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Resonance Scattering of Bremsstrahlung by ^{6}Li, ^{11}B and ^{27}Al†

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The bremsstrahlung beam from a 5 MeV electron linear accelerator was used to excite and study low-lying levels in ^{6}Li, ^{11}B and ^{27}Al. A self-absorption method was used to find the widths Γ of these levels. The following level widths are obtained: $\Gamma=(6.5^{+2.4}_{-1.7})$ eV for the 3.56 MeV level in ^{6}Li; $\Gamma=(0.23\pm0.09)$ eV for the 2.12 MeV level, and $\Gamma=(0.53\pm0.21)$ eV for the 4.44 MeV level in ^{11}B. For the 2.98 MeV level in ^{27}Al, the level width is found to be $\Gamma=(0.10\pm0.04)$ eV assuming that the lower energy member of the doublet at 3 MeV is excited.

§ 1. Introduction

The investigation of transition widths of nuclear levels is useful as a means of checking nuclear models. Among the methods used to determine nuclear transition widths is the nuclear resonance fluorescence technique which has been reviewed by Metzger.[1] The nuclear resonance fluorescence by means of bremsstrahlung suggested by Schiff[2] has been used to study the width of the level, especially highly excited levels of C,[3] Mg and Si[4] using betatron beams. By using the electron linear accelerator, a stronger γ-ray source is available, and one can reasonably expect to be able to study small cross sections with high accuracy. Seward[5] measured spectra of resonance scattering by several nuclei and Vanhyse and Vanpraet[6,24] obtained the lifetimes of low-lying levels of ^{11}B and ^{27}Al using the beam from the electron linear accelerator.

The present experiment has been carried out to obtain the transition widths of low-lying levels in ^{6}Li, ^{11}B and ^{27}Al using the Tohoku University 5 MeV electron linear accelerator. The experimental arrangement is given in § 2, in § 3 we describe the method of the analysis of data, and the result and discussion for ^{6}Li, ^{11}B and ^{27}Al are described in § 4.1∼§ 4.3, where the results are compared with other experimental results and with theoretical calculations.

§ 2. Experimental Arrangement

The experimental arrangement is shown in Fig. 1. Electrons from the linear accelerator were momentum analyzed by a double deflection magnet system[7] and hit a thin lead radiator to produce bremsstrahlung. Transmitted electrons

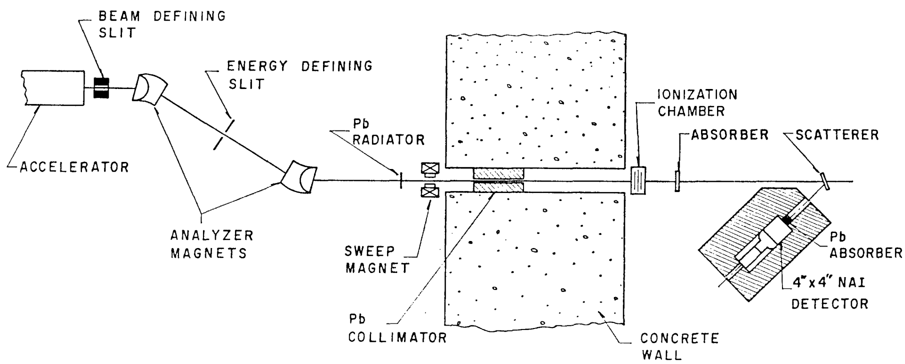

Fig. 1. Experimental arrangement.

were swept by a magnet, and electron-free collimated γ-rays hit against a scatterer. The spectrum of scattered photons was obtained by a 4-in. diam. 4-in. long NaI (Tl) crystal at an angle of 135° to the primary beam and an RCL 250-channel pulse-height analyzer. In front of the crystal, a 2.5 cm thick lead absorber was used to absorb low-energy photons. In order to find the level width, the transmission was obtained

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from the number of photons scattered with and without an absorber in the primary beam. A thin ionization chamber was used to normalize each measurement.

