LIFETIME MEASUREMENT IN THE YRAST BAND OF ^{119}I*

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(Received August 7, 1998)

The lifetime of levels in the yrast band of ^{119}I were measured by DSAM and RDM using the ^{109}Ag(^{13}C,3n) reaction at $E = 54$ MeV. The detailed description of data analysis including the stopping power determination and estimation of side feeding time is given. A modified method of RDM data analysis — Recoil Distance Doppler Shape Attenuation (RDDSA) is used.

PACS numbers: 21.10.Re, 21.10.Tg, 27.60.+j

1. Introduction

In our previous investigation of ^{119}I [1] 15 bands have been found. Four negative parity bands named as 6,7,8 and 9 (Fig. 1) one can interpret as a result of $h_{11/2}$ quasiproton coupling to an axially asymmetric core. The aim of the present work is a further investigation of the structure of these negative parity bands in ^{119}I applying Doppler shift methods for lifetime measurement. In the present paper the measured lifetime of the levels in band 8 are presented.

Special attention was given to the analysis of the experimental data. In particular, an estimation of side feeding time for high-spin states was obtained from a precise line-shape analysis and the parameters of the nuclear stopping power formula were estimated. For the RDM-experiment the

* Presented at the International Conference "Nuclear Physics Close to the Barrier", Warszawa, Poland, June 30–July 4, 1998.

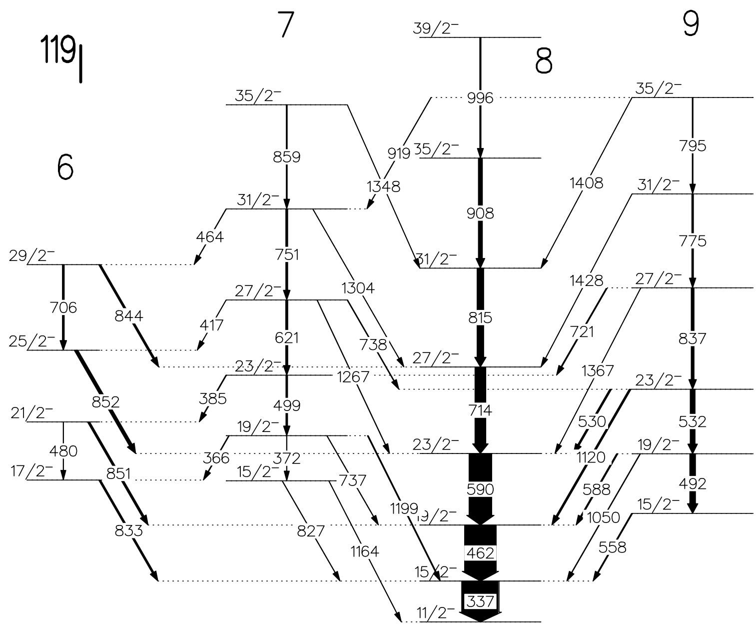

Fig. 1. Partial level scheme of ^{119}I relevant to the present analysis. The band numbering is given according to [1].

shape of γ-lines at many target-stopper distances were analyzed simultaneously. The complementary analysis of data from both experiments (RDM and DSA) allows for a determination of lifetimes for the number of excited states in band 8 and other bands in ^{119}I.

2. Experimental set-up

The experiment was carried out at the Niels Bohr Institute Tandem Accelerator Laboratory. The excited states of ^{119}I were populated via the ^{109}Ag(^{13}C,3n) reaction at a bombarding energy of 54 MeV. Two kinds of measurements were performed: the Doppler shift attenuation method (DSAM) and the recoil distance method (RDM). In the first method a thick self-supported target of 5.7 mg/cm^2 was used and in the second two self-supported thin targets of 0.82 and 0.69 mg/cm^2. In both cases the data were collected with the NORDBALL detector array completed with a plunger device. The coincidence spectra gated on γ-transitions below or above the transition of interest were analyzed. The Doppler-broadened γ-lines measured at 37° and 143° were used for the DSA-analysis. The RDM experiment was performed at 16 target-stopper distances ranging from 15μm to 8022μm.

