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YIELD MEASUREMENTS OF ALPHA PARTICLES FROM THE ^{27}Al(p, α)^{24}Mg AND ^{31}P(p, α)^{28}Si REACTIONS

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Synopsis

The yield of alpha particles from the ^{27}Al(p, α)^{24}Mg and ^{31}P(p, α)^{28}Si reactions has been measured. Of the twelve known ^{27}Al(p, γ)^{28}Si resonances in the E_p = 500–850 keV region only those at E_p = 504, 631, and 728 keV gave a detectable alpha-particle yield. Upper limits are given for the yields at the other resonance levels. Of the five ^{31}P(p, γ)^{32}S resonance levels in E_p = 400–850 keV region only that at E_p = 641 keV shows detectable alpha-particle emission.

1. *Introduction.* The yield of alpha particles from the ^{27}Al(p, α)^{24}Mg reaction at three resonances between 400 and 750 keV proton energy has been measured by Rutherglen and Smith [1]). The discovery [2]) that the alpha emitting resonance level at $E_p = 504$ keV is a doublet led to renewed interest in the subject, since for the determination of the spin and parity of a level it sometimes can be of crucial importance to know whether or not alpha particles are emitted. Moreover in the energy region above $E_p = 750$ keV there are three resonances in the ^{27}Al(p, γ)^{28}Si reaction which could also be reached by the Utrecht 850 kV cascade generator. Since the decay schemes of the twelve resonance levels between $E_p = 500$ keV and 850 keV have been determined in this laboratory [3]) and angular correlation measurements are in progress, a repetition and extension of the earlier measurements of Rutherglen and Smith was deemed necessary. In the present investigation alpha-particle yield measurements were performed, or upper limits on alpha emission determined at all of the (p, γ) resonances in the E_p = 500–850 keV region. The results are in agreement with those of Rutherglen and Smith in that alpha emission was found at proton energies of 631 and 728 keV, and in addition it was determined that the lower component of the doublet ($E_p = 504$ keV) emits alpha particles, whereas the upper component does not, and that none of the three previously uninvestigated resonance levels emits alpha particles.

The low resolution non-focussing magnetic spectrometer designed and built for this work was also suitable for the investigation of the ^{31}P(p, α)^{28}Si reaction. In earlier work Freeman and Seed [4]) had found alpha-particle emission at a proton energy of 680 keV. There is no (p, γ) resonance known at this energy and no alpha emission was found here in the present investigation. Alpha particles were detected, however, at the (p, γ) resonance at $E_p = 641$ keV. Alpha emission was not detectable at any other known (p, γ) resonance between 400 and 850 keV.

2. *Experimental.* Protons were accelerated with the 850 kV Utrecht cascade generator and analysed with a 90-degree magnet [5]) with an energy resolution of about 1 : 400.

As the Q-value for the reaction ^{27}Al(p, α)^{24}Mg is 1.6 MeV, incoming protons with an energy of 0.5 MeV produce alpha particles of 1.8 MeV at 90°. An attempt was made to detect the alpha particles in a thin CsI crystal viewing the target directly, and to distinguish the alpha particles from the elastically scattered protons by pulse height only. Since for one emitted alpha particle about 10^5 protons are scattered, and since moreover a proton pulse is about 40% higher than the pulse of an alpha particle of the same energy, a considerable number of pile-up pulses from protons were counted in the alpha particle discriminator channel. As a result magnetic separation of the scattered protons and the alpha particles was necessary.