The linear accelerator was operated with a 1.5 μ sec pulse width and a repetition rate of 150 Hz per second. The resolving power of the analyzer system was set at about 4% during this experiment.

§ 3. Analysis of Data

The transmission ρ is defined as the ratio of resonant scattered photons with the absorber placed in the primary beam to the ones without absorber, and is able to be expressed by[8]

$$\rho=e^{-\sigma'_e Nd}=\frac{\int_{\rm res}\frac{\sigma_n(E)}{\sigma_n(E)+2\sigma_e'}\left\{1-\exp\left[-(\sigma_n(E)+2\sigma_e')\frac{NT}{\cos\alpha}\right]\right\}\exp(-\sigma_n(E)Nd)\mathrm{d}E}{\int_{\rm res}\frac{\sigma_n(E)}{\sigma_n(E)+2\sigma_e'}\left\{1-\exp\left[-(\sigma_n(E)+2\sigma_e')\frac{NT}{\cos\alpha}\right]\right\}\mathrm{d}E}\,. \qquad (1)$$

In this expression, $\sigma_n(E)$ is the nuclear absorption cross section of photons of energy E, σ_e' the electronic absorption cross section[9] at the resonance energy multiplied by N'/N, N' the number of molecules per cm^3, N the number of nuclei of the resonant variety per cm^3, T and d thicknesses of scatterer and absorber, respectively, and α the angle that both the incident and the scattered beams make with the normal to the target. The cross section $\sigma_n(E)$ is given by the Doppler broadened Breit-Wigner expression:[10]

$$\sigma_n(E)=\frac{\sigma_0}{2(\pi t)^{1/2}}\int_{-\infty}^{+\infty}\frac{\exp[-(x-y)^2/4t]}{1+y^2}\mathrm{d}y\,, \qquad (2)$$

where $x=2(E-E_r)/\Gamma$, $t=(\Delta/\Gamma)^2$ and $\sigma_0=4\pi\lambda\!\!\!^{-2}\Gamma_\gamma/\Gamma\cdot(2I_e+1)/2(2I_i+1)$. Here, I_e and I_i are the spins of the excited state and initial state, respectively, E_r is the resonance energy, $\lambda\!\!\!^{-2}$ the corresponding wave length divided by 2π, Γ_γ/Γ the branching ratio, and Δ the Doppler width. The Doppler width is given by

$$\Delta=E(2kT_{\rm eff}/Mc^2)^{1/2}\,, \qquad (3)$$

where c is the velocity of light, k the Boltzmann constant and M the nuclear mass contributed to the resonance. The effective temperature $T_{\rm eff}$ is given by

$$T_{\rm eff}/T=3(T/\theta)^3\int_0^{\theta/T}t^3\left(\frac{1}{e^t-1}+\frac{1}{2}\right)\mathrm{d}t\,, \qquad (4)$$

where T is the room temperature and θ is the Debye temperature of the target. Finally, eq. (1) is able to calculate as a function of $t=(\Delta/\Gamma)^2$ only. The numerical integration has been done using a computer.

§ 4. Results and Discussion

4.1 ^6Li

The scatterer and absorber were made of LiH powder contained in thin plastic boxes, and had area densities of 3.3 and 2.6 g/cm^2, respectively. A dummy scatterer and absorber of carbon powder were used to eliminate nonresonant scattering. The yields for the following combinations of scatterers and absorbers were measured:

$C(1)$ LiH scatterer with C absorber;
$C(2)$ LiH scatterer with LiH absorber;
$C(3)$ C scatterer with C absorber.

