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THE REACTION $^{20}Ne(p, \gamma)^{21}Na$

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Synopsis

The decay scheme, the width, and the strength of the E_p = 1169, 1955, and 2138 keV resonances in the reaction $^{20}Ne(p, \gamma)^{21}Na$ are reported. The spins of the first two resonances are $J^\pi = 5/2^+$ and 5/2, respectively.

Coincidence and angular correlation measurements at the E_p = 1955 keV resonance yield the excitation energy and spin of the ^{21}Na first excited state: $E_x = 338 \pm 3$ keV and $J^\pi = 5/2^+$. The mixing ratio of the 0.34 MeV γ ray de-exciting this level is $x = 0.05 \pm 0.05$.

Measurements of the resonance- and γ-ray energies yield the reaction Q value, $Q = 2424 \pm 10$ keV. The corresponding ^{21}Na mass excess is -2177 ± 10 keV.

1. *Introduction.* A recent review[1]) of the properties of the ^{21}Na levels shows that very little information is available on the energy levels of this nucleus. Using a thin target, with ^{20}Ne adsorbed on tantalum (obtained through the kind cooperation of Dr. Arnell, Göteborg, Sweden), it was possible to investigate the $^{20}Ne(p, \gamma)^{21}Na$ reaction. The results of this experiment, pertaining in particular to the ^{21}Na first excited state, are reported here.

A short description of the experimental set-up and the method of analysis (2) precedes the discussion of the resonance curve (3), the γ decay of the resonance levels (4), and the reaction Q value (5). In the discussion (6) the results of this experiment are compared with earlier data.

2. *Apparatus and method of analysis.* The reaction was investigated with the 3.2 MV Van de Graaff accelerator of the Utrecht University. Some more details about the 90° deflection magnet, the cooling trap, the target holder, the γ-ray detection equipment (two 10 × 10 cm NaI crystals), and the electronics were given in the report of an analoguous experiment[2]). During the investigation reported here, the experimental possibilities were limited by the fact that the adsorbed ^{20}Ne target withstood a beam of at most 3 Watts.

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In addition to the single and coincidence spectra, some angular distributions and correlations were measured; the latter in four different geometries. These were analyzed in terms of the Legendre polynomials P_2 and P_4:

$$W(\vartheta) = 1 + a_2P_2(\cos\vartheta) + a_4P_4(\cos\vartheta).$$

Using the experimental a_2 and a_4 coefficients, the calculation of the (x_1, x_2) contour diagrams for different assumed spin sequences was performed with a ZEBRA digital computer; here x_1 and x_2 are the quadrupole/dipole amplitude mixing ratios of the first and the second γ rays of the cascade. A quantitative measure for the relative probabilities of the different solutions was found in a χ^2 minimization. Details of this method of analysis were given in reference 2.

3. *Resonance curve*. The ^{20}Ne$(p, \gamma)^{21}$Na resonance curve in the energy range $E_p = 1.1 - 2.2$ MeV, measured in 2–6 keV steps, is given in the lower part of fig. 1. The scintillation counter was placed at $\vartheta = 55°$ with

