LEVEL STUDIES OF ^{71}Ge VIA $(p,n\gamma)$ REACTION AND DENSITY OF DISCRETE LEVELS IN ^{71}Ge

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Abstract

The excited states of ^{71}Ge have been investigated via the ^{71}Ga $(p,n\gamma)$ ^{71}Ge reaction with proton beam energies from 2.5-4.3 MeV . The parameters of nuclear level density formula have been determined from extensive and complete level scheme for ^{71}Ge . The Bethe formula for the back-shifted Fermi gas model and the constant temperature model are compared with the experimental level densities .

Keywords: Excited states; Level density; Level scheme; Proton beam; Bethe formula; Constant temperature model .

1. Introduction

Information about the ^{71}Ge nucleus has been obtained from experimental studies by β-decay[1], $(p,n\gamma)$[2], $(\alpha,n\gamma)$ reactions[3] as well as neutron transfer (p,d)[4] and (d,p) reaction studies[5]. On the other hand, In all statistical theories the nuclear level density is the most characteristic quantity and plays an essential role in the study of nuclear structure.

In this work we have provided additional experimental information about existing level structure of ^{71}Ge through the $(p,n\gamma)$ reaction and then determined nuclear level density parameters of the Bethe formula and constant temperature model for ^{71}Ge.

2. Experimental Procedure

A thick self-supporting pellet of spectroscopically pure natural Ga was used as a target. The proton beam of 2.5-4.3 MeV energies was bombarded to excite the levels of ^{71}Ge through the $^{73}Ga(p,n\gamma)$ reaction (Q-value = - 1.017 MeV). The target was placed at an angle of 45° with respect to the beam direction and was thick enough to stop incident protons. The angular distributions were measured at 0°, 30°, 45°, 55°, 75° and 90°. The γ-rays were detected with a 70 cm^3 coaxial HPGe detector with a resolution of 1.9 keV for the 1332 keV γ-ray of ^{60}Co. The excitation functions of various γ-rays have been measured at 55° in the range of 2.5-4.3 MeV beam energies to ascertain that the channel of the compound decay is dominant as compared to the coulomb excitation at the incident proton energy of 4.3 MeV. The other details of the experimental procedure are given in our earlier publications[6,7].

3. Data Analysis

The gamma-ray spectra were analyzed using the computer code PEAKFIT [8].A typical gamma-ray spectrum at 90° for an incident proton energy of 4.3 MeV is given in our earlier publication [7]. The excitation functions of all the observed gamma-rays were analyzed carefully as a function of energy and those from the $(p,n\gamma)$ reaction were easily identified with a characteristic rise above their threshold energy. The relative branching ratios used for further analysis are the weighted average of the respective values at 4.0 and 4.3 MeV bombarding energies.

The extraction of multipole mixing ratios of the observed transitions and the assignment of spin values to the excited levels were made from the χ^2-fitting of angular distribution data at 4.3 MeV proton beam energy. The optical model parameter sets given by Perey and Perey [9],which are based on the results of Perey [10] for protons and Wilmore and Hodgson [11] for neutrons, were used to calculate the transmission coefficients. Besides the observed neutron channel, all known $(p,p'\gamma)$ channels and $(p,n\gamma)$ channels were included as competing channels. The Moldauer width fluctuation correction [12] was also taken into account. The typical experimental angular distributions of some of the observed transitions together with theoretical curves for different possible spins of the levels and the respective χ^2- fitting is given in our earlier publication [7]. The 0.1% confidence limit was used to exclude unacceptable spins and δ values. The experimental values of the A_2 and A_4 coefficients along with the multipole mixing ratios (δ) are given in Table 1.

Table 1. *Level energies and The results of the angular distribution measurements in* ^{71}Ge *.*

