

ENERGY LEVELS OF ^{36}Ar and ^{38}Ar FROM ALPHA CAPTURE IN SULPHUR AND PROTON CAPTURE IN CHLORINE

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Abstract: The reactions $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ and $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ were investigated in the energy range $E_\alpha = 2.2$ –3.2 MeV. Five resonance states in ^{36}Ar ($E_x = 8.9$ –9.5 MeV) and six in ^{38}Ar ($E_x = 9.6$ –10.1 MeV) were found. The excitation energies and resonance strengths are reported. The spins and parities of most resonances showing a ground-state transition were determined from angular distribution measurements. The relative strengths of the $J^\pi = 1^-$ resonances in ^{36}Ar and ^{38}Ar indicate that the isobaric-spin selection rule for electric dipole transitions in self-conjugate nuclei is still effective in this mass region. The slowing-down factor for these transitions amounts to about ten.

The $^{35}\text{Cl}(\text{p}, \gamma)^{36}\text{Ar}$ reaction for $E_p = 0.4$ –1.0 MeV, leads to twenty ^{36}Ar levels in the excitation range covered in the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ experiment. The yield curves of the two reactions are compared. Three ^{36}Ar resonance levels are excited in both the (p, γ) and the (α, γ) reaction.

1. Introduction

The alpha capture reaction has proven to be a useful tool in nuclear spectroscopy, even beyond the region of the very light nuclei (1^{-4}). For nuclei with $Z = 16$, detectable γ -ray intensities from (α, γ) reactions can be expected for $E_\alpha \geq 2.2$ MeV, if in the compound nucleus the α -particle binding energy is below the neutron binding energy. The possibilities of γ -ray spectroscopy with (α, γ) reactions, however, are limited by the high neutron background, mostly due to the $^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ reaction. In the case of the $\text{S}(\alpha, \gamma)\text{Ar}$ reactions, discussed here, this limitation entails that for most resonances only the ground-state gamma decay could be observed, and thus that only information about the resonance levels could be obtained. This restricted information, however, can be useful in other investigations; for instance in the analysis of the γ -ray spectra from corresponding (p, γ) reactions.

The analysis of current experiments on the $^{35}\text{Cl}(\text{p}, \gamma)^{36}\text{Ar}$ reaction ⁵⁾ is difficult due to the many three-or-more-step cascades in the decay of the resonance levels. In fact, the idea that additional information about some of the resonance levels, could be obtained through the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction, sparked the investigation reported here. In the course of the experiments it proved necessary to look into the $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ reaction in more detail.

This paper reports, after a short description of the experimental set-up (sect. 2), the results of the resonance measurements on the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$, $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ and

$^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$ reactions (sect. 3). It is concluded by a discussion (sect. 4) in which the three yield curves are compared. In the first place those of the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ and $^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$ reactions, since these give information about the same ^{36}Ar levels, and secondly those of the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ and $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ reactions, since these give some information as to the T -forbiddenness of electric dipole transitions in self-conjugate nuclei. A preliminary report of this work has been given in ref. ²).

2. Apparatus

The (α, γ) reactions were investigated with a 3 MV Van de Graaff accelerator; the (p, γ) reaction both with the Van de Graaff and with the 850 kV Utrecht Cockcroft-Walton generator.

In both experiments an analysing magnet deflected the particle beam over 90° . The magnetic field was measured with a magnetic-resonance flux meter and served as a measure of the particle energy.

In the (α, γ) experiments with natural sulphur, ZnS targets were used, whereas the $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ measurements were performed with a CdS target enriched to 35% ^{34}S , obtained from A.E.R.E., Harwell, England. The proton yield curve was measured with a CoCl_2 target enriched to 99.5% ^{35}Cl . The ^{35}Cl was obtained from Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

The ZnS and CoCl_2 were evaporated in vacuo onto copper backings. Special care was taken in preparing these backings. They were cleaned with a concentrated solution of ammonia with a few percent hydrogenperoxide. Before the evaporation of the target material the backings were dried in vacuo. This procedure reduced the background radiation from the backing and improved the quality of the target. To prevent deterioration of the water-cooled targets, the energy dissipation on the target was limited to 15 W for ZnS targets and to 10 W for CdS and CoCl_2 targets.