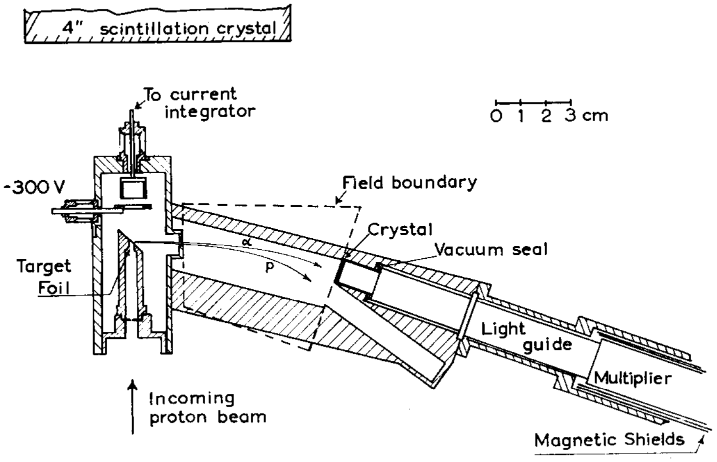

Fig. 1. The magnetic spectrometer.

A magnet was available with 10 cm pole pieces, giving a maximum field of 15 kilogauss with an air gap of 1.5 cm. For this magnet a focussing spectrometer would reach dimensions of about 2 meters, while the solid angle would be at best 5×10^{-4} steradian. If the focussing requirement is rejected, however, the distance between target and crystal can be reduced to 10 cm to obtain a solid angle of 5×10^{-3} steradian. At this distance the protons and alpha particles are adequately separated.

Figure 1 shows the spectrometer. A perspex light guide and multiple magnetic shielding had to be used in order to eliminate disturbance of the Dumont (6935) $\frac{3}{4}''$ diameter photomultiplier by the stray magnetic field of the spectrometer. In addition it was found necessary to use thick walled iron tubes surrounding the beam over the last few centimeters of its path in order to prevent undue deflection. A 4″ diameter by 4″ long NaI crystal was mounted as shown to make possible the detection of gamma radiation simultaneously with that of the alpha particles.

The spectrometer has the disadvantage that a considerable number of double scattered protons reach the crystal. To reduce this effect thin formvar foils ($\sim 10\ \mu g/cm^2$) were used as backing for the evaporated aluminium targets. The phosphorus targets were made by evaporation of zinc phosphide onto formvar. A thin layer of evaporated silver underneath was found to be necessary to increase the heat conductivity. Aluminium and phosphorus targets made in this way were able to withstand proton currents of up to 2μA over an area of about 1 mm^2.

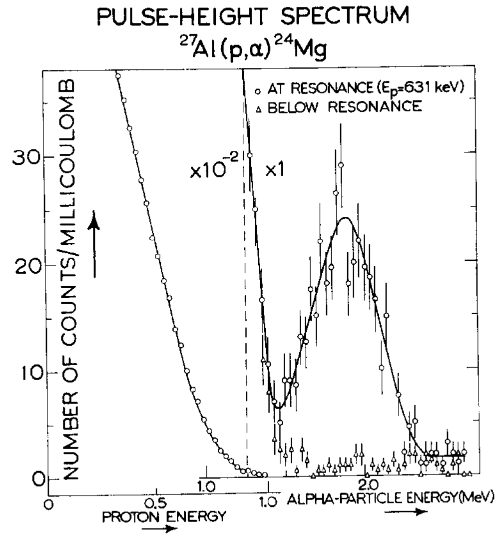

Fig. 2. Energy spectra from the detected particles at and below the 631 keV $^{27}Al(p, \gamma)^{28}Si$ resonance for a magnetic field of 14 kilogauss.

Figure 2 shows the pulse spectrum from the CsI crystal at and below the 631 keV $^{27}Al(p, \gamma)^{28}Si$ resonance for a magnetic field of 14 kgauss. The high-energy peak is due to the emitted alpha particles. The rise at low pulse heights is caused by double scattered protons.

The number of detected particles as a function of the magnetic field showed an intense flat-topped peak at low field due to elastically scattered protons deflected onto the crystal. The intensity of this peak was used for the determination of the solid angle of the spectrometer. The height of the proton pulses served as a reference for the energy calibration of recorded spectra. The fact that the top of the proton peak was flat, showed that the adjustment of the magnetic field was not critical.