Transitions	*Gamma rays (keV)*	$J_i^{\pi} \rightarrow J_f^{\pi}$	*Multipole mixing ratios*	A_2	A_4
525.1→198.4	*326.7*	$\frac{5}{2}^{+} \rightarrow \frac{9}{2}^{+}$	$0.10^{+0.05}_{-0.02}$	*-0.009(5)*	*0.010(5)*
589.8→198.4	*391.3*	$\frac{7}{2}^{+} \rightarrow \frac{9}{2}^{+}$	$-0.11^{+0.03}_{-0.02}$	*0.004(6)*	*-0.017(6)*
708.0→0	*708.0*	$\frac{3}{2}^{-} \rightarrow \frac{1}{2}^{-}$	$-0.61^{+0.78}_{-2.2}$	*-0.115(12)*	*0.060(12)*
747.1→175.0	*572.1*	$\frac{5}{2}^{-} \rightarrow \frac{5}{2}^{-}$	$-0.3^{+0.05}_{-0.08}$	*0.026(22)*	*-0.027(22)*
831.1→525.1	*306.0*	$\frac{3}{2}^{-} \rightarrow \frac{5}{2}^{+}$	$0.1^{+0.05}_{-0.02}$ *or* $-11.7^{-3.4}_{+4.4}$	*-0.003(20)*	*-0.016(20)*
831.1→0	*831.1*	$\frac{3}{2}^{-} \rightarrow \frac{1}{2}^{-}$	*-0.5±0.1*	*-0.114(13)*	*0.032(13)*
1026.6→499.8	*526.6*	$\frac{5}{2}^{-} \rightarrow \frac{3}{2}^{-}$	$-0.75^{+0.14}_{-0.12}$	*-0.173(13)*	*-0.006(13)*
1026.6→0	*1026.6*	$\frac{5}{2}^{-} \rightarrow \frac{1}{2}^{-}$	*12.5±0.25*	*0.359(75)*	*-0.237(75)*
1096.0→175.0	*921.0*	$\frac{3}{2}^{-} \rightarrow \frac{5}{2}^{-}$	$-1.0^{+0.57}_{-0.80}$	*-0.326(25)*	*0.093(25)*
1212.2→499.8	*712.5*	$\frac{5}{2}^{-} \rightarrow \frac{3}{2}^{-}$	$-0.49^{+0.09}_{-0.26}$ *-1.54±0.2*	*0.037(56)*	*-0.060(64)*
1298.6→0	*1298.6*	$\frac{3}{2}^{-} \rightarrow \frac{1}{2}^{-}$	$-0.61^{+0.74}_{-1.8}$	*-0.154(20)*	*0.090(30)*
1377.8→1096.0	*281.8*	$\frac{5}{2} \rightarrow \frac{3}{2}^{-}$	*2.9±0.1*	*0.103(950)*	*0.005(950)*
1406.5→175.0	*1231.6*	$\frac{5}{2}^{-} \rightarrow \frac{5}{2}^{-}$	$0.49^{+0.15}_{-0.11}$	*0.078(98)*	*0.011(103)*
1406.5→499.8	*906.3*	$\frac{5}{2}^{-} \rightarrow \frac{3}{2}^{-}$	*-0.2±0.1*	*-0.095(128)*	*0.002(139)*
1422.1→175.0	*1247.1*	$\frac{9}{2}^{-} \rightarrow \frac{5}{2}^{-}$	*0.1±0.07*	*0.230(63)*	*-0.009(63)*
1558.8→525.1	*1033.7*	$\frac{5}{2}^{+} \rightarrow \frac{5}{2}^{+}$	$0.48^{+0.26}_{-0.18}$	*0.072(39)*	*0.005(44)*
1566.1→589.8	*975.5*	$\frac{9}{2}^{+} \rightarrow \frac{7}{2}^{+}$	$-1.54^{+0.22}_{-0.16}$	*-0.177(98)*	*-0.004(108)*
1743.3→808.0	*935.6*	$\frac{3}{2}^{-} \rightarrow \frac{1}{2}^{-}$	$-0.5^{+0.4}_{-0.8}$	*-0.055(129)*	*0.005(143)*
1743.3→0	*1743.3*	$\frac{3}{2}^{-} \rightarrow \frac{1}{2}^{-}$	$-11.59^{+4.3}_{-3.5}$	*0.015(30)*	*-0.002(31)*

4. Statistical formula

The nuclear temperature T can be defined by the nuclear level density $\rho(E)$ *[13] .*

$$\frac{1}{T} = \frac{d}{dE} Ln\rho(E). \qquad (1)$$

Integration yields the constant temperature Fermi gas formula [14]

$$\rho(E) = \frac{1}{T}\exp(\frac{E-E_0}{T}). \qquad (2)$$

The nuclear temperature T and the ground state back shift E_0 *can be determined with experimental data .*

The Bethe formula of the level density [15] for the back-shifted Fermi gas model [16,17] can be written

$$\rho(E) = \frac{e^{2\sqrt{(E-E_1)}}}{12\sqrt{2}\sigma\ a^{1/4}(E-E_1)^{5/4}}. \qquad (3)$$

In this case the level density parameter a and the ground state back shift E_1 *are obtained by a fit to experimental results. The distribution of spins J is determined by the spin cut-off parameter* σ^2 *[14,15] .*

$$f(J) = e^{-J^2/2\sigma^2} - e^{-(J+1)^2/2\sigma^2}$$
$$\approx \frac{2J+1}{2\sigma^2}\exp[-(J+\frac{1}{2})^2 \Big/ 2\sigma^2]. \qquad (4)$$