In both the (α, γ) and (p, γ) experiments the γ rays were detected with a cylindrical NaI(Tl) crystal, 10 cm in diameter and 10 cm long, placed at $\vartheta = 55^\circ$ to the bombarding-particle beam, as close to the target as possible ($D = 0.7$ cm). For the angular distribution measurements the distance from the target to the front of the crystal was $D = 10$ cm. Gamma-ray spectra were measured with a 400-channel RIDL analyser.

A more detailed description of the apparatus, of which a cooling trap in front of the target, preventing carbon deposit, is an essential element, has recently been given ⁶).

3. Experimental Results

3.1. THE $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ AND $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ REACTIONS

To minimize the contribution of background radiation from neutron capture in the NaI crystal, the alpha capture γ rays were counted in a narrow (≈ 2 MeV) channel, set at the energy calculated for ground-state de-excitation of the resonance

levels. The yield curve of the $S(\alpha, \gamma)Ar$ reaction in the energy range $E_\alpha = 2.2\text{--}3.2$ MeV, obtained from bombardment of a ZnS target of natural isotopic constitution, is given in the lower part of fig. 1. Taking into account the observed background radiation, observation of resonances at bombarding energies below 2.2 MeV is unlikely, due to the small Coulomb barrier penetration.

At most resonances, the measured energy of the high-energy γ rays does not agree with the energy calculated for a ground-state transition from a $^{32}S(\alpha, \gamma)^{36}Ar$ resonance level 7) ($Q = 6.641$ MeV), but it corresponds well with the energy of $^{34}S(\alpha, \gamma)^{38}Ar$ ground-state 7) radiation ($Q = 7.213$ MeV). Though natural sulphur contains only 4.2% ^{34}S , it is obvious that these resonances have to be ascribed to the $^{34}S(\alpha, \gamma)^{38}Ar$ reaction. This is confirmed by the measurement of a yield curve with a CdS target, enriched to 35% ^{34}S . This curve is given in the upper part of fig. 1. Resonances in the two other stable sulphur isotopes can be excluded on the basis of the low natural abundances, 0.014% ^{36}S and 0.76% ^{33}S , and for the latter isotope also because of the competing $^{33}S(\alpha, n)^{36}Ar$ reaction with $Q = -2.002$ MeV.

TABLE 1

Resonances in the reaction $^{32}S(\alpha, \gamma)^{36}Ar$; energies, spins and parities, strengths, main decay and the corresponding $^{36}Cl(p, \gamma)^{36}Ar$ resonances

E_α (MeV)	$^{36}Ar^*$ (MeV)	$J\pi$	$(2J+1)I_\alpha I_\gamma / I$ (eV)	Main decay	$^{36}Cl(p, \gamma)^{36}Ar$ resonances (E_p in keV)
2.554	8.911	2 ⁺	0.03	γ_0	
2.785	9.117	1 ⁻	0.3	γ_0	
3.056	9.357	2 ⁺	0.05	γ_0	873
3.161	9.451		0.15	γ_1	968
3.182	9.464		0.05	$\gamma_0 \gamma_1$	986
all ± 0.005			all $\pm 30\%$		

TABLE 2

Resonances in the reaction $^{34}S(\alpha, \gamma)^{38}Ar$; energies, spins and parities, strenghts and main decay

E_α (MeV)	$^{38}Ar^*$ (MeV)	$J\pi$	$(2J+1)I_\alpha I_\gamma / I$ (eV)	Main decay
2.670	9.602	1 ⁻	4.0	γ_0
2.772	9.693	1 ⁻	1.5	γ_0
2.911	9.817	1 ⁻	0.3	γ_0
3.025	9.919	1 ⁻	4.5	γ_0
3.116	10.001	1 ⁻	3.0	γ_0
3.161	10.041	1 ⁻	4.5	γ_0
all ± 0.005			all $\pm 30\%$	

The resonances assigned to the reactions $^{32}S(\alpha, \gamma)^{36}Ar$ and $^{34}S(\alpha, \gamma)^{38}Ar$ on the basis of firstly their relative intensities in the two curves of fig. 1, and secondly the measured γ ray energies, are listed in tables 1 and 2, respectively. These tables list

the energies of the resonances and resonance levels, the resonance strengths as determined from thick target yields, the spin and parity assignments from angular distribution measurements, and for the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction the corresponding $^{35}\text{Cl}(\text{p}, \gamma)^{36}\text{Ar}$ resonances (see sect. 4). The α -particle energy calibration is based on the 2.800 ± 0.003 MeV $^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ resonance⁸⁾ and on the 2.4374 ± 0.0010 MeV $^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$ resonance³⁾.