In each case it was irradiated by 5 MeV bremsstrahlung. The pulse-height distribution of γ-rays

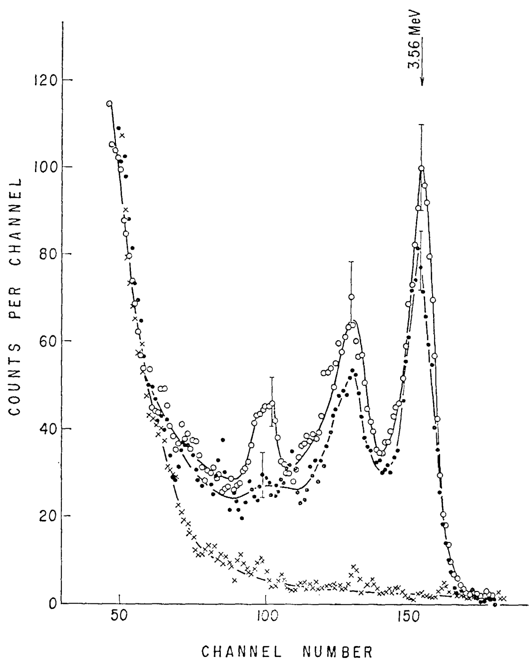

Fig. 2. Pulse-height distribution of γ-rays scattered from LiH and C. The full circles, dots and crosses represent LiH scatterer with C absorber, LiH scatterer with LiH absorber and C scatterer with C absorber, respectively.

scattered from the samples is shown in Fig. 2. In the figure the circle, dot and cross represent $C(1)$, $C(2)$ and $C(3)$, respectively. The highest peak corresponds to photo-peak of 3.56 MeV γ-rays of the transition from the 2nd excited state to the ground state in ^{6}Li. Other peaks correspond to one quantum and two quanta escape peaks of 3.56 MeV γ-rays.

The transmission was obtained from $T=(C(2)-C(3))/(C(1)-C(3))$, where the yield of photons with the energy higher than 1.8 MeV was used for the transmission of 3.56 MeV γ-rays. The transmission was $T=81.3\pm2.9\%$ where the error is statistical only.

The following numerical values were used in eq. (1): the electronic cross section of LiH at 3.56 MeV $\sigma_e=0.422$b, a peak absorption cross section $\sigma_0=64.3$b, the Doppler width $\Delta=11.8$ eV, which was obtained from a Debye temperature $\theta=620°$ estimated from a specific heat at low temperature.

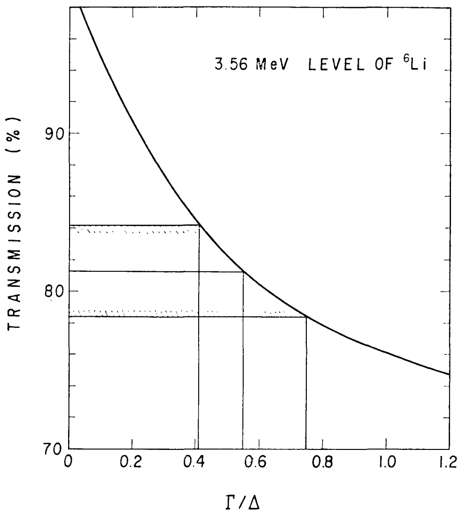

Fig. 3. The transmission as a function of Γ/Δ. The uncertainties of the observed one are indicated by hatching.

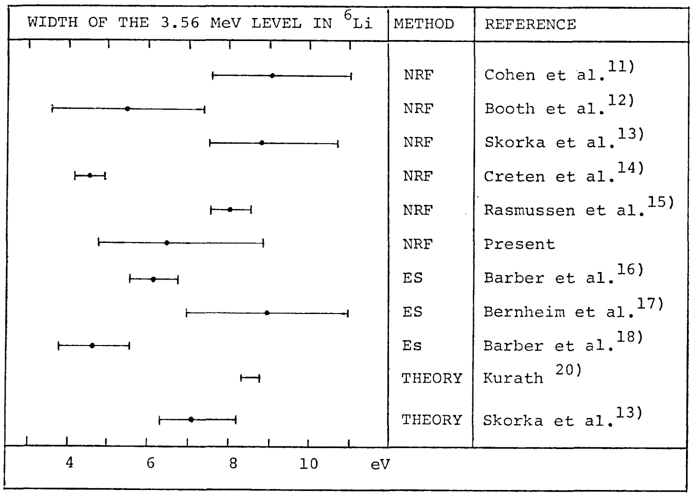

Fig. 4. Results of the width of the 3.56 MeV level in ^{6}Li measured by different authors. NRF denotes nuclear resonance fluorescence and ES denotes electron scattering. Lower two rows represent the theoretical results.

