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Accurate Branching Ratio Measurements in $^{23}Na(p, \gamma)^{24}Mg$

S. G. Boydell and D. G. Sargood

School of Physics, University of Melbourne, Parkville, Vic. 3052.

Abstract

The reaction $^{23}Na(p, \gamma)^{24}Mg$ has been investigated in the proton energy range 0·3–1·75 MeV. Gamma ray spectra were measured for 22 resonances with Ge(Li) detectors which were carefully calibrated for relative peak efficiencies. Allowance was made for the effect of anisotropies in all the emitted γ-rays. The spectra have been analysed to give branching ratios for bound and unbound levels.

Introduction

The use of Ge(Li) detectors in the measurement of γ-ray branching ratios has made it possible to obtain results which are unambiguous, accurate and reproducible. Such results can be obtained with relatively simple analysis techniques, provided detector calibrations and experimental arrangements are carefully made and well understood. This paper describes a series of such measurements, of branching ratios of levels in ^{24}Mg up to 13·4 MeV excited via the reaction $^{23}Na(p, \gamma)^{24}Mg$.

Experimental Details

The measurements were carried out with the 800 kV electrostatic accelerator at the University of Melbourne, and with the 3 MV Van de Graaff accelerator at the AAEC Research Establishment at Lucas Heights, N.S.W. Targets of Na_2WO_4 and NaBr were prepared by evaporation onto 0·025 cm tantalum or gold backings. Target thicknesses were chosen to be larger than the natural resonance widths, but much smaller than the resonance separation. The backings were sealed directly onto a knife-edge on the stainless steel target chamber, which was machined to orient the target at 55° to the incident beam. The target chamber was isolated from the main vacuum system by an in-line liquid nitrogen trap, and was maintained at a pressure of 2×10^{-7} torr during experimental runs by means of a getter-ion pump.

The measurements at the University of Melbourne were made using a five-sided coaxial Ge(Li) detector of 35 cm^3 active volume, with a resolution of 2·3 keV for 1·33 MeV γ-rays (the shaping time being 3 μs). The detector pulses were amplified by standard electronics and analysed into 4096 channels. The measurements at the AAEC Research Establishment were made using a 40 cm^3 Ge(Li) detector with 2·0 keV resolution at 1·33 MeV (shaping time 2 μs), and the pulse height analysis was also into 4096 channels.

Detector Efficiency

In the analysis of the spectra, peak areas were used in preference to total line shapes because the latter are not well understood at low pulse heights, and analysis of complex (i.e. more than 10 components) 4096 channel spectra would have required prohibitive amounts of computer storage. In this work, a physical understanding of the spectral regions immediately adjacent to the peaks allowed consistent and reproducible extraction of peak areas from spectra containing up to 25 γ-ray components. Peak areas were defined by reference to these adjacent spectral regions.

Calculated relative peak efficiencies (Wainio and Knoll 1966; Aubin *et al.* 1969; Peterman *et al.* 1972) show good agreement with experiment at energies below 4 MeV, but at higher energies the estimation of bremsstrahlung losses is difficult and can lead to significant errors (Wainio and Knoll; Aubin *et al.*; Seyfarth *et al.* 1972). An empirical calibration of the relative peak efficiency of each detector was therefore undertaken in the energy range 0·5–11 MeV.

Below 3 MeV, the method used for the calibration of the 40 cm^3 detector was an extension of that of Freeman and Jenkin (1966), using the sources ^{88}Y and ^{24}Na to extend the range of the calibration up to 2·8 MeV. For higher energies, the calibration method adopted (Boydell 1973) was based on that suggested by van der Leun *et al.* (1967), using γ-ray pairs from $^{26}Mg(p, \gamma)^{27}Al$. The method was independent of previous Ge(Li) measurements.

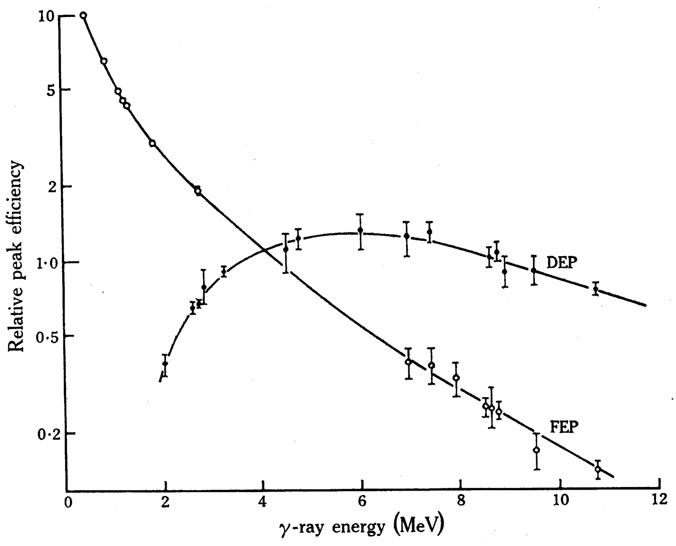


Fig. 1. Relative peak efficiency curves of the 40 cm^3 Ge(Li) detector for the full energy peak (FEP) and the double escape peak (DEP). The FEP efficiency at 0·511 MeV has been taken as 10.