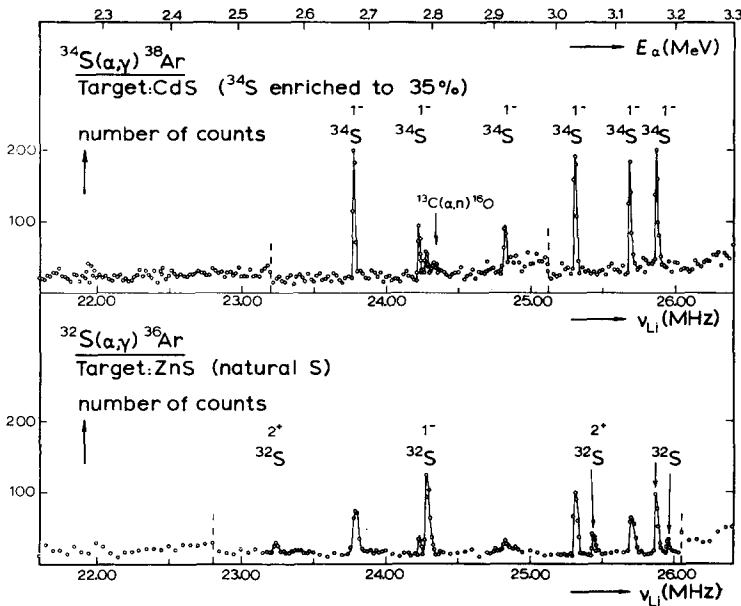


Fig. 1. Gamma-ray yield from alpha-particle bombardment of a ZnS target of natural isotopic constitution (lower part) and of a CdS target enriched in ^{34}S (upper part). The breaks in the yield curves, indicated by vertical dashed lines, mark the energies at which the channel setting was adjusted.

In the (α, γ) reactions on the $J^\pi = 0^+$ ^{32}S and ^{34}S nuclei, only resonances with natural parity will be excited. For resonances exhibiting ground-state de-excitation, the possible J^π values are limited to 1^- and 2^+ , since $0^+ \rightarrow 0^+$ transitions are forbidden, and since resonances with spin 3 or higher will decay to excited states with higher spins. The angular distributions of $1^- \rightarrow 0^+$ and $2^+ \rightarrow 0^+$ γ rays are easily distinguishable:

$$W(\vartheta) \propto \sin^2 \vartheta \propto 1 - P_2(\cos \vartheta) \text{ for } J^\pi = 1^-,$$

$$W(\vartheta) \propto \sin^2 2\vartheta \propto 1 + \frac{5}{7}P_2(\cos \vartheta) - \frac{12}{7}P_4(\cos \vartheta) \text{ for } J^\pi = 2^+,$$

where P_2 and P_4 are Legendre polynomials⁹⁾. Thus, once a ground-state transition has been found, angular distribution measurements will yield a unique $J^\pi = 1^-$ or 2^+ assignment, even for weak resonances. The angular distributions measured at the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ and $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ resonances are given in figs. 2 and 3, respectively.

The solid lines represent the theoretical angular distributions for the assigned spin values, using the solid angle attenuation factors $Q_2 = 0.92$ and $Q_4 = 0.75$.

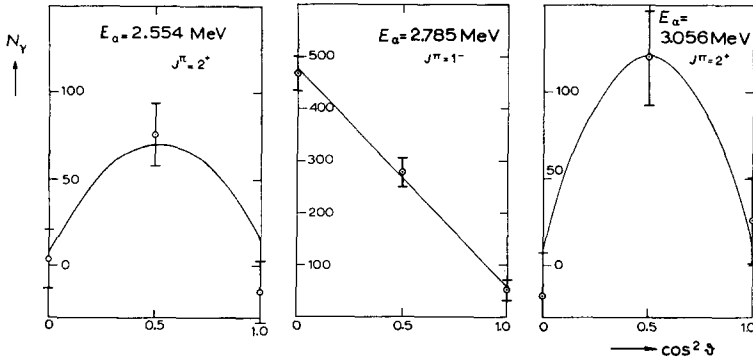


Fig. 2. Ground-state angular distributions measured at three $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ resonances; distance target-crystal, $D = 10$ cm. The solid curves give the theoretical angular distributions, including solid angle attenuation, for the assigned spins.