3. *Analysis of the measurements.* Solid angle determination. The Coulomb scattering of the protons was used to determine the solid angle of the spectrometer. This requires knowledge of the target thickness, which can be determined by measuring the yield as a function of energy, with the same target that was used for the scattering, at an arbitrary resonance in the (p, γ) reaction, as will be shown in the following paragraph.

The ratio R of scattered to incoming protons is given by

$$R = n\sigma_R \,\mathrm{d}\Omega, \tag{1}$$

where n is the number of scattering nucleons per cm^2, dΩ is the unknown solid angle and σ_R is the known differential cross section for Rutherford scattering.

The energy integral I_γ of the gamma-ray yield for a target of arbitrary thickness [6]) is given by

$$I_\gamma = nr_\gamma \int \sigma_{p\gamma}\,\mathrm{d}E, \tag{2}$$

where r_γ is the counter efficiency, including the solid angle, of the gamma counter, and $\sigma_{p\gamma}$ the total cross section for the (p, γ) reaction.

The yield Y_γ of gamma rays, on the other hand, from a target thick enough to give saturation, is:

$$Y_\gamma = \frac{1}{\varepsilon} r_\gamma \int \sigma_{p\gamma}\,\mathrm{d}E, \tag{3}$$

where ε is the atomic stopping power for protons of the resonance energy.

If the three quantities given by eqs. (1), (2) and (3) are all measured with one target one can combine these expressions to:

$$d\Omega = \frac{R}{\sigma_R}\,\frac{Y_\gamma}{I_\gamma}\,\varepsilon. \tag{4}$$

A correction of about 25% for the scattering from the formvar backing was determined in a separate measurement with a blank formvar foil. The value of ε was obtained from reference 6.

This experiment was done with several targets at several resonances. A value of (6.7 ± 0.6) × 10^{-3} steradian was obtained as a weighted average of these measurements. A value of 10 × 10^{-3} steradian was estimated from the spectrometer geometry.

Partial widths. Neglecting angular distribution effects, the maximum alpha-particle yield [6]) for a thick target is given by

$$Y_\alpha = \frac{1}{\varepsilon}\,\frac{\mathrm{d}\Omega}{4\pi}\int \sigma_{p\alpha}\,\mathrm{d}E, \tag{5}$$

where $\sigma_{p\alpha}$ is the total cross section for the (p, α) reaction. If the spin and the mixing parameters are known, a correction for the angular distribution can be made. From equation (4) we know $d\Omega$, and thus a yield measurement determines $\int \sigma_{p\alpha}\, dE$. Using the Breit-Wigner formula for $\sigma_{p\alpha}$ we find

$$\int \sigma_{p\alpha}\, dE = \frac{\lambda^2}{4}\,\frac{2J_r+1}{2I+1}\,\frac{\Gamma_p \Gamma_\alpha}{\Gamma},$$

where J_r is the resonance spin, I the spin of the target nucleus, λ the wavelength of the incoming proton, Γ_p and Γ_α the partial widths for proton and alpha emission, respectively, and $\Gamma = \Gamma_p + \Gamma_\alpha + \Gamma_\gamma$ the total width of the resonance level.

Knowing the resonance spin, $\Gamma_p \Gamma_\alpha / \Gamma$ can be calculated yielding a lower limit for Γ_α. From Γ_α one can deduce the reduced width $\gamma_\alpha{}^2$ by dividing by the penetration factor for alpha particles of the energy and orbital momentum in question.

The penetration factor was computed from the tables by Sharp, Gove and Paul [7]), using a value of $1.41\, A^{\frac{1}{3}} \times 10^{-13}$ cm for the nuclear radius.

An upper limit for the reduced width is given by $\hbar^2/2M_\alpha R^2$, where M_α is the reduced alpha-particle mass. The dimensionless reduced width $\theta_\alpha{}^2$ is then defined as the ratio between $\gamma_\alpha{}^2$ and this limit.

