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TITLE: STUDY OF ALUMINUM 27 (N,X GAMMA) REACTIONS UP TO A NEUTRON ENERGY OF 400 MEV

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# STUDY OF $^{27}Al(n,x\gamma)$ REACTIONS UP TO $E_n$ = 400 MeV

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## ABSTRACT

The prompt γ-radiation from the interaction of fast neutrons with Al was measured using the white neutron beam of the WNR facility at the Los Alamos National Laboratory. Partial production cross sections for residual nuclei in the range from F to Al were measured from threshold up to 400 MeV by observing the most intense γ-transitions between low lying levels of these nuclei. Two-dimensional neutron time-of-flight versus gamma pulse height spectra from the interaction of the neutrons with Al were observed after flight-paths of about 20 and 40 m with a high-purity Ge-detector. The neutron cross sections for prominent γ-transitions in a large number of residual nuclei could be derived with typical uncertainties of 10 - 20 % up to a neutron energy of 400 MeV. The energy resolution varies from ≈ 0.2 MeV at 10 MeV to ≈ 50 MeV at 400 MeV. In the low energy range (up to 60 MeV) the results are compared with nuclear model calculations using the code GNASH. A very good overall agreement is obtained without special adjustment of parameters.

## I. INTRODUCTION

Up to now studies of neutron-induced reactions above 30 MeV have been restricted mostly to the measurements of total, elastic scattering and inclusive particle emission cross sections. This is mostly due to the fact that the standard method for this purpose, the activation method, needs monoenergetic neutron sources which do not exist above 30 MeV. One possibility to circumvent this difficulty is the study of the prompt γ-reaction from neutron-induced reactions produced by pulsed high energy "white" neutron beams. Such measurements, if performed with high resolution Ge detectors allow the measurement of neutron-induced reactions for the formation of specific energy levels of specific residual nuclei over a wide neutron energy range. Therefore a program for such measurements was initiated at the WNR facility at Los Alamos some years ago.[1,2] As a part of this effort the prompt γ-radiation from neutron-induced reactions with aluminum were studied. Al is mono-isotopic and thus well suited for testing of model calculations and it is also of considerable interest for applications. In addition there exists a good data base for proton-induced reactions allowing detailed comparisons between the results of proton- and neutron-induced reactions.

## II. EXPERIMENT AND DATA ANALYSIS

The measurements were performed using the white neutron beam of the WNR facility at Los Alamos National Laboratory.[3,4] Data were taken with samples positioned at distances of 20.06 m and 41.48 m from the neutron production target at the 30° left flight path.[1] The experimental set-up was the same as described by Pavlik et al.[2] The neutron fluence was determined with a $^{238}U$ fission chamber. In the 41 m run a 15 cm thick polyethylene layer was inserted into the neutron flight path to suppress low-energy neutrons which would have caused frame-overlap problems. The prompt γ-radiation was registered by two high-purity Ge detectors at γ-emission angles of 90° and 125°. The efficiencies of the Ge detectors were measured using calibrated radioactive sources. The samples were 2 mm and 6 mm thick Al plates, for the 20 m and the 41 m set-up, respectively. Only results from the 125° detector are reported in this paper. At this angle the angle-integrated γ-production cross-section is approximately given by 4π times the measured differential cross section.[2]

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From two-dimensional neutron time-of-flight versus gamma pulse height spectra, one dimensional gamma pulse height spectra were derived for 59 neutron energy groups with increasing widths according to the energy resolution of the experiment. The energy resolution was ≈ 0.2 MeV at 10 MeV and ≈ 50 MeV at 400 MeV neutron energy due to the rather poor time resolution of the Ge detector. Examples of γ-spectra for different neutron energies are given in Figs. 1 and 2.

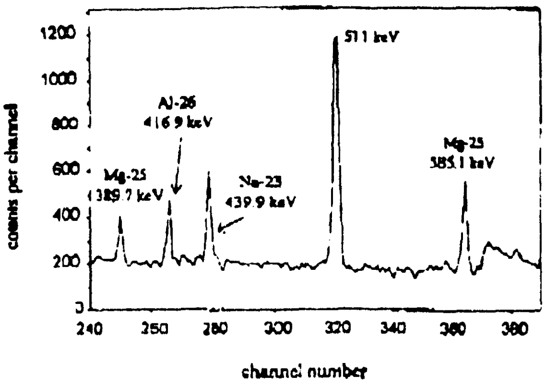


Fig. 1: part of the γ-spectrum from the interaction of 45 - 50 MeV neutrons with aluminum