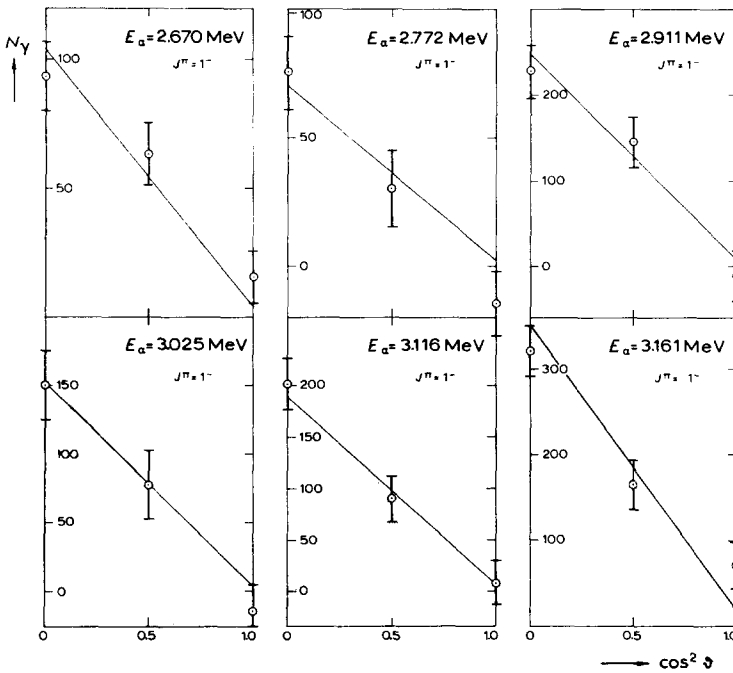


Fig. 3. Ground-state angular distributions measured at six $^{34}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ resonances. The solid curves give the calculated distributions for the assigned spin values, taking into account the solid angle attenuation.

The increasing background at higher energies, the less stable working conditions at the high-energy limit of the accelerator, and in one case the complication of a

conterminous $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ resonance, prevented the spin and parity determination of the highest two $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ resonances.

In a search for sources of background radiation, a strongly resonant 1.63 MeV γ ray was observed in addition to several other readily understandable γ rays. From subsequent measurements using an oxygen target and a target enriched in ^{17}O , the 1.63 MeV γ ray could be ascribed to the $^{17}\text{O}(\alpha, n)^{20}\text{Ne}$ reaction. This indicates that, in spite of the low natural abundance of ^{17}O , the latter reaction is a not negligible source of neutrons, in addition to the well known neutron producing $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction.

3.2. THE $^{35}\text{Cl}(\text{p}, \gamma)^{36}\text{Ar}$ REACTION

Five levels in ^{36}Ar with excitation energies in the 8.9-9.5 MeV range have been found from the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction reported above. If these levels are also excited in the $^{35}\text{Cl}(\text{p}, \gamma)^{36}\text{Ar}$ reaction, they should correspond to resonances in the $E_p = 0.4$ -1.0 MeV range. For comparison of the alpha and proton capture reactions, a yield curve has been measured with an enriched CoCl_2 target in the complete proton-energy range of interest. In the energy range $E_p = 0.4$ -0.6 MeV, investigated using the Cockcroft-Walton accelerator, four resonance are found at $E_p = 444, 522, 533$ and 575 keV. The weak 522 keV resonances has not been found previously ^(10, 12). The results of the measurements with the Van de Graaff accelerator in the $E_p = 0.6$ -1.0 MeV range are given in fig. 4.

