*References*

1. A. C. Wahl, R. L. Ferguson, D. R. Nethaway, D. E. Troutner and K. Wolfsberg, Phys. Res. 126 (1962) 1112.
2. H. V. Weiss, Phys. Rev. 139 (1965) B 304.
3. P. Armbruster, D. Hovestadt, H. Meister and H. J. Specht, Nucl. Phys. 54 (1964) 586.
4. H. Göbel, Diplomarbeit, Physik-Department, TH München, 1965 (unpublished). Earlier results see: E. Konecny, H. Opower, H. Gunther and H. Göbel, Symposium on The physics and chemistry of fission, Salzburg 1965, SM - 60/33.

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# TRIPLE CORRELATIONS IN MULTIPLE GAMMA CASCADES IN $^{36}$Ar

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The excitation energies of the bound levels in $^{36}$Ar are accurately known from the $^{39}$K(p, $\alpha$)$^{36}$Ar reaction [1]. The branching ratios of many of these levels were recently established in an investigation of 65 resonances in the reaction $^{35}$Cl(p, $\gamma$)$^{36}$Ar at proton energies below 3 MeV [2]. In this letter the main results are reported from (p, $\gamma\gamma$) triple correlation and polarization measurements at eight resonances. The complete results and a description of the method of analysis will be published elsewhere.

Protons were accelerated with a 3 MeV Van de Graaff generator. Gamma radiation was detected with two cylindrical NaI scintillation crystals (10 cm long, 10 cm in diameter). The target material, $BaCl_2$ enriched to 99.5% $^{35}$Cl, was evaporated onto tantalum backings. A 400-channel RIDL pulse-height analyser recorded the spectra. As several of the levels in $^{36}$Ar decay through multiple cascades, the angular correlation measurements mainly were performed by taking coincidence spectra. These were taken in four geometries (the geometries I, II, V and VI, see ref. 3, and at four angles per geometry. The intensity distributions per geometry were first analysed in a series of Legendre polynomials $W(\theta) \propto 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$. Altogether 90 of these distributions were measured at the eight resonances indicated in table 1. The experimental errors in $A_2$ and $A_4$ generally lie between 0.02 and 0.05.

Next, the theoretical values of the $A_2$ and $A_4$ coefficients were compared with the experimental $A_2$ and $A_4$ values by a least squares procedure

Table 1
Energies, strengths, spins, parities, isospins and $l_p$ values of the investigated resonances in the $^{35}$Cl(p, $\gamma$)$^{36}$Ar reaction.

| $E_p$ (keV) | $E_x$ (MeV) | $\frac{(2J+1)\Gamma_p\Gamma_\gamma}{\Gamma_{tot}}$ (eV) | $J^\pi$ | $T$ | $l_p$ |
|---|---|---|---|---|---|
| 733 | 9.22 | 0.8 | $1^{(+)}$ | (1) | 0 (or 1) |
| 860 | 9.34 | 5 | $3^-$ | 1 | 1 + 3 |
| 1097 | 9.57 | 2.7 | $4^{(-)}$ | (1) | 3 (or 2) |
| 1118 | 9.59 | 0.6 | $2^+$ | 0 | 0 |
| 1129 | 9.61 | 0.3 | (0) | 1 | 1 or 2 |
| 1761 | 10.22 | 2.1 | 4 | (1) | 3 or 2 + 4 |
| 1845 | 10.30 | 1.4 | $4^+$ | 0 | 2 + 4 |
| 2595 | 11.03 | 17 | $3^+$ | 1 | 2 |

for all possible spin combinations. In the computer program used for this purpose, all relevant parameters of a cascade, as quadrupole/dipole or octupole/quadrupole mixing parameters and formation parameters, were varied in small steps and a $\chi^2$ value was calculated for each combination of the parameters. This method allows addition of $\chi^2$ values from several cascades and considerably facilitates the calculation of errors. Simultaneous analysis of several steps in a multiple cascade and of several cascades per resonance was generally needed. In the theoretical analysis the spin orientation of the resonance state was described with population parameters, following a procedure promoted by Litherland and Ferguson [4] and by Smith [5].