Figure 3 shows the calculated transmission curve and the experimental result with its uncertainties indicated between the hatching. From Fig. 3, the ratio Γ/Δ is obtained to be $\Gamma/\Delta=0.55^{+0.20}_{-0.14}$. Assuming $\Delta=11.8$ eV, we obtain a width $\Gamma=6.5^{+2.4}_{-1.7}$ eV. This corresponds to a mean lifetime of $\tau=(1.0^{+0.4}_{-0.3})\times10^{-16}$ sec.

Figure 4 shows the summary of the results for the 3.56 MeV level (which is a similar one presented in ref. 13). In nuclear resonance fluorescence (NRF), a self-absorption method was used except for the case of Booth *et al.*[12] who used a scattering method. This level was also studied by electron scattering (ES) including 180° scattering.[18]

As shown in Fig. 4, the results obtained by different method lie between 5 and 9 eV. The present result $\Gamma=6.5^{+2.4}_{-1.7}$ eV is in agreement with these ones. The transition from the 3.56 MeV state to the ground state is a pure $M1$ transition since J^π of these states are 0^+ and 1^+. By the single particle model, the radiative width is given to be $\Gamma(M1)=0.95$ eV, which is a factor of 7 smaller than the experimental value. The p shell nuclei such as Li and B have been well explained by the intermediate coupling model.[19] Kurath[20] calculated the radiative width of the 3.56 MeV level using intermediate coupling and obtained a value of 8.35∼8.8 eV which is in good agreement with the present result.

4.2 ^{11}B

The scatterer and absorber were natural boron powder packed in aluminium containers and their thicknesses were 0.89 and 1.0 g/cm^2, respectively. Also carbon powder was used as a dummy scatterer. The targets were irradiated by 5 MeV bremsstrahlung. The pulse-height distribution of γ-rays scattered from B and C is shown in Fig. 5. In the figure, higher energy peaks correspond to a photo and one quantum escape peaks of 4.44 MeV γ-ray of the transition from the 2nd excited state to the ground state. A lower energy peak is a photo peak of 2.12 MeV γ-ray of the transition from the 1st excited state to the ground state.

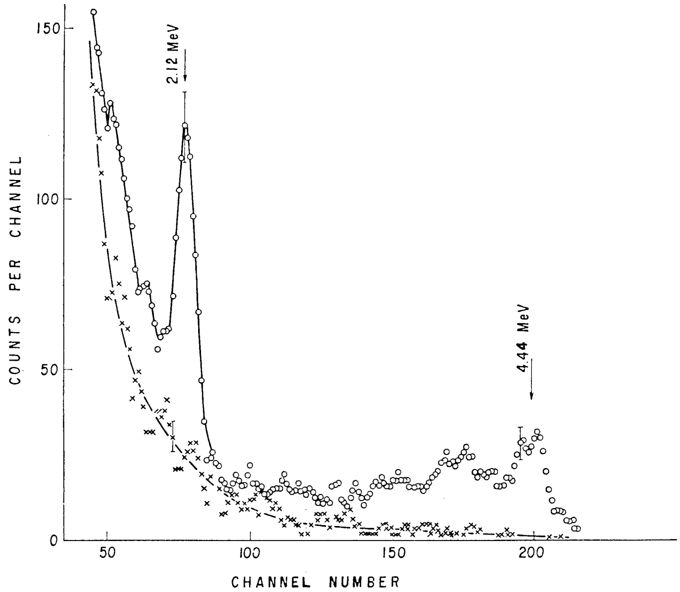

Fig. 5. Pulse-height distribution of γ-rays scattered from B and C.