The relative peak efficiency curves are displayed in Fig. 1. An overall uncertainty of $\pm 6\%$ was assigned to both curves. This degree of accuracy was confirmed from tests of the internal consistency of decay schemes from ^{56}Co and $^{27}Al(p, \gamma)^{28}Si$, $^{23}Na(p, \gamma)^{24}Mg$ and $^{31}P(p, \gamma)^{32}S$. All the spectra for these tests were measured in the same geometry as that in which the efficiency calibration was measured, and angular distributions were measured where necessary in order to average out any anisotropies.

The 35 cm^3 detector used with the 800 kV Melbourne electrostatic accelerator was calibrated using the 40 cm^3 detector calibration curves as standard. This was achieved by comparing peak areas in the pulse height spectra from the two detectors obtained from a ^{56}Co source and from the 655 keV resonance in $^{27}Al(p, \gamma)^{28}Si$. The calibration curves are displayed in Fig. 2; they are considered accurate to $\pm 10\%$.

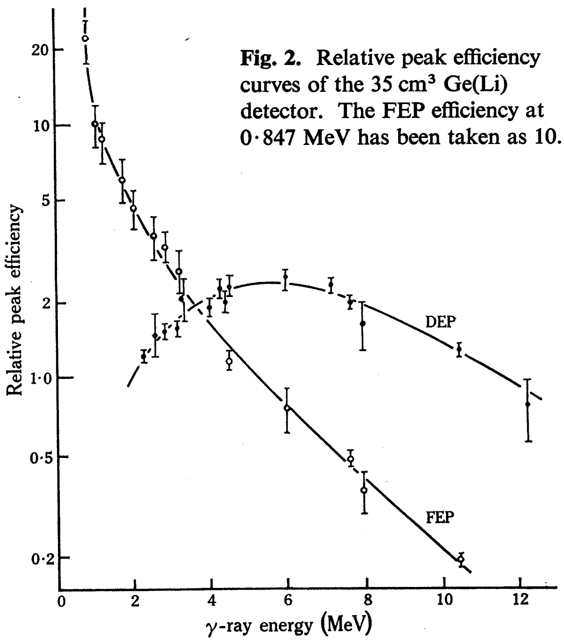


Fig. 2. Relative peak efficiency curves of the 35 cm^3 Ge(Li) detector. The FEP efficiency at 0·847 MeV has been taken as 10.

Detector Geometry

Gamma rays from the reactions under study are in general anisotropic, their angular distributions being normally written in the form

$$W(\theta) = a_0 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta). \qquad (1)$$

Higher order terms are very unlikely, since their presence requires the combination of octupole or higher multipole radiation with f-wave or higher angular momentum protons. Branching ratios are given by the relative values of a_0 for the γ-rays of interest, and measurements must therefore be made in such a way that nonzero values of a_2 and a_4 do not contribute to the observed intensities.

The finite solid angle subtended by a detector will modify equation (1). However, for a cylindrically symmetric detector whose axis passes through the target spot, this modification takes the simple form (Yates 1965)

$$W_m(\theta) = a_0 + Q_2 a_2 P_2(\cos\theta) + Q_4 a_4 P_4(\cos\theta),$$

where Q_2 and Q_4 are the solid angle attenuation coefficients, functions of the detector efficiency and geometry but not dependent on θ. For the above class of detector, therefore, subtension of a finite solid angle does not affect the complexity of the angular distribution. Also, the effect of the $P_2(\cos\theta)$ term is eliminated if measurements are made at $\theta = 55°$. At this angle, the effect of the term in $P_4(\cos\theta)$ relative to a_0 is

$$Q_4(a_4/a_0)\,P_4(\cos 55°) = Q_4(a_4/a_0)\,0{\cdot}38\,.$$

Calculations of Q_4 carried out for the detectors used indicated that at detector–target distances of $<1{\cdot}5$ cm, the value of Q_4 was always sufficiently small ($\sim 0{\cdot}15$) to reduce the effect of the $P_4(\cos\theta)$ term to a few per cent of a_0 (for realistic a_4/a_0 values, i.e. $<0{\cdot}25$). This geometrical arrangement also maximized the count rate.

The calculations were also extended to include off-axis positions of the detector and finite target spots. These indicated that neither the experimental size of the target spot nor the experimental uncertainties in the detector location had any significant effect on the γ-ray relative intensities.

Table 1. Comparison of measured relative intensity values

The intensities have been normalized to a value of 100 for the least anisotropic γ-ray. In method A the detector–target distance was $1{\cdot}3$ cm in the 55° direction, while in method B the distance was $8{\cdot}5$ cm and a full angular distribution was measured. The errors displayed are the sum of the uncertainties in the peak area and the detector placement

Reaction, resonance	E_γ (MeV)	Angular distribution coeffs a_2/a_0	a_4/a_0	Relative intensity method A	method B
^{26}Mg(p, γ)^{27}Al,	0·84	Isotropic	Isotropic	100	100
E_p = 2141 keV	7·35	0·42±0·01	—	74·7±0·8	74·3±0·7
	9·33	0·54±0·03	—	9·3±0·2	9·7±0·2
	9·49	0·38±0·04	—	6·5±0·2	6·5±0·1
^{31}P(p, γ)^{32}S,	1·62	0·33±0·01	0·25±0·01	166±1·5	168±0·5
E_p = 1438 keV	2·16	0·31±0·03	0·01±0·03	38·0±0·6	37·9±0·3
	2·23	0·27±0·01	−0·04±0·01	277±2	276±0·6
	2·78	−0·20±0·01	—	100	100
	3·65	0·44±0·01	0·01±0·02	86·5±0·5	87·6±0·3
	5·01	0·40±0·07	0·00±0·09	1·8±0·2	1·6±0·1
	5·25	−0·54±0·04	0·06±0·04	5·2±0·2	4·7±0·1
	5·80	0·43±0·02	−0·01±0·03	22·1±0·2	21·8±0·5

The calculations depend on the assumption of detector symmetry, and this was checked with narrow beam scans. The location of the germanium crystal within the detector can was also checked, by X-ray photography.