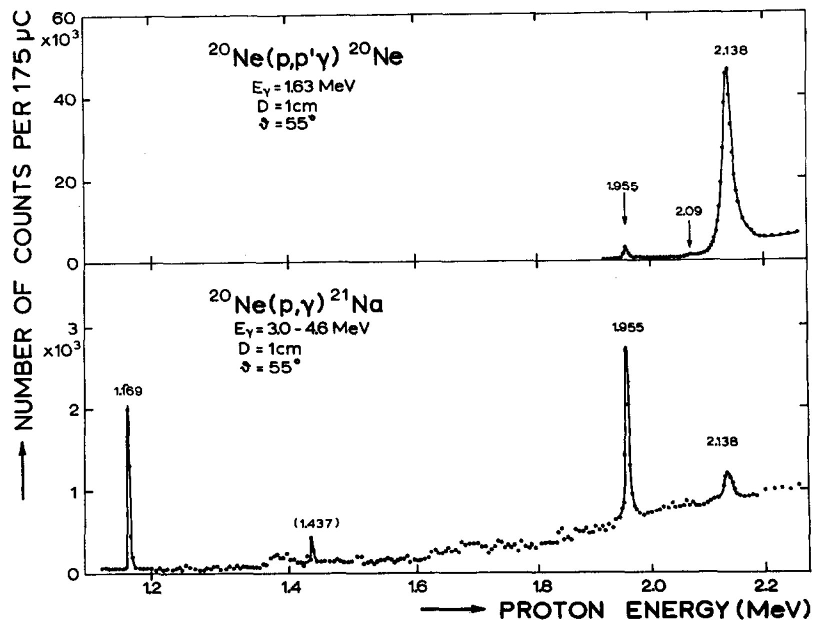

Fig. 1. The ^{20}Ne$(p, \gamma)^{21}$Na and ^{20}Ne$(p, p_1\gamma)^{20}$Ne resonance curves.

respect to the proton beam, at a distance $D = 1$ cm from the target. The γ-ray channel was adjusted in steps to select only transitions from the resonance levels to the ground state and first excited state. The excitation curve measured with a channel set for low-energy γ rays was measured simultaneously. Since it does not give any additional information, it is not plotted in fig. 1.

The yield curve exhibits resonances at $E_p = 1169 \pm 2$, 1437 ± 3, 1955 ± 4, and 2138 ± 5 keV (after relativistic correction), with experimental widths of 3.5, 0.6, 6.3, and 21 keV, respectively. The 992.0 keV $^{27}Al(p, \gamma)^{28}Si$ resonance was used for calibration. The first and the last of the four resonances were known to decay by γ emission. The third resonance has been reported only in the $^{20}Ne(p, p_1)^{20}Ne$ reaction. If the resonance at 1437 keV could be ascribed to the $^{20}Ne(p, \gamma)^{21}Na$ reaction, it would correspond to a ^{21}Na level at 3.82 MeV. Since this energy agrees with that of the level at 3.88 ± 0.05 MeV, found from the $^{20}Ne(d, n)^{21}Na$ reaction, some effort was put in the measurement of the γ-ray spectra of this weak and narrow resonance. It exhibits, however, no γ rays that fit into the ^{21}Na level scheme. Therefore it probably has to be ascribed to some unknown contaminant. This conclusion is confirmed by the measured width of this resonance, $\Gamma_{exp} = 0.6$ keV, which is distinctly less than the target thickness. Comparison of the experimental width of the 1169 keV resonance, $\Gamma_{exp} = 3.5$ keV, with its natural width, $\Gamma \leq 0.7$ keV[3,4]), leads to a target thickness of at least 3 keV for 1169 keV protons.

At the 1955 and 2138 keV resonances, the measured widths, Γ_{exp}, exceed the instrumental widths, Γ_i. An approximate measure of the natural widths, Γ, was found using the relation $\Gamma = \sqrt{\Gamma_{exp}^2 - \Gamma_i^2}$.

The relative resonance strengths were calculated from the areas of the (p, γ) resonance peaks, taking into account the decay schemes of the resonances as discussed below and the variation of the proton wave length. The absolute strengths listed in table I (together with the resonance energies and widths) were calculated by normalization to the value $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma = 1.13 \pm 0.07$ eV for the 1169 keV resonance measured with a gas target[5]).

In the energy range $E_p = 1.9 - 2.2$ MeV a third γ-ray channel was set to select the 1.63 MeV γ rays from the first excited state in ^{20}Ne, populated

TABLE 1

Resonances in $^{20}Ne + p$

Present experiment						Earlier results	
E_p (keV)	$^{21}Na^*$ [a]) (MeV)	Γ (keV)	J^π	$(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ [b]) (eV)	decay	Γ (keV)	J^π
1169 ± 2	3.54		$5/2^+$	1.13 ± 0.07	γ p_0	≤ 0.7 [c])	$3/2^+$, $(5/2^+)$[d])
1955 ± 4	4.29	5.3 ± 1.0	5/2	4.0	γ p_0 p_1	6[e]), 17[f])	$5/2^+$[e])
2090 ± 20	4.41				p_0 p_1		
2138 ± 5	4.46	21 ± 3		1.6	γ p_0 p_1	17[e]), 27[f])	$3/2^+$[e])