The transmission for 2.12 MeV γ ray obtained from photo peak only was $T=76\pm7\%$. For 4.44 MeV γ ray the transmission obtained from the yield of photons with energies higher than 3 MeV was found to be $T=81\pm6\%$.

For the 2.12 MeV level, the following values were used to calculate a transmission: $\sigma_e=0.707$b at 2.12 MeV and $\Delta=6.03$ eV obtained from a Debye temperature $\theta=1100°$ of B.[25] The calculated transmission and the experimental one are shown in Fig. 6. From the figure, Γ/Δ is found to be 0.038 ± 0.015. Using $\Delta=6.03$ eV, we obtain a width $\Gamma=0.23\pm0.09$ eV for the 2.12 MeV level. This corresponds to a mean lifetime of $\tau=(2.9\pm1.1)\times10^{-15}$ sec.

The summary of the results for the 2.12 MeV level is shown in Fig. 7. Ajzenberg-Selove and Lauritzen gave the mean value of existing results $\Gamma=0.122\pm0.005$ eV. The present result $\Gamma=0.23$

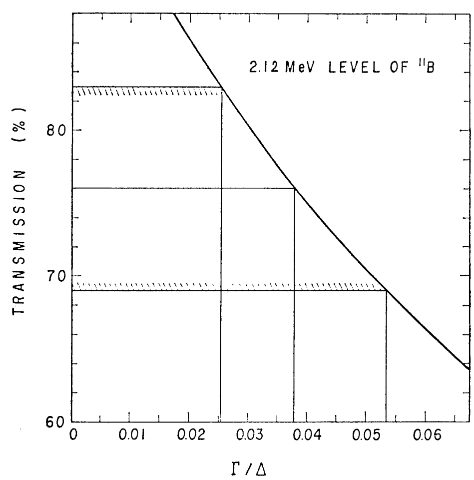

Fig. 6. The transmission as a function of Γ/Δ.

±0.09 eV is larger than the above value, but agrees well with $\Gamma=0.22\pm0.06$ eV obtained by

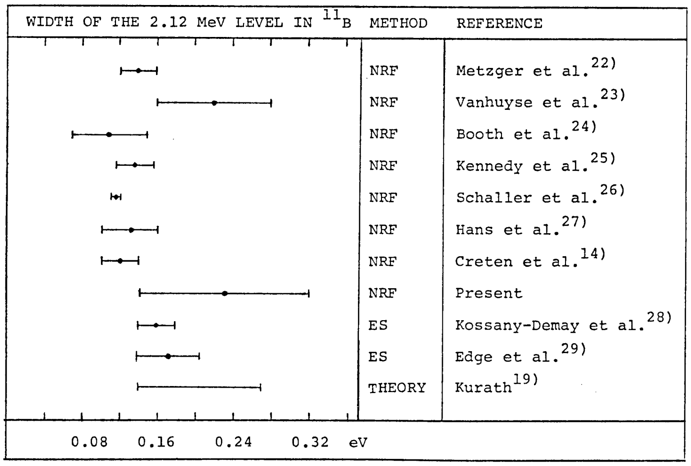

Fig. 7. Results of the width of the 2.12 MeV level in ^{11}B measured by different authors.

Vanhuyse and Vanpraet. The single particle value for this transition is $\Gamma_w(M1)=0.21$ eV, while the radiative width calculated from the intermediate coupling model[19] is $\Gamma=0.14\sim0.17$ eV. Both the values calculated are consistent with the experimental value.