3. Data analysis

3.1. General concepts

The analysis of the experimental line shapes was carried out using the package of computer codes COMPA, GAMMA and SHAPE [2]. The velocity and direction of recoils after the reaction were calculated (COMPA) using a statistical model of the nuclear reaction. The distribution of recoils was calculated by the Monte-Carlo method which takes into account the change of motion of the recoils after evaporation of each particle (proton, neutron or α-particle). The calculation had to be done for any depth in the target, taking into account the slowing-down process of the projectiles in the target and backing. The output file contained at least 10000 recoil histories, i.e. the initial velocity and direction of each recoil, the depth in the target in which the reaction occurred as well as the excitation energy and angular momentum of the recoil. Such an analysis did not require the use of any approximate functions for description of the recoil features in comparison to other known codes [3].

As the next step the code GAMMA simulated (by the Monte-Carlo method) the slowing-down process and multiple scattering of the recoils when they move through the target and backing. The slowing-down process was described by the expression [2, 10]:

$$\frac{d\varepsilon}{d\rho} = f_e k \varepsilon^{1/2} + \frac{f_n \varepsilon^{1/2}}{0.67\varphi_n + 2.07\varepsilon},$$

where ε and ρ are the energy and range in the Lindhard's units, k is the electronic Linhard's stopping power coefficient; f_e and f_n are the correction factors of the Lindhard's cross sections [4] for the electronic and nuclear stopping power, respectively. The additional factor φ_n introduced in [2] corrected the nuclear stopping power formula which approximates the LSS-theory [5]. When $\varphi_n = 1$ this expression approximates the energy dependence of the nuclear stopping power with an accuracy better than 5% in the energy range $0.3 \leq \varepsilon^{1/2} \leq 10$. In the present RDM experiment the target thickness was close to the recoil range. A part of the recoils was stopped in the target and the shape of stopped peak is influenced by the slowing-down process of the recoils. Therefore, the determination of the stopping power is important not only for the DSA experiment but also for the RDM experiment. Multiple scattering of the recoils is described by a model function [2] which is suitable for low-angle scattering only. The large angle scattering is calculated by dividing the recoil trajectory into 10–100 segments. This procedure gives an adequate shape of the γ-lines even when the Doppler effect is caused mainly by multiple scattering [6]. When the recoil escapes from the target into the backing or vacuum the calculations are performed in the same way, when the recoil moves through the vacuum, the vacuum is regarded as a "third material".

The γ-line shapes (depending on the velocity of the recoils) for each detector angles were stored in "time-shape" matrices with 20 time steps from 0.01 to 10 ps and from 0.1 to 1000 ps for DSA and RDM experiments, respectively. Thus, each matrix contains the complete set of γ-line shapes from fully shifted peaks to stopped ones. At the last stage of analysis the code SHAPE calculates the shape of lines for selected γ-ray energy taking into account the cascade and side feeding. This code performs a least-square fit of the calculated shape to the experimental one regarding the level lifetime as a variable parameter. The present analysis automatically takes into account a complex feeding pattern up to 13 levels and 100 decay branches feeding the investigated level. In the case of a single peak the code performs the least square fit regarding the lifetime and peak position as variable parameters. For two and more overlapping γ-peaks there is a possibility for their simultaneous analysis. The reliability of this procedure depends on the degree of overlap and closeness of corresponding level lifetimes. Examples of this procedure can be found in [7–9].

3.2. Determination of stopping power parameters

In the present work experimental information about the correction factors of the stopping power and the time of side feeding, $\tau_{\rm sf}$, was obtained. The stopping power was determined using the "*semi-thick target*" — method [10] which can be applied when the target thickness is comparable with the range of the recoils. It means that the recoils move partly through the target and partly trough the vacuum. The lifetime τ of the level should be much larger than a characteristic time, $\tau_{\rm st}$, for stopping of the recoils in the target. The kinematics of the reaction and target thickness should be known. With these conditions fulfilled the shape of the γ-line is fully determined by the slowing-down process and multiple scattering of the recoil in the target. Therefore, it is possible to get the correction factors of the stopping power even if the lifetime τ is not known. This method was applied in COULEX experiments [10] and compound nuclear reactions with α-particles and heavy ions [11–13]. In the present work the RDM target thickness (0.82 mg/cm^2) fulfil the requirement of the "semi-thick target" method. The shape of the most intensive γ-lines: 337 keV ($\tau \approx 45$ ps) and 462 keV ($\tau \approx 8$ ps) observed in a coincidence spectrum gated on the 590 keV line were analyzed at a distance of 8022 μm. The large distance between target and stopper assures that the intensity of the unshifted γ-line component from the stopper is negligible.