[a]) Calculated using $Q = 2424 \pm 10$ keV (see section 5).
[b]) Measured relative strengths normalized to the value 1.13 ± 0.07 ev at $E_p = 1169$ keV (ref. 5).
[c]) References 3 and 4.
[d]) Reference 7.
[e]) Reference 6.
[f]) Reference 12.

in the reaction $^{20}Ne(p, p_1)^{20}Ne$; the result is presented in the upper part of fig. 1. The curve clearly exhibits the 1955 and 2138 keV resonances discussed above. The small bump at 2.09 MeV probably corresponds to the earlier reported inelastic scattering resonance at this energy[6]).

Besides the resonances discussed above, a broad resonance at $E_p = 1810$ keV has been found from elastic proton scattering. In the (p, γ) yield curve this resonance is, apparently, too weak to be distinguishable from background.

4. *Gamma decay.* a. The $E_p = 1169$ keV resonance. The γ rays with their assignments and relative intensities, as found from the analysis of single γ-ray spectra, are listed in table II. The decay mainly proceeds to the ground state. Comparison of the shape of the 3.54 MeV γ ray with that of

TABLE II

Gamma-ray energies, relative intensities, and quadrupole/dipole amplitude mixing ratios measured at three $^{20}Ne(p, \gamma)^{21}Na$ resonances

E_p (keV)	E_γ (MeV $\pm$ keV)	assignment	intensity	quadrupole/dipole ampl. mixing ratio x
1169	3.54 $\pm$ 15	$(r) \to 0$	94 $\pm$ 4	+0.07 $\pm$ 0.02
	1.80 $\pm$ 20	$(r) \to 1.72$	6 $\pm$ 2	
	1.39 $\pm$ 15	$1.72 \to 0.34$	6 $\pm$ 2	
	(1.06 $\pm$ 30)	$2.81 \to 1.72$	$\leqslant 1$	
	(0.73 $\pm$ 30)	$(r) \to 2.81$	$\leqslant 1$	
1955	4.30 $\pm$ 30	$(r) \to 0$	40 $\pm$ 5	+0.20 $\pm$ 0.05
	3.96 $\pm$ 40	$(r) \to 0.34$	60 $\pm$ 5	−0.09 $\pm$ 0.07
	0.338 $\pm$ 3	$0.34 \to 0$		+0.05 $\pm$ 0.05
2138	4.49 $\pm$ 50	$(r) \to 0$	45 $\pm$ 10	
	4.11 $\pm$ 40	$(r) \to 0.34$	55 $\pm$ 10	

the 3.51 MeV gamma from the $^{12}C(p, \gamma)^{13}N$ resonance at $E_p = 1698$ keV, indicates no contribution from a possible transition to the first excited state; its intensity is at most 4%. In addition to the direct transition from the resonance level to the 1.72 MeV level (intensity 6%), a cascade between these two levels, probably through the 2.81 MeV level, is suggested by weak low-energy peaks in the spectrum; its intensity is at most 1%. The proposed decay scheme is given in fig. 2.

The angular distribution of the ground-state transition, $W(\vartheta) = 1 - (0.25 \pm 0.03) P_2 + (0.01 \pm 0.03) P_4$, excludes the resonance spins $J_r = 1/2$ (isotropy) and 7/2 (large P_4 coefficient). The values $J_r = 3/2^-$ and $5/2^-$ can be excluded since the $M2/E1$ mixing ratio which follows from the angular distribution measurement, and the resonance strength, would entail $M2$ transitions of at least 1000 and 15 Weisskopf units, respectively. For $J_r = 3/2^+$, the $E2/M1$ amplitude mixing ratio, $x_{3.54} = -0.48 \pm 0.04$, yields an $E2$ transition strengths of at least 40 Weisskopf units; an improbable value for a d–s shell nucleus. Assuming $\Gamma_\gamma \ll \Gamma_p$, the only remaining possibility, $J_r = 5/2^+$, yields the amplitude mixing ratio $x_{3.54} = +0.07 \pm \pm 0.02$, and the reasonable values $|M|^2 = 0.5$ and 0.2 for the $E2$ and $M1$ contributions, respectively.