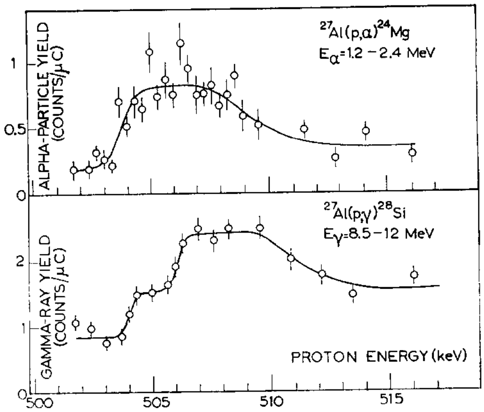

Fig. 3. The alpha-particle and the gamma-ray yields from an aluminium target as a function of proton energy for the E_p = 500–520 keV region.

4. *Results.* The reaction ^{27}Al$(p, \alpha)^{24}$Mg. At all known resonances in the 500–850 keV region resonance curves were recorded for (p, α) and (p, γ) simultaneously. Figure 3 shows the result for the 504–506 keV doublet from which it is clear that only the lower component emits alpha particles. At, and just below, every known (p, γ) resonance a pulse-height spectrum of the detected particles was recorded. An example was shown in Fig. 2.

Table I gives a review of the results. For the 504 keV and the 631 keV resonances the angular distribution has been taken into account. The spins and mixing parameters have been obtained from recent measurements in this laboratory [9][10]. The observed yields are about three times smaller than those given by Rutherglen and Smith. The origin of this discrepancy is unknown.

TABLE I

Results for the ^{27}Al(p, α)^{24}Mg yield measurements and values for the reduced alpha-particle width. The errors amount to about 10%, composed of a statistical error of 6% and a systematic error in the solid angle determination estimated as 8%. The values used for the (p, γ) strengths were obtained from reference 3.

Proton energy (keV)	Alpha-particle yield (per 10^{10} protons)		$(2J_r + 1)\,\dfrac{\Gamma_\alpha \Gamma_p}{\Gamma}$ (eV)	$\Gamma_\alpha/\Gamma_\gamma$	J_r^π	$\theta_\alpha^2\,\dfrac{\Gamma_p}{\Gamma}$
	Present experiment	Rutherglen and Smith				
504	0.52	1.2	0.80	1.8	2+	0.05
506	<0.09		<0.14			
611	<0.06		<0.10			
631	1.38	3.6	2.59	0.9	3−	0.14
654	<0.09	<0.15	<0.16			
678	<0.11	<0.15	<0.21			
731	1.54	4.8	3.05	1.7		
735	<0.20	<0.35	<0.39			
742	<0.11		<0.22			
760	<0.08		<0.15			
767	<0.19		<0.38			
773	<0.12		<0.26			

TABLE II

Results for the ^{31}P (p,α)^{28}Si yield measurements. The error in the yield at E_p = 641 keV amounts to 12%.

Proton energy (keV)	Alpha-particle yield (per 10^{10} protons)	$(2J_r + 1)\,\dfrac{\Gamma_\alpha\Gamma_p}{\Gamma}$ (eV)
439	<0.06	<0.08
541	<0.08	<0.15
641	2.4	4.6
811	<0.7	<1.6
820	<0.7	<1.6

For the resonances where no alpha emission was established, upper limits for the yield are given, obtained by adding two times the experimental error to the difference in counting rates at and below resonance. The values for $\Gamma_p\Gamma_\gamma/\Gamma$ used to calculate $\Gamma_\alpha/\Gamma_\gamma$ were obtained from reference 3. The reduced width θ_α^2 was only computed for the two alpha-emitting resonances of which the resonance spin is known with certainty [9][10].

Comparing the results for θ_α^2 with values known for other, mostly lighter, nuclei, one finds rough agreement. With some exceptions, these values lie between 0.01 and 0.20 8).

The reaction $^{31}P(p, \alpha)^{28}Si$. The same experimental procedure was followed for the reaction $^{31}P(p, \alpha)^{28}Si$ in the 400–850 keV region. Only one alpha emitting resonance was established.

Table II gives the results for this reaction. No correction could be made for angular distribution.

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