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# Resonances in $^{27}$Al + p for $E_p = 3.1-3.6$ MeV

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With the use of Ge(Li) detectors for gamma ray yield measurements, several resonances were located in proton-induced reactions on a $^{27}$Al target for bombarding energies of $E_p = 3.1-3.6$ MeV ($E_x = 14.62-15.04$ MeV in $^{28}$Si). Decay modes of the resonances were determined.

The unbound levels in $^{28}$Si above 14.5 MeV excitation have been the subject of several nucleon transfer reactions,[1,2] radiative alpha capture,[3] and electron scattering studies.[4] The emphasis has been on the population of these levels and establishing the fragmentation of the giant resonances. In the literature, little is known about the fine structure of these levels and their decay modes. This work was initiated to provide that information, exploiting the good resolution possible with a Van de Graaff accelerator in conjunction with the high resolution of Ge(Li) detectors. This report describes the results of gamma decay studies following proton bombardment of $^{27}$Al in steps of 2 keV or less for $E_p = 3.1-3.6$ MeV. It corresponds to the region of excitation $E_x = 14.62-15.04$ MeV in $^{28}$Si. Previous work[5] has shown that the average $^{28}$Si level spacing for $E_x = 13.1-14.5$ MeV is approximately 15 keV, so the present experimental resolution of $\sim 2.5$ keV was chosen to be considerably smaller than this.

The measurements were carried out using the proton beam from the 7 MV CN Van de Graaff at Laval University. The energy resolution of the beam was about 1 keV and beam currents of about 1 $\mu$A were employed. The experimental details have been previously described.[6] The targets were self-supporting aluminum foils of $35 \pm 5$ $\mu$g/cm$^2$ thickness, corresponding to about 2.5 keV at 3.5 MeV. The target thickness was ascertained by measuring the excitation function of the narrow resonance at $E_p = 1.724$ MeV in the $^{27}$Al(p,$\gamma$) reaction. During the measurements, a surface barrier detector served as a monitor of variations in the target composition. No such variations were found. Two efficiency-calibrated Ge(Li) detectors of 50 cm$^3$ were employed for gamma ray detection. One of them, fixed at 90° with respect to the proton beam, served to monitor the slight energy shifts in the primary proton beam during the long accumulation.

Gamma ray excitation functions were measured over the energy region $E_p = 3.1-3.6$ MeV in steps of 2 keV or less. During the data acquisition, preliminary identification of the resonances was done by inspecting the gamma ray yield in the photopeak regions of characteristic gamma rays. This analysis was done for $E_\gamma = 0.84$, 1.01, 1.37, 1.78, and 2.22 MeV gamma rays corresponding, respectively, to the (p,p$_1\gamma$), (p,p$_2\gamma$), (p,$\alpha_1\gamma$), (p,$\gamma$), and (p,p$_3\gamma$) channels. Also, the yield of gamma rays for energy

TABLE I. Resonances in the $^{27}$Al + p reaction. Levels from other reactions are included for comparison. (An × means observed.)

| $E_p$ (MeV) | $E_x$ (MeV) | (p,p$_1$)[a] | (p,p$_2$)[a] | (p,p$_3$)[a] | (p,$\alpha_1$)[a] | ($\alpha,\gamma$)[b] | (e,e′)[c] | (d,n)[d] |
|---|---|---|---|---|---|---|---|---|
| 3.153 | 14.626 | | | | × | | × | × |
| 3.170 | 14.643 | | | × | × | | | × |
| 3.25 | 14.72 | broad | broad | | × | | × | |
| 3.30 | 14.77 | | | | × | | | |
| 3.32 | 14.79 | | | | × | | | × |
| 3.33 | 14.80 | | | × | × | | | |
| 3.38 | 14.85 | | | | × | | | × |
| 3.40 | 14.86 | | | × | | | | |
| 3.42 | 14.88 | broad | broad | | × | | | |
| 3.43 | 14.89 | | | | × | | | |
| 3.46 | 14.92 | broad | complex | × | | | × | |
| 3.48 | 14.94 | | | | × | | | |
| 3.51 | 14.97 | | × | | × | × | × | |
| 3.53 | 14.99 | | | | × | | | |
| 3.55 | 15.01 | broad | | × | | | | |
| 3.58 | 15.04 | | × | | × | | | |

[a]Present work.
[b]Reference 3.
[c]Reference 4.
[d]Reference 2.

 

higher than 9 MeV was monitored.

In the (p,$\gamma$) channel, two narrow resonances at $E_x = 14.8$ and 15.04 MeV are seen. The one at 14.8 MeV appears sharply in the 1.78 MeV gamma ray yield, while the other appears in the window for $E_\gamma > 9$ MeV. At 15.04 MeV excitation, the yield of the 1.78 MeV gamma ray shows a complex structure, indicating that quite a few levels, riding over a broad resonance, contribute to the yield. In view of this fact, it is surprising that the high energy gamma yield ($E_\gamma > 9$ MeV) shows a simple structure.