Polarization measurements at the 860, 1097

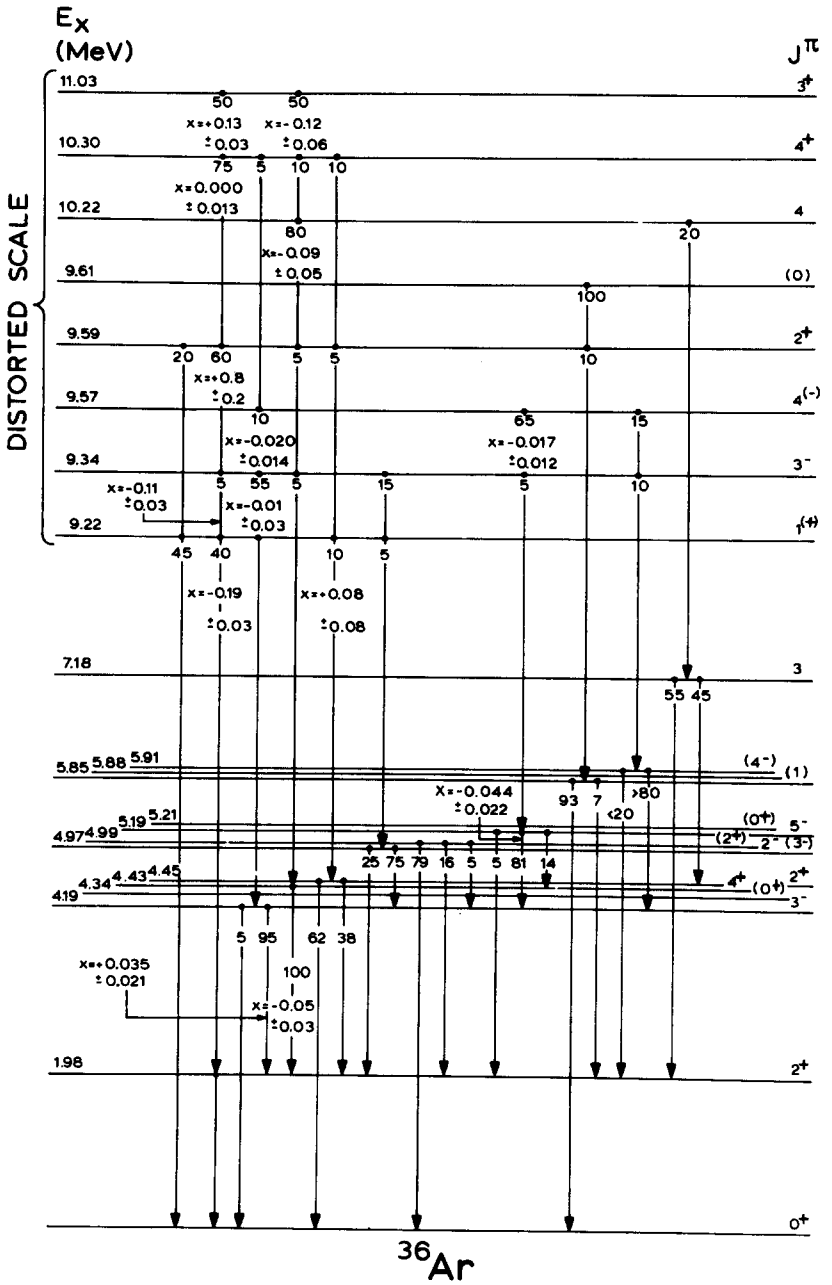


Fig. 1. Decay scheme of $^{36}Ar$. The energies and decay modes are taken from ref. 2; spins, parities and multipolarity mixing parameters follow from the present investigation.

and 1761 keV resonances determined the parities of the levels at 1.98, 4.19, 4.43, 4.98, 5.19 and 9.34 MeV (see fig. 1). The measurements were performed as described in a recent Utrecht paper [6]. The parities of the 4.45, 9.59 and 10.30 MeV levels followed from a consideration of ra-

diation strengths. The parity of the 11.03 MeV resonance level was derived from the formation parameters.