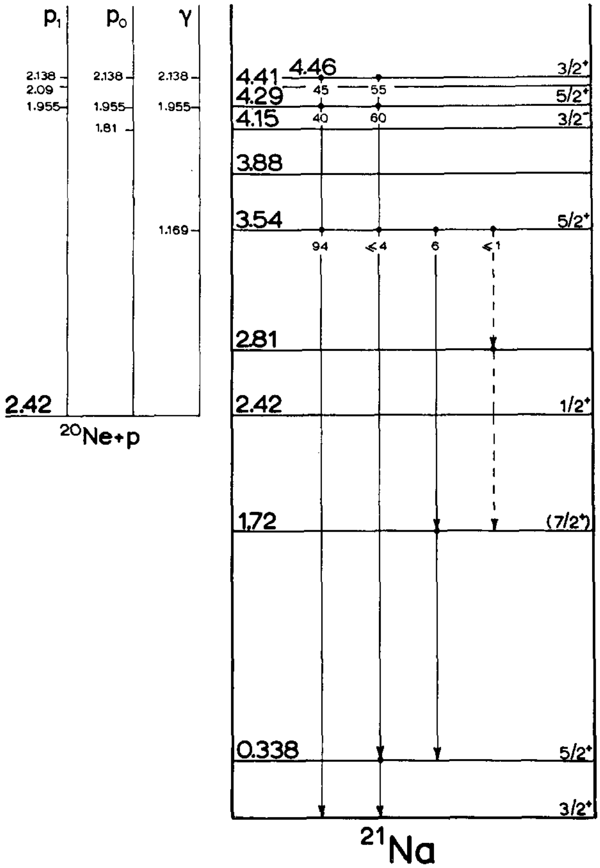

Fig. 2. Decay scheme of the three $^{20}Ne(p, \gamma)^{21}Na$ resonance levels.

b. The $E_p = 1955$ keV resonance. The γ decay at this resonance (see table II and fig. 2) mainly proceeds to $^{21}Na^* = 0$ and 0.34 MeV. Any other transition has an intensity less than 2%.

The γ-ray spectrum coincident with the 3.96 MeV γ ray was measured several times, alternated with calibration spectra. It yields the excitation energy of the ^{21}Na first excited state, $E_x = 338 \pm 3$ keV.

The analysis of the single spectra measured at four different angles with respect to the proton beam, yields the angular distribution coefficients a_2 and a_4 of the 4.30 and 3.96 MeV γ rays listed in table III. This table also gives the angular correlation coefficients of the $(r) \to 0.34 \to 0$ cascade, measured in four different geometries.

TABLE III

Angular distribution and correlation coefficients measured at the $E_p = 1955$ keV resonance

transition	a_2*)	a_4*)
$(r) \to 0$	0.06 ± 0.06	0.02 ± 0.06
$(r) \to 0.34$	0.35 ± 0.05	0.04 ± 0.07
$(r) \to 0.34 \to 0$ (I)	0.48 ± 0.06	0.11 ± 0.07
$(r) \to 0.34 \to 0$ (II)	0.02 ± 0.06	-0.03 ± 0.06
$(r) \to 0.34 \to 0$ (V)	0.13 ± 0.07	0.09 ± 0.07
$(r) \to 0.34 \to 0$ (VI)	-0.31 ± 0.07	0.13 ± 0.08

*) The solid angle correction was applied only to the angular distribution coefficients.