For the 4.44 MeV level, $\sigma_e=0.472$b at 4.44 MeV and $\Delta=12.6$ eV were used to calculate a transmission. Figure 8 shows the calculated transmission curve and experimental one. From the figure, Γ/Δ is found to be 0.040 ± 0.019. Using $\Delta=12.6$ eV, we obtain a width $\Gamma=0.53\pm0.21$ eV. This corresponds to a mean lifetime of $\tau=(1.2\pm0.5)\times 10^{-15}$ sec. For the 4.44 MeV level, the self-absorption method of resonant γ rays was employed by Cohen *et al.*,[8] Rasmussen *et al.*[30] and Hans *et al.*[27] The electron scattering measurements were carried out by Kossany-Demay and Vanpraet[28]

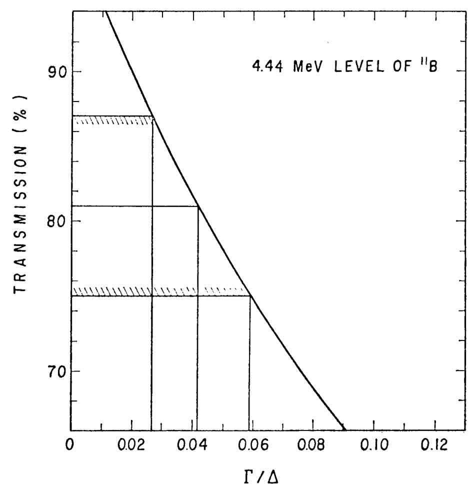

Fig. 8. The transmission as a function of Γ/Δ.

and Spamer and Artus.[31] The results are around of the mean value $\Gamma=0.54\pm0.05$ eV given by Ajzenberg-Selove and Lauritsen.[21] The present result $\Gamma=0.53\pm0.21$ eV agrees well with the mean value. The single particle value for this transition is $\Gamma(M1)=0.26$ eV. The radiative width calculated by using the intermediate coupling model is 0.34 eV which is also smaller than the experimental one for this transition.

4.3 ^{27}Al

A scatterer and absorber of Al had area densities of 5.46 and 8.20 g/cm^2, respectively, and were bombarded by 3.5 MeV bremsstrahlung. The pulse-height distributions of γ-rays from Al and from a dummy scatterer of Mg are shown in Fig. 9. The two peaks about at 72 and 113 channels correspond to 2.2 MeV γ-rays of the transition from the 3rd excited state to the ground state and 3 MeV γ-rays from the doublet state to the ground state, respectively. The transmission of $T=66\pm10\%$ was obtained from the yield of the photo peak for the doublet state at 3 MeV.

The following values were used to calculated a transmission: $\sigma_0=183.6$ b assuming of the excitation of the 2.98 MeV level ($J^\pi=3^+/2$), and of a branching ratio $\Gamma_\gamma/\Gamma=1$,[32] $\sigma_e=1.58$b and $\Delta=4.38$ eV calculated from the Debye temperature $\theta=375°$. The result is shown in Fig. 10. From the figure a value of Δ/Γ is found to be $0.022^{+0.010}_{-0.003}$. Using $\Delta=4.38$ eV, the width $\Gamma=0.10\pm0.04$ eV is obtained for the 2.98 MeV level.

The low-lying level scheme of ^{27}Al[33] is shown in Fig. 11. The level excited by this experiment is the doublet state at 3 MeV whose energies and J^π are assigned as 2.9 MeV, $3^+/2$ and 3.00 MeV, $9^+/2$, respectively. Recently Robinson *et al.*[34]

measured the resonant scattering of bremsstrahlung by the doublet state using a Ge(Li) detector and resolved the 2.98 MeV and 3.00 MeV contribution in the spectrum. Their result shows that the 3.00 MeV γ-ray is very small portion in the spectrum compared with 2.98 MeV γ-ray.