With this spin distribution the spin-dependent level density is

$$\rho(E,J) = \rho(E) f(J). \qquad (5)$$

σ^2 *is related to an effective moment of inertia* I_{eff} *and to the nuclear temperature T [13,16].*

$$\sigma^2 = \frac{I_{eff}T}{\hbar^2}. \qquad (6)$$

The nuclear moment of inertia for a rigid body is $I_{Rigid} = \frac{2}{5}MR^2$ *(where M=A, the amu nuclear mass; R=1.25*$A^{1/3}$ *fm, the nuclear radius) resulting in [16]*

$$\sigma^2 = 0.0150A^{5/3}T. \qquad (7)$$

Gilbert and Cameron [14] calculated the spin cut-off parameter for the Bethe formula with reduced moment of inertia,

$$\sigma^2 = 0.0888A^{2/3}\sqrt{a(E-E_1)}\ . \qquad (8)$$

5. Fit of level density formulae

Each of the models considered has two free parameters , which were fitted to the above-mentioned data of ^{71}Ge and the parameters a and E_1 of the level density formula of Bethe and the parameters T and E_0 of the constant temperature model have been determined by least square fits to the experimental data (Fig. 1)

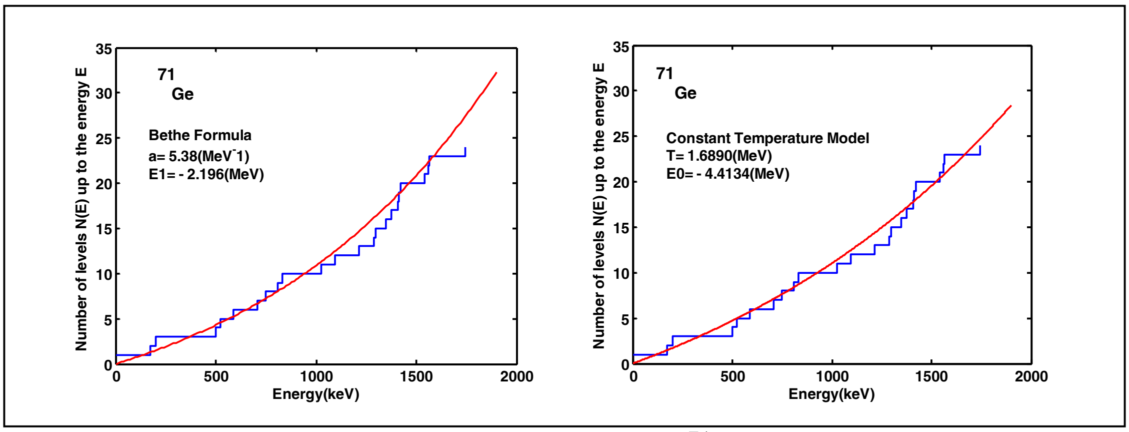

Fig. 1. *Plot of the number of levels N(E) up to the energy E for ^{71}Ge together with fitted curves calculated* with the Bethe and constant temperature formulae.

Furthermore, spin cut-off parameter σ^2 deduced from fits of Eq. (4) to the number N(J) of levels with a particular spin (J) value (see Fig. 2) and the values of I_{eff} / I_{Rigid} are presented in table 2.

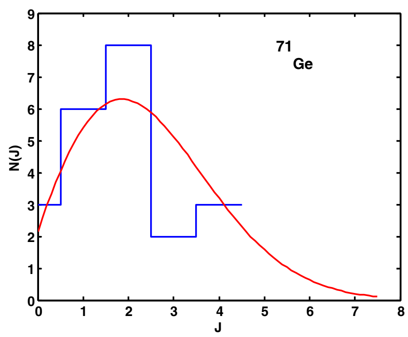

Fig. 2. *The spin distribution of low-lying states. The histograms is experimental data(Data from Table 1), the curve is the description by the statistical distribution with $\sigma^2 = 5.54$.*

Table 2. *Deduced spin cut-off parameter σ^2 and effective moment of inertia I_{eff} .*

σ^2	*U (MeV)*	I_{eff} / I_{Rigid}, ($r_0 = 1.25\, fm$)
5.54	***0.1984***	***1.0767***
	0.8311	***0.6638***
	1.4221	***0.5358***

6. Conclusion

The purpose of the present study was to provide additional experimental information on the existing level structure of ^{71}Ge *through* $(p,n\gamma)$ *reaction .We have measured the* γ*-ray energies, branching ratios and multipole mixing ratios of various transitions in* ^{71}Ge*. Complete and extensive nuclear level scheme of* ^{71}Ge *provide a sufficient basis for statistical interpretations of low energy nuclear level schemes and for various tests of statistical theories. The level density near the ground state is well reproduced by the Bethe formula and by the constant temperature formula if two parameters are fitted. Then spin cut-off parameter and effective moment of inertia of* ^{71}Ge *have been determined from analysis of the experimental data on spins of low-lying states. It isn't confirmed the rigid body value of effective moment of inertia.*

7. References

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