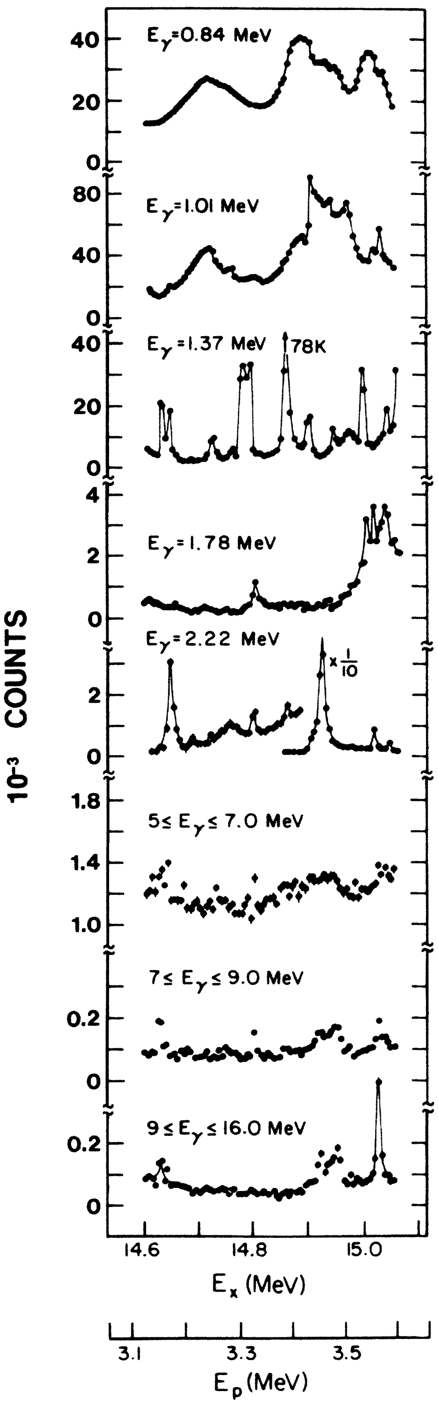


FIG. 1. Gamma ray excitation function of the $^{27}$Al + p reaction in the proton energy range 3.1–3.6 MeV. The top five plots are the background subtracted photopeak areas for the $^{27}$Al(p,p$_1\gamma$)$^{27}$Al ($E_\gamma = 0.84$ MeV), $^{27}$Al(p,p$_2\gamma$)$^{27}$Al ($E_\gamma = 1.01$ MeV), $^{27}$Al(p,$\alpha_1\gamma$)$^{24}$Mg ($E_\gamma = 1.37$ MeV), $^{27}$Al(p,$\gamma$)$^{28}$Si ($E_\gamma = 1.78$ MeV), and $^{27}$Al(p,p$_3\gamma$)$^{27}$Al ($E_\gamma = 2.22$ MeV) reactions. The bottom ones are $^{27}$Al(p,$\gamma$)$^{28}$Si yields summed over the gamma ray energies indicated in the figure.

TABLE II. Radiative decay properties of 14.8 and 15.04 MeV levels in $^{28}$Si.

| Transition | Branching ratio (%) | $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma_{tot}$ (eV) | $\Gamma$ (keV) |
|---|---|---|---|
| 14.8→6.89 | 45±7 | 7.6±1.4 | 11.7±1.3 |
| →6.28 | 48±12 | 8.1±2.2 | |
| →4.62 | 2±1 | 0.35±0.12 | |
| →1.78 | 5±2 | 0.80±0.21 | |
| 15.04→1.78 | 100 | 9.2±2.5 | 5.9±0.5 |

Figure 1 shows the yield of the characteristic gamma rays from the off line analysis. In this analysis, the yield of the photopeaks of the gamma rays was obtained by subtracting the Compton contributions from the higher energy gamma rays. The (p,p$_1\gamma$) gamma resonances, seen in the yield of the 0.84 MeV gamma ray, are broad with peaks at the excitation energies in $^{28}$Si of $E_x = 14.72$, 14.88, 14.93, and 15.01 MeV. Of these, the resonances at 14.72 and 14.88 MeV are seen in the (p,p$_2\gamma$) channel also via the characteristic gamma ray of energy $E_\gamma = 1.01$ MeV. In the literature,[2,3] a level is reported at 14.74 MeV with $J^\pi = 2^+$ and width $\Gamma_{tot} < 0.15$ MeV. It is likely that the broad structure we see at 14.72 MeV is the same level. Friebel[4] reports the ground state transition strength as $\Gamma_\gamma^0 = 0.34 \pm 0.02$ eV, too small to be observed in our thin target measurements. In the 14.9 MeV region the (p,p$_2\gamma$) channel shows a complex structure with peaks apparent at $E_x = 14.9$, 14.93, and 14.97 MeV. The (p,p$_3\gamma$) channel as seen in the $E_\gamma = 2.22$ MeV gamma ray yield does not exhibit broad structures. Instead, five narrow resonances at $E_x = 14.64$, 14.8, 14.86, 14.92, and 15.01 MeV are seen. The observation that the 14.8 MeV level is seen to feed only the 2.22 MeV level of $J^\pi = \frac{7}{2}^+$ in $^{27}$Al indicates that this level has a spin $J > 3$. Further support for this constraint on the spin is found from the gamma decay of this level (see below).