Since the spin of the resonance level ($J^\pi = 5/2^+$) is known from elastic proton scattering experiments[6]), the angular distribution measurement directly yields the $E2/M1$ amplitude mixing ratio $x_{4.30} = 0.20 \pm 0.05$. With the a_2 and a_4 coefficients found for the $(r) \to 0$ angular distribution and the $(r) \to 0.34 \to 0$ angular correlations, the (x_1, x_2) contour diagrams were calculated for the assumed spin values $J(0.34) = 1/2, 3/2, 5/2$, and $7/2$. The analysis absolutely excludes the values $J = 1/2$ and $7/2$. The contour diagram gives an area of overlap for $J = 5/2$ and an area of near-overlap for $J = 3/2$. A χ^2 minimization had to be applied to find the relative probabilities of these two solutions. It follows that the $J = 5/2$ assignment is twenty times more probable than the $J = 3/2$ assignment. Since, moreover, the $J = 3/2$ assignment would entail an improbably large $E2$ admixture ($|M|^2 = 25$) for the $(r) \to 0.34$ transition, we conclude that $J(0.34) = 5/2$. The parity of the 0.34 MeV level could not be determined from this experiment. In conjunction, however, with the results from $^{20}Ne(d, n)^{21}Na$ angular distribution measurements[7]) [8]), yielding $J^\pi(0.34) = 3/2^+$ or $5/2^+$, it may be concluded that $J^\pi(0.34) = 5/2^+$. The following $E2/M1$ amplitude mixing ratios correspond with this assignment:

$$x_{0.34} = +0.05 \pm 0.05 \text{ and } x_{3.96} = -0.09 \pm 0.07.$$

To check the $J = 5/2$ assignment to the resonance level, the data were also analysed assuming the resonance spins $J = 1/2$, $3/2$, and $7/2$. The correlation data uniquely exclude the assignments $J_r = 1/2$ and $7/2$, but for $J_r = 3/2$ a solution can be found. In this case, however, an improbably large $E2$ admixture has to be ascribed to either the first or the second γ ray of the cascade. This result thus corroborates the $J = 5/2$ assignment found in earlier experiments[6]).

c. The $E_p = 2138$ keV resonance. This resonance decays with roughly equal intensities to the ground state and first excited state (see table II and fig. 2). No further conclusions could be drawn due to the weakness of the resonance and the increasing background at higher energies.

5. *The reaction Q value.* Using the resonance energies listed in table I and the γ-ray energies of table II, the Q value for the reaction $^{20}Ne(p, \gamma)^{21}Na$ was calculated. The three values found at the three resonances are in good mutual agreement; the average is $Q = 2424 \pm 10$ keV. With the ^{20}Ne mass excess of -7041.3 ± 0.5 keV[9]) this Q value yields a ^{21}Na mass excess of -2177 ± 10 keV. This result can be compared with the values $-2207 \pm$ ± 30 keV[10]) and -2197 ± 20 keV[11]) found from the β decay of ^{21}Na.

6. *Discussion.* The resonance energies found in this experiment are in good agreement with the values from several earlier experiments[1]). The resonance widths are compared with the results from other investigations in table I; our data are in better agreement with the work of Haeberli[6]) than with that of Valter *et alii*[12]).

The qualitative decay scheme of the 1169 keV resonance given by Benenson and Lidofsky[7]) is in agreement with our results. Their angular distribution measurement of the ground-state transition is in accordance with our measurement, but the conclusions as to the resonance spin differ. Experiments on other (p, γ) resonances have not been reported.

Recently, precision measurements of the excitation energy of the ^{21}Na first excited state have been reported: $E_x = 345 \pm 15$ keV from the $^{20}Ne(d, n\gamma)^{21}Na$ reaction[13]) and $E_x = 335 \pm 5$ keV from the $^{20}Ne(p, \gamma)^{21}Na$ reaction. An abstract with some preliminary results of the latter investigation has been published[14]); the results are in good agreement with our work.

The $J = 5/2^+$ assignment to the 338 keV level in ^{21}Na, and the small $E2/M1$ mixing ratio of the 338 keV γ ray are in agreement with the interpretation of this level as the second level of the $K = 3/2$ rotational band on the ground state.

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