The reliability of the calculations was tested at two resonances: the 2141 keV resonance in ^{26}Mg(p, γ)^{27}Al and the 1438 keV resonance in ^{31}P(p, γ)^{32}S. Branching ratio measurements were made with a detector–target distance of $1{\cdot}3$ cm in the 55° direction, and with a detector–target distance of $8{\cdot}5$ cm, at which distance a full angular distribution was measured and used in determining the branching ratios. The results obtained from the two methods were in excellent agreement; they are displayed in Table 1, together with the angular distribution coefficients of the γ-rays.

Branching Ratio Results

Resonance levels

The measured branching ratios of resonance levels in ^{23}Na(p, γ)^{24}Mg for $E_p < 1750$ keV are presented in Table 2. The errors (displayed as superscripts) arise from peak area errors and the estimated uncertainty (6%) in the relative peak efficiency curve. The values in parentheses are those for which secondary components were obscured, and are tentative. The relative intensities displayed in Table 2 are normalized so that the sum of all non-tentative primary transitions equals 100%. The energies quoted in Table 2 and elsewhere are taken from Meyer *et al.* (1972) and Switkowski *et al.* (1975), as are the J^{π} values given. A typical γ-ray spectrum is displayed in Fig. 3.

A recent measurement (Switkowski *et al.* 1975) of the ^{23}Na(p, γ)^{24}Mg excitation function lists 26 resonances with $E_p < 1 \cdot 75$ MeV whose total strengths are greater than 0·2 eV. All these were investigated, with the exception of the resonances at 1092, 1136, 1638 and 1652 keV. Of these, two (1136 and 1638 keV) are very broad (25 and 45 keV), and the other two are 5 keV wide and weak compared with the (p, p_1 γ) and (p, α_1 γ) channels, causing pile-up difficulties. Machine time considerations precluded measurement of resonances with total strengths below 0·2 eV.

Off-resonance 'background' spectra were measured above and below the resonances to check for nonresonant, contaminant or competing reactions. The most prevalent of these was ^{19}F(p, $\alpha\gamma$)^{16}O, with ^{12}C(p, γ)^{13}N and ^{13}C(p, γ)^{14}N also being observed at several resonances. Such reactions did not mask any of the primary transitions, though in a few cases peak area errors were increased where peaks were superimposed on the severely Doppler-distorted 7·12 MeV γ-ray from ^{19}F(p, $\alpha\gamma$)^{16}O.

Two resonances, at 1021 and 1395 keV, were measured using both target materials (NaBr and Na_2WO_4), as a spot check on any possible contaminant γ-rays from target constituents other than sodium; none was observed.

Measurements of branching ratios of the resonance levels in the energy range considered here have been made by other workers with NaI(Tl) detectors (Flack *et al.* 1954; Glaudemans and Endt 1962, 1963; Prosser *et al.* 1962; Nordhagen and Steen 1964), and by workers with Ge(Li) detectors (Baxter *et al.* 1969; Meyer *et al.* 1972). The most comprehensive of these is the study by Meyer *et al.* (1972).

Comparison of the present work with previous NaI(Tl) results showed overall good agreement. Some ambiguities present in the decay schemes deduced from NaI(Tl) measurements were removed by the present work, and weak components were more easily detected with the Ge(Li) detector.

Comparison of the present work with the Ge(Li) results of Baxter *et al.* (1969) and Meyer *et al.* (1972) showed excellent agreement for most resonances. However, a number of cases arose where weaker transitions observed in the present work were not reported by Baxter *et al.*, possibly because of poorer counting statistics, and in a number of cases it was not possible to reconcile the present results with those of Meyer *et al.* within combined errors. The latter authors quote very small errors ($\sim 5\%$) for their measurements of γ-rays of intensity $>10\%$ of the total decay, but do not quote the accuracy of their relative efficiency calibration, which seems unlikely to be better than 5%.

In the list of further comments which follows, note is made of discrepancies with other workers only where the results fall outside two error bars of each other.

Resonance Level at 512 keV

At this resonance, Meyer *et al.* (1972) report a transition to a non-existing level at 10·26 MeV, of strength 3·6%. If this is assumed to be a typographical error, the level being at 10·06 MeV, then the present results agree with those of Meyer *et al.* and Baxter *et al.* (1969).