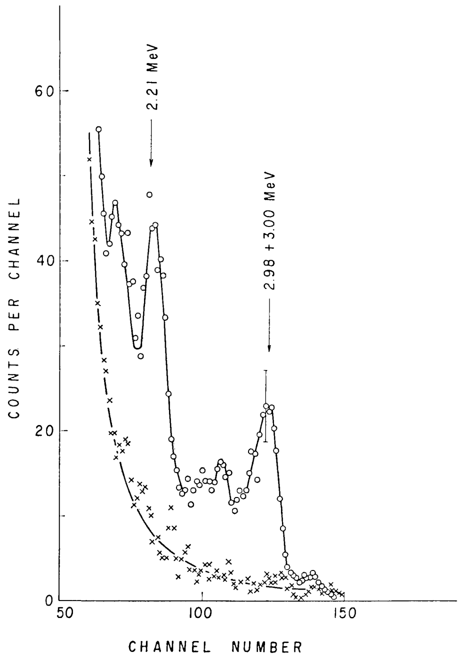

Fig. 9. Pulse-height distribution of γ-rays scattered from Al and Mg.

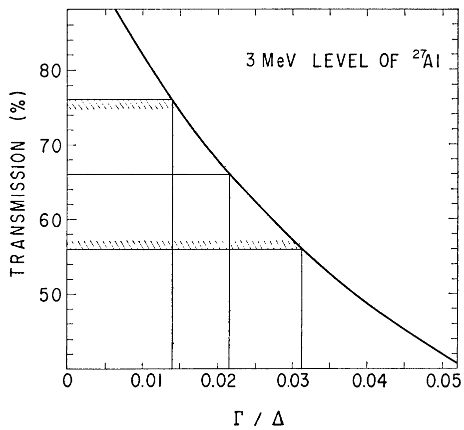

Fig. 10. The transmission as a function of Γ/Δ.

For the 2.98 MeV transition, Robinson *et al.*[34] found a level width of $\Gamma=0.125^{+0.014}_{-0.013}$ eV. Vanhuyse *et al.*[35] found $\Gamma=0.123^{+0.041}_{-0.034}$ eV by the self-absorption method. Schaller and Miller[36] and Khan and Rasmussen[37] found $\Gamma=0.124\pm0.012$ and $\Gamma=0.110\pm0.011$ eV, respectively, from both the scattering and self-absorption measurements. Smulders *et al.*[38] found $\Gamma=0.047\pm0.020$ eV by the Doppler-shift attenuation method. The present result $\Gamma=0.10\pm0.04$ eV agrees with the results mentioned above within the experimental errors.

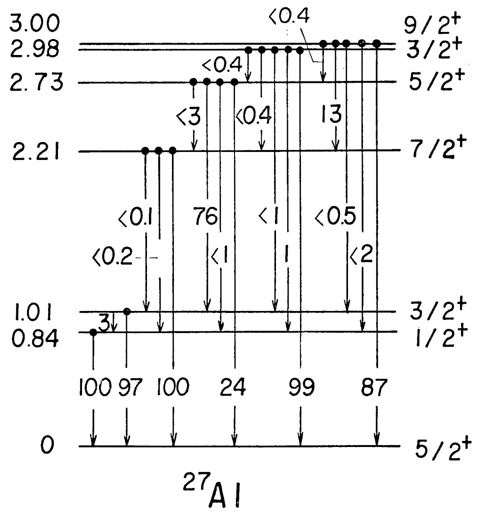

Fig. 11. Low-energy levels of ^{27}Al.

The low-lying levels of ^{27}Al have been explained by the strong-coupling,[39] weak-coupling[40] and rotational-vibrational models.[41] For the 3.00MeV ($9^+/2$) level of the doublet, the strong-coupling model caused difficulty in the energy and γ-decay strength of this level. Both weak-coupling and rotational-vibrational models explain well this excitation energy and $E2$ strength, but the latter gives a better description than the former in reproducing of the recent results[42] of the $E2/M1$ mixing ratios.

The 2.98 MeV transition is expected to be mainly $M1$ transition.[42] A single particle value is $\Gamma_w(M1)=0.56$ eV which is by the factor of 6 as large as present result. Evers *et al.*[40] calculated a radiative width using the weak-coupling model and obtained $\Gamma(M1)=0.105$ eV which agrees well with present result $\Gamma=0.10\pm0.04$ eV.

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