The (p,$\alpha_1\gamma$) excitation function is obtained from the analysis of the characteristic 1.37 MeV gamma ray yield. Several narrow resonances were observed as seen in Fig. 1 and are listed in Table I. Also shown in Table I are the resonances in (p,p$'\gamma$) channels, along with the levels known from previous works.

Figure 1 also shows the gamma excitation functions for $E_\gamma = 1.78$ MeV and for $E_\gamma > 9$ MeV to identify the resonances feeding the g.s., first excited, and second excited levels at 1.78 and 4.62 MeV in $^{28}$Si. The conspicuous ones are at $E_x = 14.62$, 14.8, 14.92, 14.97, and 15.04 MeV. It is clear from the excitation functions that they are of different nature. The resonances at $E_x = 14.62$, 14.92, and 14.97 MeV did not exhibit any cascade gamma decays in the on-resonance long accumulations. It is likely that they all feed the ground state exclusively. Due to rapidly decreasing photopeak efficiency for the Ge(Li) detector, no quantitative measurements were possible. The resonance at 14.8 MeV does not appear in the high energy gamma yield, showing that it populates higher excited levels in $^{28}$Si. To ascertain this aspect, we accumulated spectra on the resonance for large integrated charge (20 mC). It is seen to populate predominantly the levels at 6.28 ($J^{\pi}=3^{+}$) and 6.89 ($J^{\pi}=4^{+}$) MeV. The branching ratios are shown in Table II. This observation, as mentioned above, supports the conjecture that the level has a spin $J>3$ and is made up of complicated configurations. The fact that this level is not seen in (e,e′) (Ref. 4) and $(\alpha,\gamma_0)$ (Ref. 3) reactions adds further support to our speculation. We measured the angular distributions of the resonant gamma rays, but no definitive conclusions could be drawn.

In the 15 MeV region, the 1.78 MeV gamma ray yield shows a complex structure. Some fine structure riding over a broad bump is apparent. The origin of this structure is not understood. However, the high energy gamma ray yield ($E_{\gamma}>9$ MeV) shows a sharp peak at $E_x=15.03$ MeV. Spectra accumulated with better statistics over this resonance showed a single transition feeding the 1.78 MeV level. Table II shows the gamma ray branching ratios and radiative widths for the levels at 14.8 and 15.04 MeV excitation. Measured gamma angular distributions for the primary gamma 15.04→1.78 MeV transition show it to be pure dipole with the angular distribution coefficient $A_2=-0.23\pm0.04$. This observation restricts the spin values to $J=1,2,3$ for 15.04 MeV level. As the isoscalar transitions are very weak in self-conjugate nuclei, the isospin $T=1$ can be assigned for this level. The corresponding parent analog lies at about 5.8 MeV excitation in $^{28}$Al. It is tempting to identify the 15.04 MeV level as the analog of the well established level at 5.80 MeV excitation in $^{28}$Al with $J^{\pi}=(0-2)^{-}$. Our measurements clearly rule out $0^{-}$ assignment for the 15.04 MeV level. From the measured transition strength $(2J+1)\Gamma_p\Gamma_{\gamma}/\Gamma_{tot}=9.2\pm2.5$ eV for the 15.04→1.78 MeV transition, one can deduce the lower limit on the radiative width as $\Gamma_{\gamma}(E1)=2.1$ and 1.3 mW.u., respectively, for the spin assignments of $J^{\pi}=1^{-}$ and $2^{-}$ for the 15.04 MeV level.

In summary, we have observed several narrow resonances in the $^{27}$Al + p reaction for the incident energies of 3.1–3.6 MeV. Various decay modes of these levels are ascertained. Also provided are the gamma decay modes of the levels at 14.8 and 15.04 MeV excitation in $^{28}$Si. The 15.04 MeV level is likely to be of spin $J^{\pi}=(1,2)^{-}$ and the analog of 5.8 MeV level in $^{28}$Al. We could conclude that the 14.8 MeV level has the spin $J>3$ from the gamma and particle decay mode. No corresponding analog states in $^{28}$Al could be identified.

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