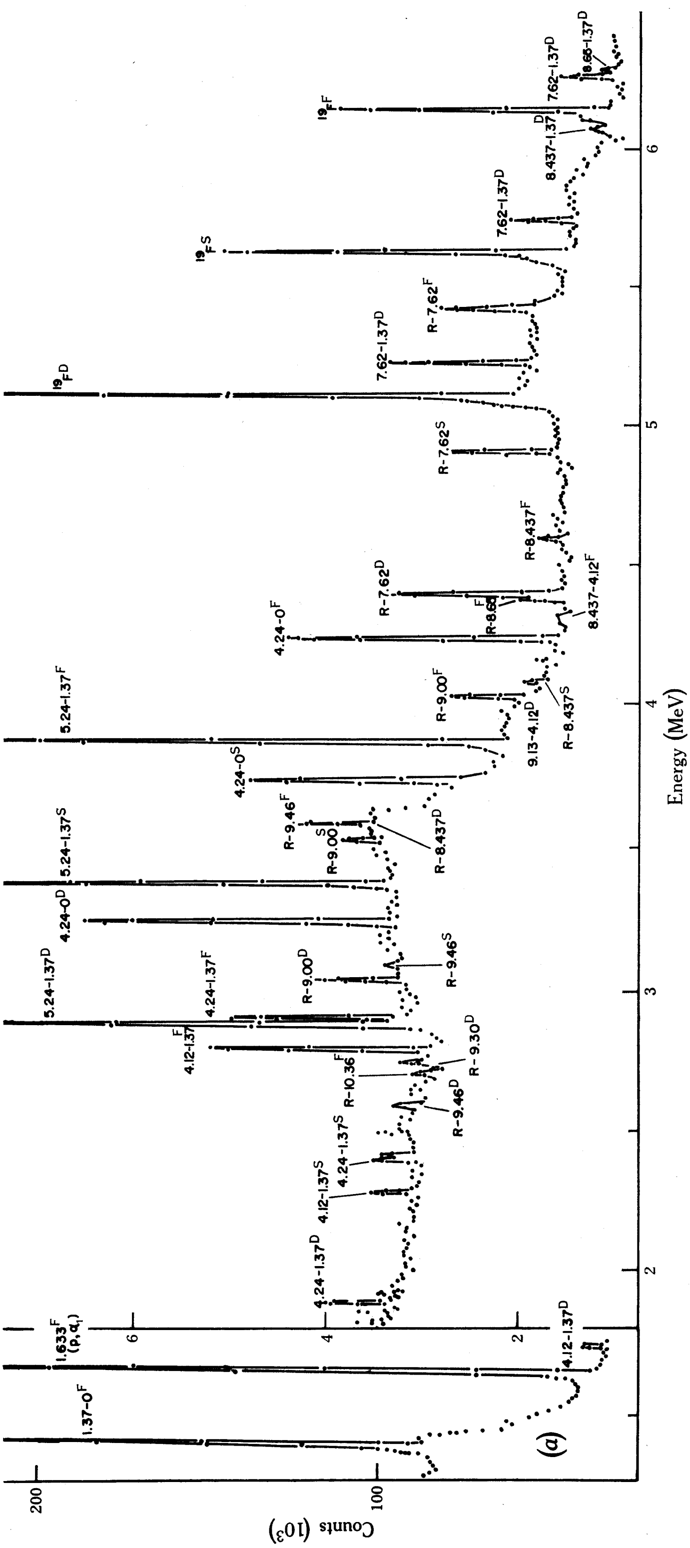
Table 2. Branching ratios of resonance levels in $^{23}Na(p,\gamma)^{24}Mg$

The branching ratios shown for each resonance are normalized so that the sum of all non-tentative primary transitions (printed in bold) equals 100%. The errors which arise from uncertainties in the peak areas and in the efficiency calibrations are displayed as superscripts