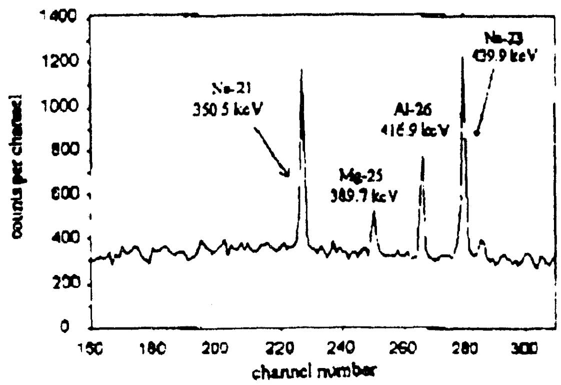


Fig.2: part of the γ-spectrum from the interaction of 240 - 270 MeV neutrons with aluminum

Gamma-production cross sections were determined from the corresponding peak areas in the one-dimensional pulse-height spectra. The cross sections were normalized to the results of a 14-MeV measurement performed at the Institute of Physics of the Slovak Academy of Sciences in Bratislava. [5]

The results were corrected for γ-absorption in the sample; those for the low Q-value reactions (n,n'γ) and (n,pγ) were also corrected for γ-production due to secondary neutrons produced in the Al-target.

## III. CROSS SECTION CALCULATIONS

Calculations of the γ-production cross sections studied experimentally up to a neutron energy of 60 MeV were performed by means of the code GNASH,[6] which describes the precompound mechanism of nuclear reactions by the exciton model and allows the addition of contributions from direct-reactions. Model parameters were not adjusted, but were kept at values typical of a large number of analyses of a variety of data at low energies in order to check the predictive power of this "standard parameter set".

For neutrons, the potential of Petler et al.[7] was utilized. For the proton channel, the global potential of Perey[8] was utilized to proton energies of 44 MeV, and the potential of Madland[9] was used at higher energies. Finally, the potential of Arthur and Young,[10] which was derived for n + $^{56}$Fe calculations, was used at all alpha energies.

The exciton model of Kalbach[11] was used including surface effects[12] and taking account of multiple precquilibrium particle emission. The damping matrix element was taken as 140 MeV.[13] The excitation energy dependence of the Ignatyuk level density formula[14] was incorporated into particle-hole state densities used in the exciton model calculations. By means of an energy-dependent level density parameter, the Ignatyuk model includes the theoretically expected disappearance of shell effects in the nuclear level densities at higher excitation energies. Within this model the nuclear moment of inertia was given the full rigid body moment of inertia. The level density parameters were chosen using the systematics of Arthur.[15] Minor adjustments were made to the pairing energies of $^{24}$Na, $^{27}$Mg and $^{27}$Al to improve agreement with (n,x) and (n,2n) cross section measurements.

## IV. RESULTS AND DISCUSSION

Our preliminary analysis of the data has resulted in the determination of 21 excitation functions of transitions between low-lying levels in 12 different residual nuclei for neutron energies from threshold to 400 MeV (see Table I). Typical excitation functions are shown in Figs. 3 - 5 for reactions with low, medium and high thresholds. Figs. 3 - 5 also show the results of previous measurements,[16,17,18] which only exist for neutron energies up to 14 MeV, and the calculations described in the previous section. As is apparent from the figures, there is a good agreement between our measurements, the results reported in the literature and the calculated cross sections. This is also true for most of the excitation functions not shown due to the limited space, especially for all strong transitions from the first excited level to the ground state. Somewhat larger deviations (in absolute value not in shape) up to a factor of two are observed for weaker transitions between excited levels of the investigated residual nuclei, e.g. the $3_1^+ \rightarrow 2_1^+$ transition in $^{26}Mg$.

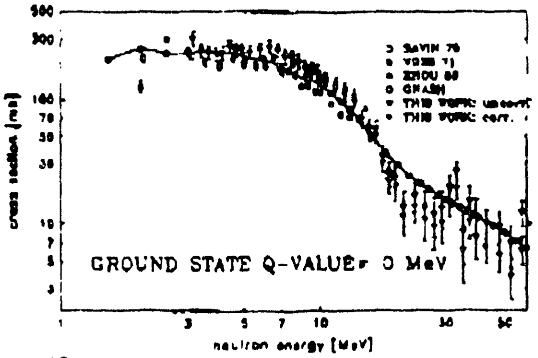


Fig. 3: $^{27}Al(n,n')^{27}Al$: $E_\gamma$=1014.46 keV, corrected for secondary neutron effects ;[16,17,18]