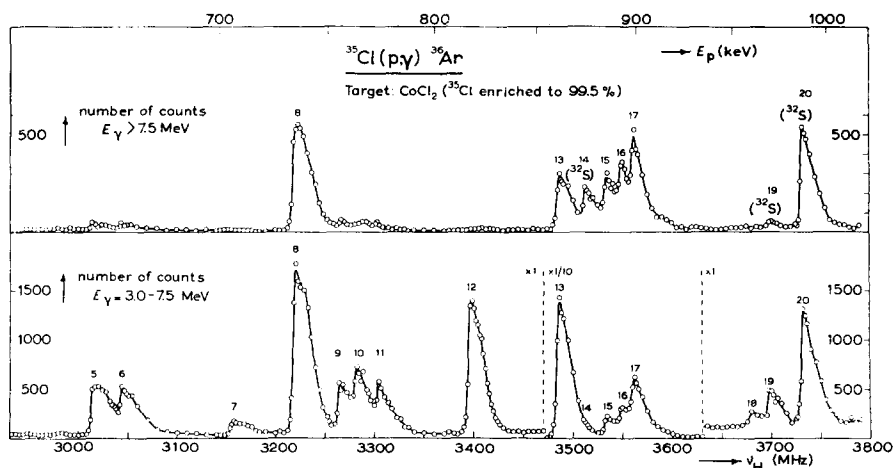


Fig. 4. Gamma-ray yield from proton bombardment of a CoCl_2 target enriched to 99.5 % ^{35}Cl as measured with the Van de Graaff accelerator. The upper- and lower parts give the yields in the channels $E_\gamma > 7.5$ MeV and $E_\gamma = 3.0$ -7.5 MeV, respectively. The resonances marked ^{32}S , correspond to resonances found in the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction. The resonances numbered 1 through 4, observed with the cascade generator, are not given in this figure.

The yield curves for two different channels, plotted in fig. 4, exhibit sixteen resonances. The resonance energies are listed in table 3. For the energy calibration the

resonance energies given in ref. ¹²⁾ were used. Another calibration, using well-known $^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$ resonances, yields resonance energies agreeing with the former ones within the experimental errors. The table also compares our results with those of previous investigations. In general the agreement is excellent. Seven new resonances, however, were found in this region.

TABLE 3

Resonances in the reaction $^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$; energies, comparison with literature values and strengths

Resonance number	E_p (keV)				$^{36}\text{Ar}^*$ (MeV)	$(2J+1)I_p I_\gamma / I'$ (eV)
	this work	ref. ¹⁰⁾	ref. ¹¹⁾	ref. ¹²⁾		
1	444.0	445.9		444.1 ± 0.5	8.938	0.3
2	522.2				9.014	0.04
3	533.0	533.8		532.9 ± 0.6	9.025	0.7
4	575.4	575.9		575.2 ± 0.6	9.065	0.6
5	643.1	644.2		643.2 ± 0.7	9.131	0.6
6	656.0	656.8		656.0 ± 0.7	9.143	0.4
7	704.5				9.190	(0.2)
8	733.4	734.6	736		9.219	2.4
9	754.3	755.4			9.239	0.5
10	762.4				9.247	0.6
11	772.6				9.257	0.4
12	817.0	818.2	819		9.300	1.9
13	859.7	861.4	861		9.341	16
14	873.3				9.355	0.5
15	883.5	885.7	883		9.365	3
16	891.6	893.0	890		9.372	3
17	897.6	899.2	896		9.378	6
18	958.6				9.438	0.2
19	968.0				9.447	0.5
20	985.9				9.464	2.5
	all ± 1.0	all ± 1.5	all ± 5			all $\pm 30\%$

The last column of table 3 lists the resonance strengths. The relative strengths were calculated from the resonance curve, taking into account the decay scheme measured at each resonance. A report on the analysis of the measured γ -ray spectra will be published shortly ⁵⁾. The relative strengths were converted to absolute values by measuring the strength of the $E_p = 575$ keV resonance with a natural NaCl target. The resonance strengths found here, are about a factor of 100 higher than those reported by Kuperus ¹⁰⁾. The strength of the $E_p = 860$ keV resonance is of the same order of magnitude as that reported by Towle *et al.* ¹⁴⁾.

4. Discussion

4.1. THE $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ AND $^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$ RESONANCES

In the corresponding energy range, the $^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$ reaction (see table 3) exhibits many more resonances than the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction (see table 1). This

difference is to be expected, since in the latter reaction only levels with a predominant $T = 0$ character will be observed, and from these only the levels with natural parity. In the (α, γ) experiment discussed here, moreover, only resonances with $J^\pi = 1^-$ or 2^+ could be observed.