Final level		Proton energy (keV) and J^π of resonance										
E_x (MeV)	J^π	309 2^+	512 $1^{(+)}$	592 2^-	677 3^+	739 3^+	744 2^+	872 1^+	988 4	1009 $2^\pm,3^\pm,4^+,5^-$	1011 3^-	1021 2^-
0	0^+	**0·9**$^{0·4}$	**5·4**$^{0·5}$	**1·6**$^{0·4}$	<0·1	<0·9	**2·6**$^{0·3}$	**52**^{4}	<0·6	<1·5	<3	<0·6
1·37	2^+	**32**^{4}	**74**^{5}	**31**^{4}	**13**^{1}	**15**^{1}	**3·6**$^{0·4}$	**6·9**$^{0·6}$	**1·9**$^{0·4}$	<4	**33**^{10}	**11**^{1}
4·12	4^+	<0·7	<0·3	<0·8	**3·0**$^{0·4}$	**1·7**$^{0·4}$	**0·8**$^{0·3}$	<0·6	**74**^{7}	**8·0**^{3}	**18**^{9}	<1
4·24	2^+	**43**^{5}	**9·2**$^{0·7}$	**44**^{4}	**46**^{4}	**42**^{4}	**68**^{4}	**15**^{1}	**3·5**^{1}	**24**^{15}	**23**^{23}	**72**^{6}
5·24	3^+	**8·6**$^{0·6}$	<1·1	**8·8**$^{3·2}$	**20**^{2}	**16**^{2}	**1·3**$^{0·3}$	<1·2	**7·2**^{1}	**10**^{3}	<5	<1
6·01	4^+	<0·5	<0·8	<1·6	<0·3	<0·8	<0·5	<0·5	**10**^{1}	<4	<3	<1
6·43	0^+	<0·5	**1**$^{0·2}$	<1·2	<0·3	<1·1	<0·8	**4·1**$^{0·9}$	<0·6	<3	<4	<1
7·35	2^+	<0·6	<1	**5·1**^{1}	**12**^{1}	**14**$^{1·4}$	<1·6	<0·6	<0·6	**12**^{4}	**10**^{10}	<1
7·55	1^-	(1·8)$^{0·3}$	<0·5	<1	<0·3	<1·2	<0·7	<0·7	<0·6	<3	<3	<1·2
7·62	3^-	<0·6	<0·5	<1	**3·7**$^{0·3}$	**3·4**^{1}	**7·3**$^{0·5}$	<0·6	<0·7	<3	<3	<1·3
7·75	1^+	**4·9**$^{0·5}$	**3·1**$^{0·4}$	<1	<0·3	<1	<0·7	**7·0**$^{0·6}$	<0·5	(4·0)^{2}	<3	**3·4**$^{0·7}$
7·81	(5^+)	<0·5	<0·5	<1	<0·3	<1	<0·8	<0·6	**3·4**$^{0·5}$	<3	<3	<1·4
8·36	3^-	—	—	—	—	—	<0·8	—	—	<2	—	(1·3)$^{0·9}$
8·438	1^-	**2·9**$^{0·4}$		**3·5**$^{0·7}$			**2·3**$^{0·5}$	**3·9**^{1}				
8·65	2^+		**2·3**$^{0·5}$		**0·5**$^{0·2}$		**10**$^{1·2}$	**5·4**$^{0·4}$				
8·86	2^-	**6**$^{0·5}$		**6**^{1}			**2·8**$^{0·8}$	**2·2**$^{0·3}$		<4	**2**^{2}	**14**^{2}
9·00	2^+	(0·4)$^{0·2}$		<2·6	**1·9**$^{0·5}$	(1·5)$^{0·4}$	(0·6)$^{0·4}$					
9·28	2^+	(0·5)$^{0·3}$										
9·46	3^+					(0·9)$^{0·2}$			(1·3)$^{0·4}$			
9·52	4^+					**7·9**$^{0·9}$				**28**^{9}	**9**^{9}	
9·83	1^+			(4·3)^{2}			**1·2**$^{0·2}$	(1·1)$^{0·2}$		<2		(1·3)$^{0·4}$
9·97	1^+		(1·3)$^{0·7}$	<1·9								
10·06	$1^+,2^+$	**0·8**$^{0·1}$	**5**^{1}	(2·5)$^{0·7}$		(1·1)$^{0·5}$		**2·3**$^{0·2}$		**18**^{2}	**2**^{2}	
10·36	2^+						(0·6)$^{0·2}$					
10·66					**0·6**$^{0·1}$							
10·73	1^+	**1**$^{0·3}$	<1·2					**1·1**$^{0·1}$		(1)$^{0·5}$	**2·6**$^{1·5}$	(0·8)$^{0·3}$
11·21	$1^+,2^+$		(1·4)$^{0·2}$									

Table 2 (*Continued*)

