of the $\pi h_{9/2}\nu i_{13/2}^{-1}$ configuration. Assuming an electric dipole character for the 121 keV transition depopulating the 807 keV isomer, a reduced transition probability $B(E1)$ of 1.22×10^{-7} Weisskopf units (W. u.) could be obtained for the 121 keV transition from the measured half-life of 908 ns, indicating a hindrance of 8.19×10^{6} over the Weisskopf estimate for the 121 keV transition. This hindrance is very close to that for the corresponding $E1$ transition in ^{208}At, and is typical for $E1$ transitions in the lead region. The above argu-

ment strongly supports the assignment of the $\pi h_{9/2}\nu i_{13/2}^{-1}$ configuration to the 807 keV isomer, and suggests the spin and parity values of 9^+ to the state at 686 keV. In Ref. [1], it was suggested that the 9^+ state in ^{208}At arises from the configuration of $(\pi h_{9/2}\nu f_{5/2}^{-1})\otimes 2^+$ or $(\pi h_{9/2}^3\nu p_{1/2}^{-1})\otimes 0^+$, so the 9^+ state in ^{206}At might originate from the same configuration. From the result of the γ-ray angular distribution measurement, a quadrupole character is obtained for the 686 keV transition which feeds the lowest energy level in the level scheme. Considering the low-lying level structures in ^{204}Bi[5] and ^{208}At, the $\pi h_{9/2}\nu f_{5/2}^{-1}$ configuration may be assigned to the lowest level, to which a zero energy was set as a reference in the present work. The spin and parity value of 5^+ was assigned to the ground state in ^{206}At[6]. Maybe, the transition energy linking the 7^+ state and the ground state is too low to be observed in the present work.

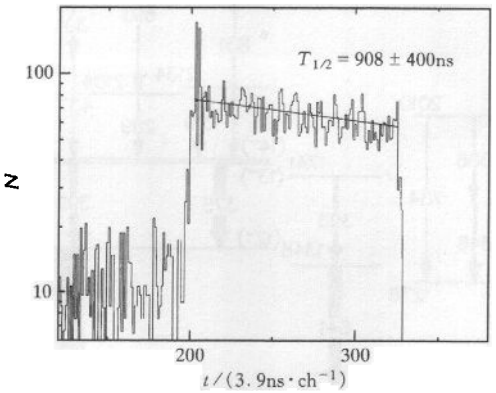

Fig. 4 The time distribution between the two γ-ray groups in ^{206}At, which lie above and below the isomer, respectively

In each of the odd-odd ^{206,208,210}At nuclei the low-lying isomeric 10^- state has a spin next to the highest in the $[\pi h_{9/2}\nu i_{13/2}^{-1}]\ J^\pi$ multiplet[1,2]. All of the states in this multiplet are two quasiparticle states with their energies and energy spacings determined by the interactions between the $h_{9/2}$ proton and the $i_{13/2}^{-1}$ neutron hole. The ground states of the odd-A At nuclei have the spin and parity $9/2^-$ determined by the $h_{9/2}$ proton. The degeneracy energy E_0 of the $[\pi h_{9/2}\nu i_{13/2}^{-1}]\ J^\pi$ multiplet in the odd-odd At nucleus (^{A}At) can then be written in terms of the binding energies of the odd-odd At nucleus (^{A}At), odd-even At nucleus ($^{A+1}$At), even-even Po nucleus (^{A}Po), and the excitation energy $E[\nu i_{13/2}^{-1}]$ of the $i_{13/2}$ neutron hole state in the even-odd Po nucleus ($^{A-1}$Po) with binding energy $B[^{A-1}\mathrm{Po}]$ in the ground state as[7]

$$E_0 = B[^A\mathrm{At}] + B[^A\mathrm{Po}] - B[^{A+1}\mathrm{At}] - B[^{A-1}\mathrm{Po}] + E[\nu i_{13/2}^{-1}], \qquad (1)$$

in the absence of a residual interaction between the $\pi h_{9/2}$ and $\nu i_{13/2}^{-1}$. Here, B is the binding energy of the particular nucleus described in the bracket. The two-body interaction then breaks the degeneracy in the multiplet giving a final energy E_J^* to each energy level in the multiplet that depends on its spin J. The energy difference $E_J = E_J^* - E_0$ is then a measure of the interaction strength between the $\pi h_{9/2}$ and $\nu i_{13/2}^{-1}$.

Such degeneracy energies E_0 and interaction energies E_J for the 10^- states in two odd-odd nuclei ^{208,210}At[1,2] have been determined and tabulated in Table 1. The average of these interaction energies E_J over the two At isotopes was assumed to be the appropriate energy for

the 10^- isomer in ^{206}At. The energies for ^{206}At given in the right column of Table 1 then resulted in an estimated excitation energy of 817 keV for the 10^- state in ^{206}At. This estimated excitation energy for the 10^- isomer in ^{206}At is in good agreement with that measured in the present work. The agreement strongly supports the assignment of the configuration of $\pi h_{9/2}\nu i_{13/2}^{-1}$ to the 10^- isomer in ^{206}At.

Table 1. The degeneracy energies E_0 of the multiplet and the two-body interaction energies E_J for odd-odd ^{210,208}At. The column headed by ^{206}At contains the corresponding energies for ^{206}At

	^{210}At	^{208}At	^{206}At
E_0	1651	1035	770
E_J	38	55	47

The authors wish to thank the staffs of the Accelerator Division of CIAE for providing ^{12}C beam.

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^{206}At 的$[\pi h_{1/2}\nu i_{13/2}^{-1}]$ 10^-同质异能态研究*

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摘要　利用能量为 60—80MeV 的^{12}C 束流，通过^{197}Au(^{12}C,3n)^{206}At 反应研究了^{206}At 核的高自旋能级结构. 用 7 台 BGO(AC)HPGe 探测器和一台用于探测低能 γ 射线的平面型 HPGe 探测器进行了 γ 射线的激发函数、γ－γ－t 符合及 γ 射线的角分布测量. 基于这些测量，首次建立了包括 25 条 γ 跃迁的^{206}At 高自旋能级纲图. 确定了一个半寿命为(908±400)ns、自旋和宇称为 10^- 的同质异能态. 基于较重的双奇核 ^{208,210}At 能级结构的系统性，对^{206}At 的 10^- 同质异能态进行了讨论.

关键词　同质异能态　半寿命　两体相互作用

1999－10－27 收稿
* 国家自然科学基金(19575059,19635030)，中国科学院"百人计划"和"九五"特别支持项目(KJ95T－03)资助