The spins and parities determined are presented in fig. 1. The spin assignments of thirteen levels are unique; the uncertain assignments are given in brackets. The spins indicated for the 4.97, 5.85, 5.91 and 9.61 MeV levels are uncertain, though strongly favoured by decay properties and measurements of angular distributions or triple correlations. The tentative $2^+$ assignment to the 4.99 MeV level is derived from the decay properties only. The $J^\pi = 0^+$ suggested for the 4.34 and 5.21 MeV levels is a good guess rather than an assignment. These levels are not excited in the 65 resonances reported earlier [2]; it seems to be a general phenomenon that excited states with $J^\pi = 0^+$ in even-even nuclei are at best very weakly populated in (p, $\gamma$) reactions, see e.g. ref. 8 or 9. Moreover the 4.34 and 5.21 MeV $^{36}$Ar levels are weakly excited in the $^{39}$K(p, $\alpha$)$^{36}$Ar reaction [1]; this may be due to a $(2J+1)$ dependence of the cross section for this reaction.

The parity and isospin assignments to the 9.59 MeV level are confirmed by the observation of $\alpha$ particles from the $^{35}$Cl(p, $\alpha_0$)$^{32}$S reaction by Bošnjaković [7]. No $\alpha$ particles were observed at the other resonances mentioned in table 1.

The proton energies and the resonance strengths are indicated in table 1.

Fig. 1 also gives the decay modes of the resonances and lower excited states involved in this investigation, as established in ref. 2. The values of the multipolarity mixing parameters of several transitions are indicated. Isobaric spin selection rules for E1 and M1 radiation appear to work effectively in this self-conjugated nucleus. The 1118 and 1845 keV resonances mainly decay through E2 radiation. In the decay of the $3^-$ level at 4.19 MeV an E3 ground-state transition competes with the E1 transition to the first excited state. The $5^-$ level at 5.19 MeV mainly decays through E2 radiation to the 4.19 MeV level, with weaker E1 and E3 decay modes to the 4.43 and 1.98 MeV levels. The isospin assignments to the resonances, derived from the observed strengths of dipole transitions, are given in table 1. The 860 keV resonance may be the isobaric analog of the 2.47 MeV level in $^{36}$Cl, for which Van Middelkoop and Spilling [10] recently found $J^\pi = 3^-$ from the $^{35}$Cl(n, $\gamma$)$^{36}$Cl reaction. After correction for the Coulomb energy and the proton-neutron mass difference the level energies differ by about 200 keV.

Interpretation of the population parameters by formation through the lowest possible incoming proton angular momentum is not always possible. The formation of the 860 keV resonance goes through p capture with 16 ± 4% f capture, the formation of the 1845 keV resonance through d capture with 4.0 ± 1.3% g capture. Other solutions with higher percentages of f and g capture, respectively, are not excluded in these cases. The competing $l_p$ values are indicated in table 1.

The observed odd parity levels can be interpreted as excitations from the $1d_{\frac{3}{2}}$ shell to the $1f_{\frac{7}{2}}$ shell. A shell model calculation is going on in which the level positions are calculated in the $j$-$j$ coupling limit using methods proposed by Talmi and De-Shalit [11]. In this calculation the energies of about thirty odd parity levels in nuclei from $^{33}$S to $^{41}$Ca are fitted together with the energies of even parity levels from configurations in the $1d_{\frac{3}{2}}$ shell to fourteen energy parameters [12]. Though the r.m.s. deviation of the calculated energies from the experimental values is about 0.5 MeV, the experimental order of the known odd parity levels can be reproduced correctly.

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*References*

1. R. G. Allas, L. Meyer-Schützmeister and D. Von Ehrenstein, Nucl. Phys. 61 (1965) 289.
2. F. C. Erné and P. M. Endt, Nucl. Phys. 71 (1965) 593.
3. H. Van Rinsvelt and P. B. Smith, Physica 30 (1964) 59.
4. A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39 (1961) 788.
5. P. B. Smith, in: Nuclear reactions II, ed. by P. M. Endt and P. B. Smith (North-Holland Publ. Comp., Amsterdam, 1962).
6. H. Van Rinsvelt and P. M. Endt, Phys. Lett. 9 (1964) 266.
7. B. Bošnjaković, private communication.
8. P. M. Endt and A. Heyligers, Physica 26 (1960) 230.
9. H. P. Leenhouts and P. M. Endt, submitted to Physica.
10. G. Van Middelkoop and P. Spilling, submitted to Nuclear Physics.
11. A. De-Shalit and I. Talmi, Nuclear shell theory (Academic Press, New York, 1963).
12. F. C. Erné, to be published.

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