The value of the correction factor for the electronic stopping power was determined as $f_e = 1.27{\pm}0.07$ with the error mainly being due to the uncertainty in the target thickness (≈5%). This value agrees well with previous ones for stopping of Cd recoils in a Cd target (1.28±0.10, [10]) and for In ions in a Mo target (1.30±0.15 [14]).

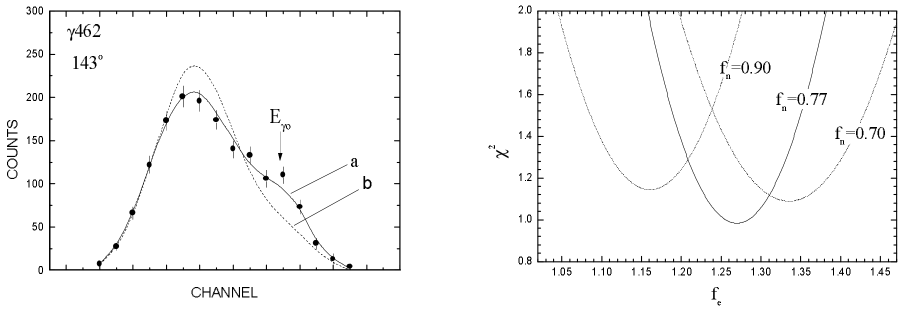

Fig. 2. Dependence of the 462 keV γ-line shape on stopping power formula parameters.The spectrum was measured at 143°, at distance 8022μm and at target thickness 0.82 mg/cm^2. Left side: (a) line shape calculated with the optimal set of parameters $f_e = 1.27$, $\varphi_n = 1$, $f_n = 0.77$; (b) line shape calculated with $f_e = 1.07$, $\varphi_n = 1$, $f_n = 0.77$. Right side: an example of fitting of electronic and nuclear stopping power parameters for φ_n=1

The correction factors for the nuclear stopping power were determined under two assumptions: (a) φ_n=1 and (b) $\varphi_n = f_n$. The result for both case (a) $f_n = 0.77 \pm 0.07$ (Fig. 2) and for case (b) $\varphi_n = f_n = 0.70 \pm 0.07$ agree with the case of stopping of Cd ions in a Cd target (0.62 ± 0.06). Both sets of correction factors agree with the systematics of stopping power [2] and give equally good description of the γ-line shapes

3.3. Treatment of side-feeding problems

The correction for the side-feeding time ($\tau_{\rm sf}$) is the most difficult problem of the DSA method unless gating from above is possible. Nevertheless, for many cases when the maximum of the entry state spin distribution is close to the spin values of the investigated states the side-feeding is composed mainly of statistical dipole transitions and the influence of stretched cascades is negligible. The $\tau_{\rm sf}$-value can be estimated as:

$$\tau_{\rm sf} \approx k_{\rm sf}(E * - E_{\rm lev})\,,$$

where $E*$ is the excitation energy of the entry states of recoils and $E_{\rm lev}$ is the energy of the observed level in MeV. The value of $k_{\rm sf}$ ≈(0.01-0.02) ps/MeV is typical for light nuclei ($A \leq 60$). The value $k_{\rm sf} \approx$ (0.02-0.03) ps/MeV is more suitable for heavier nuclei [11, 15, 16].

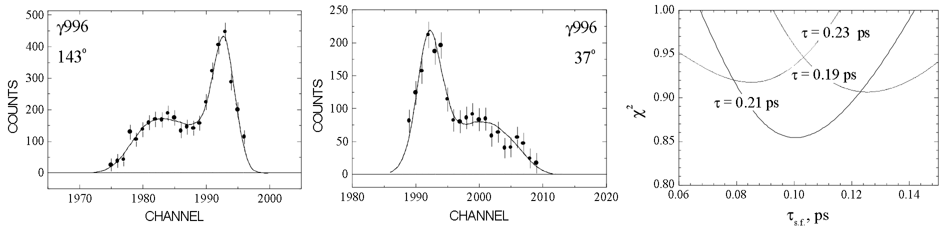

Fig. 3. Shapes of the 996 kev γ-line and examples of the χ^2 calculations for different side-feeding times $\tau_{\rm sf}$. The χ^2 is divided by the number of degrees of freedom.