Final level E_x (MeV)	J^π	1164 2^+	1174 1^+	1205 $2^+,3^\pm,4^+$	1255 1^+	1283 2^+	1318 1	1395 3^+	1416 4^+	1457 3^-	1726 3^-	1748 $1^-,2^\pm,3^\pm,4^\pm,5^-$
		Proton energy (keV) and J^π of resonance										
0	0^+	**70^{7}**	**36^{3}**	<1	<2	<0·2	**$8{\cdot}7^{0{\cdot}9}$**	<0·3	<0·2	<1	**$0{\cdot}9^{0{\cdot}2}$**	<1
1·37	2^+	**26^{3}**	**10^{1}**	**$9{\cdot}8^{1{\cdot}0}$**	**91^{10}**	**3^{2}**	**90^{9}**	**$2{\cdot}7^{0{\cdot}6}$**	**$0{\cdot}8^{0{\cdot}2}$**	**$5{\cdot}8^{1}$**	**$4^{0{\cdot}6}$**	**$2^{0{\cdot}5}$**
4·12	4^+	<2	<0·4	**37^{3}**	<4	**15^{2}**	<0·7	**$3{\cdot}0^{0{\cdot}4}$**	**91^{7}**	**18^{4}**	**$9{\cdot}0^{0{\cdot}8}$**	**$4^{1{\cdot}5}$**
4·24	2^+	**$4{\cdot}0^{0{\cdot}5}$**	**20^{2}**	**47^{5}**	**5^{2}**	**23^{4}**	<1	**26^{2}**	<0·9	**13^{4}**	**$9{\cdot}7^{1{\cdot}5}$**	<5
5·24	3^+	<2	**$2^{0{\cdot}6}$**	**$2^{0{\cdot}7}$**	**4^{4}**	**36^{17}**	<0·7	**46^{4}**	**$2{\cdot}2^{0{\cdot}3}$**	**27^{9}**	<1	<8
6·01	4^+	<2	<0·5	**4^{1}**	<10	<3	<0·5	<0·6	**$2^{0{\cdot}3}$**	<4	<1·1	<11
6·43	0^+	<2·2	**$6{\cdot}8^{2}$**	<2	<11	<3	**$1{\cdot}4^{1}$**	<0·5	<0·5	<5	<1·2	<12
7·35	2^+	<1·4	$(0{\cdot}5)^{0{\cdot}2}$	<1·4	<10	<3	<0·5	<0·6	<0·4	<4	**$1{\cdot}5^{0{\cdot}6}$**	<24
7·55	1^-	<3	<0·5	<1·3	<8	<3	<0·5	<0·6	<0·4	<2	<1	<10
7·62	3^-	<1·4	<0·5	<1·3	<8	<2·5	<0·5	**10^{1}**	<0·4	<2	**$9{\cdot}2^{3}$**	<11
7·75	1^+	<3	**10^{2}**	<1·4	$(8)^{3}$	<2·5	<0·6	<0·6	<0·4	<2	<1	<11
7·81	(5^+)	<1·4	<0·6	<1·4	<7	<2·5	<0·6	<0·6	<0·4	<2	<1	**24^{3}**
8·36	3^-	—				**18^{2}**				**24^{5}**		
8·437	4^+							**$1{\cdot}6^{0{\cdot}2}$**			**41^{3}**	
8·438	1^-		**$2{\cdot}9^{0{\cdot}4}$**									
8·65	2^+		**$6{\cdot}9^{0{\cdot}8}$**		<15	<3		**$1{\cdot}2^{0{\cdot}7}$**		**4^{1}**		
8·86	2^-		**$2{\cdot}3^{0{\cdot}3}$**									
9·00	2^+							**$3{\cdot}8^{0{\cdot}3}$**			<1·2	
9·28	2^+					**$5^{2{\cdot}5}$**						
9·30	$2^+,3,4$						$(0{\cdot}9)^{0{\cdot}3}$	**$3{\cdot}1^{1}$**			**11^{1}**	
9·46	3^+							**$1{\cdot}7^{0{\cdot}3}$**	**$2{\cdot}1^{0{\cdot}3}$**		**$6{\cdot}7^{3{\cdot}5}$**	
9·83	1^+		**$1{\cdot}7^{0{\cdot}3}$**				$(1{\cdot}2)^{0{\cdot}3}$			**$8{\cdot}9^{0{\cdot}9}$**		
10·02									$(0{\cdot}5)^{0{\cdot}3}$			
10·36	2^+		**$1{\cdot}2^{0{\cdot}2}$**				$(1)^{0{\cdot}2}$	**$1^{0{\cdot}2}$**				
10·58a	$3^\pm,4$								**$1{\cdot}5^{1}$**			
10·58b	$3,4,5$											**70^{15}**
10·66		—									**$7{\cdot}3^{1}$**	
10·73	1^+		**$0{\cdot}3^{0{\cdot}1}$**									
11·52	2^+										<0·5	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100
Energy (MeV)
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3
4
5
6
(a)
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1.633F (p, α1)
4.12-1.37D
4.24-1.37D
4.12-1.37S
4.24-1.37S
R-9.46D
R-10.36F
R-9.30D
4.12-1.37F
5.24-1.37D
4.24-1.37F
R-9.00D
R-9.46S
4.24-0D
5.24-1.37S
R-9.00S
R-9.46F
R-8.437D
4.24-0S
5.24-1.37F
R-9.00F
9.13-4.12D
R-8.437S
4.24-0F
R-8.68F
R-7.62D
8.437-4.12F
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19FF
7.62-1.37D
8.68-1.37D