Comparison of the ^{36}Ar excitation energies as found from both experiments, leads to the identification of the $E_p = 873, 968$ and 986 keV resonances in the $^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}$ reaction, with the $E_\alpha = 3.056, 3.161$ and 3.182 MeV resonances in the $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ reaction, respectively. The identification is confirmed by the observation that corresponding resonances show the same γ_0/γ_1 intensity ratio, within the experimental error. A more detailed comparison of the decay schemes of the (p, γ) and (α, γ) resonance levels is impossible due to the difficulty of measuring the low-energy part of the γ -ray spectrum at the (α, γ) resonances. The ^{36}Ar excitation energies found from the (α, γ) reaction are 2, 4 and 0 keV higher than those from the (p, γ) reaction. These differences are within the experimental errors.

The (p, γ) resonances corresponding to the $E_\alpha = 2.554$ and 2.785 MeV (α, γ) resonances have not been found. Their strengths are less than 0.03 eV.

4.2. THE $^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ AND $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ RESONANCES

The large strengths of the six $^{34}\text{S}(\alpha, \gamma)^{38}\text{Ar}$ resonances and the fact that all these resonances have $J^\pi = 1^-$ require some comments. The latter result is remarkable, especially when compared with the data on the $^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$ reaction¹⁾, where the strongest resonances have $J^\pi = 2^+$ or 4^+ .

A similar phenomenon, the relative strength of $J^\pi = 1^-$ resonance in the $^{30}\text{Si}(\alpha, \gamma)^{34}\text{S}$ reaction compared with those in the $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ reaction, has been discussed recently⁴⁾. There it was concluded that the T -selection rule for E1 radiation in self-conjugate nuclei accounts for the difference in strengths.

Since for most resonances the strength is determined by the radiative width, any inhibition of the decay γ rays will diminish the resonance strengths. Thus in self-conjugate nuclei, e.g. ^{36}Ar and ^{32}S , the T -selection rule for E1 radiation will weaken the strength of $J^\pi = 1^-$ resonances (all (α, γ) resonance levels have predominantly $T = 0$ character) in comparison with the $J^\pi = 2^+$ resonances decaying by uninhibited E2 radiation. In nuclei that are not self-conjugate, such as ^{38}Ar and ^{34}S , however, where neither E1 nor E2 radiation is inhibited, the p-capture 1^- resonances decaying by E1 radiation will naturally be stronger than the d-capture 2^+ resonances decaying by E2 radiation.

To find a quantitative measure for the isospin forbiddenness of the E1 transitions in self-conjugate nuclei in this mass region, the radiative widths of all E1 transitions in ^{36}Ar and ^{38}Ar found in this experiment, were computed; these are listed in table 4. The E1 transition strengths found for ^{38}Ar are representative for these transitions in 2s1d shell nuclei^{4, 13)}. The only E1 radiative width found in ^{36}Ar is about equal to the weakest found in ^{38}Ar . Since weaker transitions are easily overlooked in experiments of the type discussed here, and since, more important, the cut-off will

be found at the same absolute width for both nuclei, one should compare the ^{36}Ar radiative width not with the average width found in ^{38}Ar , but rather with the strongest transitions in ^{38}Ar . Then again, as in the case of ^{32}S and ^{34}S , it follows that the T -selection rule inhibits E1 transitions in this mass region by about one order of magnitude.

TABLE 4
Radiative widths of E1 ground-state transitions in ^{36}Ar and ^{38}Ar

Nucleus	E_γ (MeV)	Γ_γ^a (eV)	$ M^2 $ ($\times 10^3$) ^{b)}
^{36}Ar	9.117	0.1	0.1
^{38}Ar	9.602	1.3	1.2
	9.693	0.5	0.4
	9.817	0.1	0.1
	9.919	1.5	1.2
	10.001	1.0	0.8
	10.041	1.5	1.2

a) Calculated from the resonance strengths assuming $\Gamma_\gamma \ll \Gamma_\alpha$ and (for ^{36}Ar) $\Gamma_p \ll \Gamma_\alpha$. The latter relation follows from comparison of the strengths of the (p, γ) and (α , γ) resonances corresponding to this level: < 0.03 and 0.3 eV, respectively.

b) Radiative widths in Weisskopf units; calculated using $R = 1.5A^{1/3}$ fm.

In view of the very scarce material available here, it seems worthwhile to suggest a check of these first indications of the effectiveness of the isospin selection rule in this mass region by searching for more $J^\pi = 1^-$ resonances, both in ^{36}Ar and ^{38}Ar , at higher bombarding energies.

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