The high-spin states of ^{119}I for which lifetimes were measured by DSA have (E*-$E_{\rm lev}$)$\approx$ 5-7 MeV and a small difference of the angular momentum from entry-states. Therefore, the stretched cascades are absent and $k_{\rm sf}$ not exceeds 0.020-0.025 ps/MeV. When the lifetime is comparable with $\tau_{\rm sf}$ the line shape becomes sensitive to the later one and it gives in some cases an opportunity to determine the $\tau_{\rm sf}$ value [17]. For this purpose in the present work the intense γ-lines 996, 908 and 815 keV in band 8 were analysed. The results of the $\tau_{\rm sf}$ evaluation for 996 keV line is shown in Fig. 3 with examples of the γ-line shape. The value $k_{\rm sf}$ =0.020 $\pm$ 0.005 ps/MeV was adopted. Examples of lifetimes measured by DSAM are presented in Table I.

TABLE I

Lifetimes values(in picoseconds) measured in the present experiment for band 8. E_γ is the transition energy used for lifetime determination.

$J_i - J_f$	E_γ(keV)	RDDSA	DSA
15/2–11/2	337	44.5±3.0	
19/2–15/2	462	7.8±0.7	
23/2–19/2	590	2.5±0.4	2.2(+0.6;-0.4)
27/2–23/2	714		0.89±0.15
31/2–27/2	815		0.42±0.05
35/2–31/2	908		0.29±0.04
39/2–35/2	996		0.21±0.04

3.4. DSA analysis of RDM-experiment — RDDSA method

The main feature of the analysis of the present RDM-experiment consists in precise analysis of γ-line shapes which is regarded as a particular case of DSA. This method was used instead the usual analysis of decay curves. It was previously applied for α-particle induced reactions when shifted and unshifted components of γ-lines were not well resolved as well as for heavy ion induced reactions. In the present work the γ-lines from all distances sensitive to lifetimes were analyzed simultaneously using as the fitting parameters the lifetime of the state studied and lifetimes of states lying above.

This method (called RDDSA) allows to increase the number of states for which lifetime values can be estimated. Since in this method shifted and unshifted peaks are regarded as components of one γ-line, even for cases when both components overlap, it is possible to get reliable lifetime values. For low-energy γ-lines where both components overlap and for the cases where target thickness is comparable with the recoil range the RDDSAM is the only possible method. Using a thick target increases the intensity of the radiation and improves the experimental conditions. The asymetric shape of the shifted component can be calculated exactly at a large target-stopper distances. As an example of such a calculation the 462 keV lineshape is shown in Fig. 2. The unshifted component of this γ-line is caused by recoils which are stopped in the target (not in the stopper).

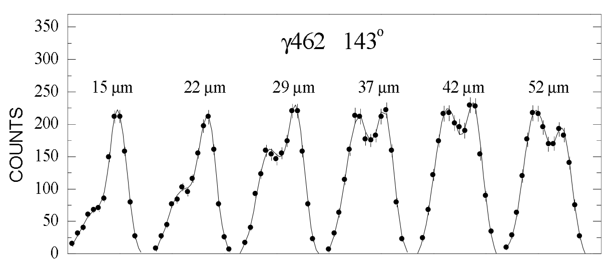

Fig. 4. Shapes of the 462 keV γ-line for different target-stopper distances and for a target thickness 0.82 mg/cm^2. Solid lines are results of RDDSA fits. Spectra are gated on the 590 kev γ-transition.

The examples of the 462 keV line shape at some distances sensitive for measured lifetimes are shown in Fig. 4. The results of RDDSAM are presented in Table I. One can see that the lifetime for the 590 keV γ-transition obtained from both experiments are in a good agreement. The complete experimental data including lifetimes evaluated for other bands in ^{119}I will be published elsewhere.

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