Fig. 3a

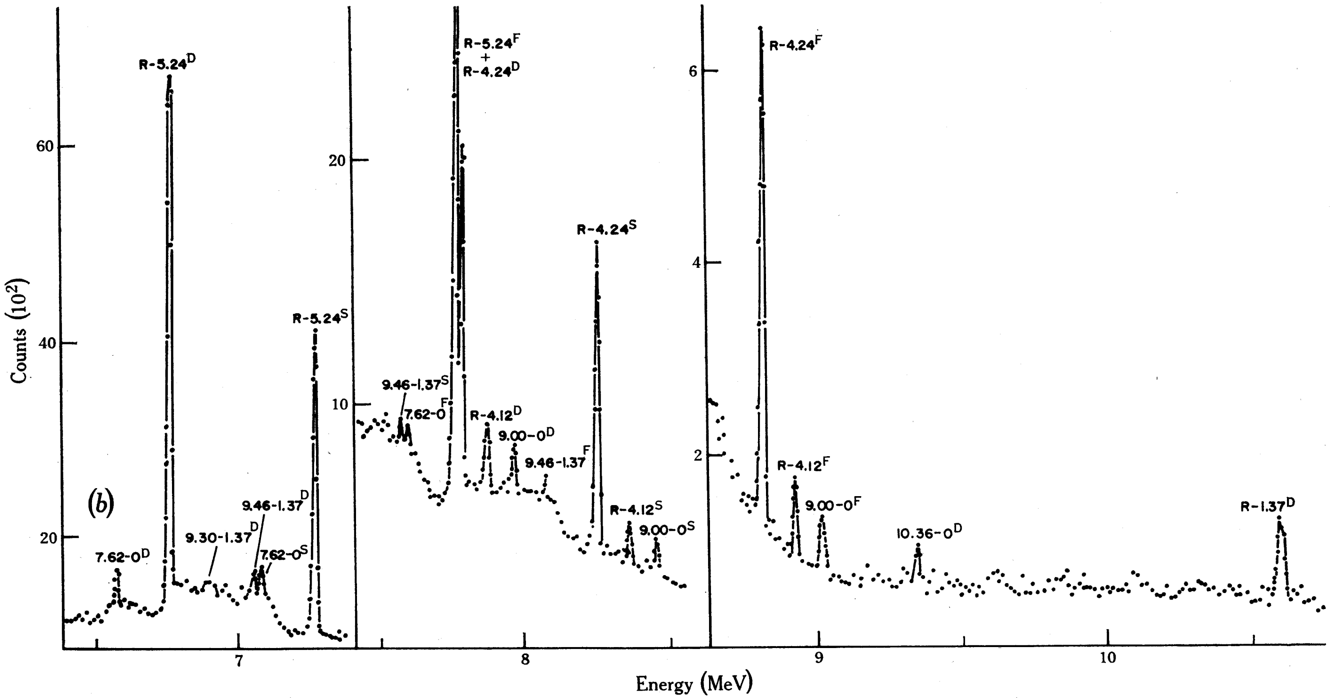

Fig. 3(*a,b*). Gamma ray spectrum from the $E_p = 1395$ keV resonance in $^{23}Na(p, \gamma)^{24}Mg$ measured with the 40 cm^3 detector. The full energy (F), single escape (S) and double escape (D) peaks for the transitions are labelled. Between the peaks only every fifth point is plotted.

Resonance Level at 744 keV

The strength of the transition to the 9·002 MeV level reported by Meyer *et al.* (1972), 2·8%, is significantly stronger than the tentative strength in the present work, 0·6 ± 0·4 %. Glaudemans and Endt (1962), who observed transitions as weak as 0·7%, did not observe this transition. However, Meyer *et al.* would not have resolved the DEP of the 8·654→4·239 MeV transition from the FEP of the transition from the resonance to 9·002 MeV (these peaks were not clearly resolved in the present work, and our overall resolution was some 3 keV better than that of Meyer *et al.*). Analysis of the combined peak in our spectrum, as if it were simply the FEP of the primary transition, led to a value of 2·4 ± 0·4 %, consistent with the value of Meyer *et al.* of 2·8%. The tentative value of 0·6 ± 0·4 % reported here for the transition from the resonance to 9·002 MeV corresponds to the residue after the 8·654→4·239 MeV DEP contribution to the peak area was subtracted. This DEP contribution was calculated from the FEP area and the known DEP–FEP area ratio at this energy.

Resonance Level at 872 keV

Meyer *et al.* (1972) list the intensity of the branch to the 6·432 MeV level as 14%; the present result is 4·1 ± 0·9 % (consistent with the observed decay of this level, which was 4·3 ± 0·4 %). This case is very similar to the previous one. Meyer *et al.* may not have resolved the DEP of the R→6·432 MeV transition from the FEP of the 6·432→1·369 MeV transition, and their high value for the primary transition may be explained if they attributed the whole peak to the primary transition.

The results for the ground state transition are: 52 ± 3·3 % (present paper) and 42 ± 2·1 % (Meyer *et al.*). However, the value of Meyer *et al.* increases to 47 ± 2·4 % if it is assumed that the strength of the branch to the 6·432 MeV level was overestimated (by 10%), as just suggested, and this 10% is distributed amongst the other primary transitions.

Resonance Level at 988 keV

There is general disagreement at this resonance concerning the relative intensity of the branch to the 4·239 MeV level. Prosser *et al.* (1962), using an NaI(Tl) detector, give it as 7%, the present result is 3·5 ± 1 %, Meyer *et al.* give 0·5% and Baxter *et al.* (1969) did not observe it at all. The cause of this disagreement is not understood.

Resonance Levels at 1009 and 1011 keV

Meyer *et al.* (1972) did not resolve these resonances, and they quote branching ratios for the two combined. Comparison with their results is difficult, as both resonances sit on the quite significant tail of the strong broad 1021 keV resonance located 10 keV (about 2·5Γ) away. Contributions from this tail will depend on target thickness and beam energy. However, a comparison did show agreement as to which transitions were present. Intensities also were in general agreement, except for the branch to the 4·24 MeV state, which is also excited strongly by the 1021 keV resonance. The present result is 48 ± 4·5 %, whereas Meyer *et al.* estimated 37%.

In the present work, correction was made for the contribution of the 1021 keV resonance to the spectra measured at 1009 and 1011 keV, using Breit–Wigner resonance shapes together with the total strength and width values of Switkowski *et al.* (1975). The 1009 and 1011 keV resonances were separated by careful monitoring of the 1·63 MeV γ-ray from the α_1 channel, which is strongly fed by the 1011 keV resonance but not observed at the 1009 keV resonance (Endt and van der Leun 1973). Some unavoidable overlap of the spectra of these two resonances gave rise to errors rather larger than normal.

Resonance Level at 1748 keV

At this resonance, there is general agreement between the present results and those of Meyer *et al.* (1972) for the branches with relative intensity greater than 10%, but for branches weaker than 10% there is general disagreement, for which no explanation could be found.

Table 3. Decay modes of bound levels in ^{24}Mg

The errors which arise from uncertainties in the peak areas and in the efficiency calibrations are displayed as superscripts