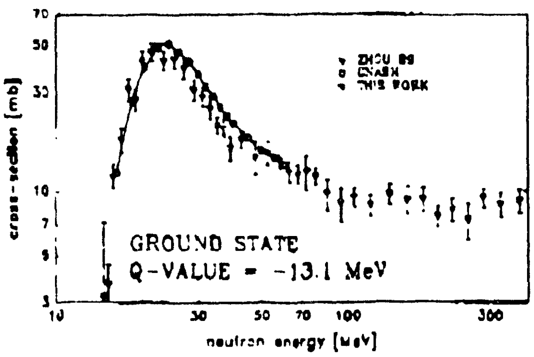


Fig. 4: $^{27}Al(n,2n)^{26}Al$: $E_\gamma$= 416.9 keV; [16]

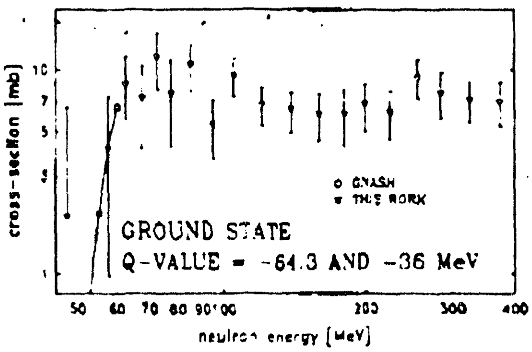


Fig. 5: $^{27}Al(n,3p\ 5n)$ and $(n,\alpha\ p\ 3n)^{20}Ne$: $E_\gamma$=1633.8 keV

Table I: analyzed gamma lines:

| transition in residual nuclei | reaction | energy [keV] | Q-value of the ground state [MeV] |
|---|---|---|---|
| $^{27}Al: \frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ | (n,n') | 793.0 | 0 |
| $^{27}Al: \frac{3}{2}^+ \rightarrow g.s.$ | | 1014.46 | |
| $^{27}Al: \frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ | | 1719.54 | |
| $^{27}Al: \frac{7}{2}^+ \rightarrow g.s.$ | | 2211 | |
| $^{26}Al: 3^+ \rightarrow g.s.$ | (n,2n) | 416.9 | -13.1 |
| $^{26}Al: 1^+ \rightarrow 0^+$ | | 829.6 | |
| $^{27}Mg: \frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ | (n,p) | 955.3 | -1.8 |
| $^{27}Mg: \frac{3}{2}^+ \rightarrow g.s.$ | | 984.6 | |
| $^{27}Mg: \frac{5}{2}^+ \rightarrow g.s.$ | | 1698.3 | |
| $^{26}Mg: 3_1^+ \rightarrow 2_1^+$ | (n,pn)<br>(n,d) | 1002.5 | -8.3<br>-6.1 |
| $^{26}Mg: 2_2^+ \rightarrow 2_1^+$ | | 1129.7 | |
| $^{26}Mg: 2_1^+ \rightarrow g.s.$ | | 1808.7 | |
| $^{25}Mg: \frac{3}{2}^+ \rightarrow \frac{1}{2}^+$ | (n,p2n)<br>(n,dn) | 389.7 | -19.4<br>-17.2 |
| $^{25}Mg: \frac{3}{2}^+ \rightarrow g.s.$ | | 974.8 | |
| $^{24}Mg: 2^+ \rightarrow g.s.$ | (n,p3n)<br>(n,d2n) | 1368.59 | -26.7<br>-24.5 |
| $^{23}Na: \frac{5}{2}^+ \rightarrow g.s.$ | (n,2p3n)<br>(n,αn) | 439.9 | -38.4<br>-10.1 |
| $^{22}Ne: 2^+ \rightarrow g.s.$ | (n,3p3n)<br>(n,α1p1n) | 1274.58 | -47.2<br>-18.9 |
| $^{21}Ne: \frac{5}{2}^+ \rightarrow g.s.$ | (n,3p4n)<br>(n,α1p2n) | 350.5 | -57.5<br>-29.2 |
| $^{20}Ne: 2^+ \rightarrow g.s.$ | (n,3p5n)<br>(n,α1p3n) | 1633.8 | -64.3<br>-36 |
| $^{18}F: 3^+ \rightarrow g.s.$ | (n,4p6n)<br>(n,α2p4n)<br>(n,2α2n) | 937.1 | -87.5<br>-56.8<br>-31.0 |
| $^{18}O: 2^+ \rightarrow g.s.$ | (n,5p5n)<br>(n,α3p3n)<br>(n,2α1p1n) | 1982.2 | -82.2<br>-53.9<br>-25.6 |

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