Initial level E_i (MeV)	J_i^π	$E_f = 0$, $J_f^\pi = 0^+$	Relative intensities for decay to E_f (MeV): 1·37, 2^+	4·12, 4^+	4·24, 2^+	5·24, 3^+	6·01, 4^+	8·437, 4^+
1·37	2^+	**100**						
4·12	4^+	<0·8	**100**					
4·24	2^+	**77**$^{1\cdot5}$	**23**$^{1\cdot5}$					
5·24	3^+	<0·9	**98·5**^{3}	<0·5	**1·5**$^{0\cdot3}$			
6·01	4^+	<6	**87**^{3}	<3	**13**^{3}			
6·43	0^+	<15	**79**^{2}	<6	**21**^{2}	<4		
7·35	2^+	**60**^{4}	**40**^{4}	<7	<1·5	<1	<1	
7·62	3^-	**23**^{6}	**68**^{4}	**9**^{4}	<5	<11	<1·5	
7·75	1^+	**25**^{3}	**75**^{3}	<6	<7	<4	<3	
7·81	(5^+)	<23	<21	**25**^{12}	<18	**55**^{21}	**20**^{9}	
8·36^A	3^-	<15	<11	**34**^{10}	<8	**20**^{6}	**16**^{3}	
8·437	4^+	<2	**60**^{13}	**34**^{13}	**6**^{3}	<4	<1	
8·438	1^-	**82**^{5}	**18**^{5}	<12	<13	<13	<7	
8·65	2^+	<6	**73**^{3}	<10	**27**^{3}	<9	<3	
8·86	2^-	<7	**93**^{5}	<13	**7**^{5}	<10	<5	
9·00^A	2^+	**62**^{15}	<15	<16	<14	<14	<11	<2
9·28	2^+	<17	**100**	<26	<26	<26	<17	<11
9·30	2^+,3,4	<40	**58**^{11}	**42**^{11}	<18	<11	<15	<8
9·46	3^+	<12	**100**	<62	<20	<39	<20	<8
9·52	4^+	<5	<8	**57**^{4}	<9	<12	<16	**43**^{4}
9·83^A	1^+	**60**^{12}	<29	<33	<34	<42	<37	—
10·06	1^+,2^+	<6	**100**	<13	<21	<13	<16	<5
10·58a	$3^\pm$,4^+	<30	<70	<27	**43**^{18}	**57**^{18}	<26	<14
10·58b^A	3,4,5	<2	—	<10	<15	**28**^{10}	**13**^{4}	<25
10·66^A		<7	**60**^{20}	<16	<16	<28	<40	<14
10·73	1^+	<60	**57**^{20}	<50	**43**^{20}	<35	<35	<20

^{A} The decay of these levels is not fully accounted for by the observed transitions (see also Meyer *et al.* 1975); but see Table 5 for 10·58b→8·437 MeV transition.

Bound levels

The measured branching ratios of bound levels in ^{24}Mg excited in this work are displayed in Table 3. The errors (displayed as superscripts) arise from uncertainties in the peak areas and in the relative efficiency curves. Where the branching ratios were measured at more than one resonance, the weighted mean has been taken, with an appropriate reduction in the size of the errors. Upper limits were found for all unobserved transitions in the energy range of the spectrum, and those not displayed in Table 3 may be seen in Table 4. A number of levels were clearly excited but too weakly for extraction of useful branching ratios; they are not listed in Table 3. Table 5 gives a comparison, for a number of levels, of the present work with previous results. The decays of some of the levels require further comment.

Table 4. Upper limits on unobserved decay modes of bound levels in ^{24}Mg

The upper limits are expressed as a percentage of the total decay of each level

E_i (MeV)	Upper limits for decay to E_f (MeV) $E_f = 6{\cdot}43$	7·35	7·55	7·62	7·75	7·81	8·36	8·437	8·438	8·65	8·86
7·35	1										
7·55	3										
7·62	0·6	0·6									
7·75	3	3									
7·81	10	3									
8·36	4	5	11								
8·437	2	3	—	2							
8·438	8	4	3	4	3	3					
8·65	8	2	2	2	3	3					
8·86	4	3	3	3	3	3	3				
9·00	9	4	4	4	3	3	2	2	2		
9·28	2	8	7	—	7	14	19	11	12		
9·30	24	7	—	6	8	11	8	8	8		
9·46	18	9	8	—	8	—	9	8	8	5	
9·52	6	5	5	5	10	6	6	Obs.[A]	4	3	3
9·83	14	12	12	12	22	11	23	—	20	20	40
10·06	25	9	8	8	7	7	5	5	5	5	5
10·58a	27	20	33	19	16	—	23	14	14	13	11
10·58b	14	10	10	Obs.[A]	20	7	7	25[A]	25[A]	5	5
10·66	32	28	12	21	11	17	7	14	14	6	7
10·73	45	50	40	40	30	30	20	20	20	18	16

E_i	$E_f = 9{\cdot}00$	9·28	9·30	9·46	9·52	9·83	9·97	10·02	10·06	10·36
10·06	5	4								
10·58a	11	13	13	14	12					
10·58b	5	7	7	7	Obs.[A]	3	—	3		
10·66	—	—	10	16	8	7	7	8		
10·73	13	12	12	15	15	13	10	10	10	10

[A] See Tables 3 and 5.

Bound Level at 8·36 MeV

The present results differ significantly from those of Ollerhead *et al.* (1968) and Meyer *et al.* (1972) with regard to the branch to the 4·12 MeV level, which was not reported by these authors. The 8·36 MeV level was strongly excited at both the $E_p = 1283$ and 1457 keV resonances. The source of the disagreement may lie in the fact that the transition to the 4·12 MeV level, of energy 4·237 MeV, is indistinguishable from the strong transition from 4·239 MeV to the ground state which is also present at both the above resonances. In the present work, this combined spectral peak had too large an intensity to be accounted for solely in terms of the 4·239 MeV to ground transition. The intensity of the 4·239→1·369 MeV transition (and knowledge of the relevant branching ratio) was used to subtract the intensity of the 4·239 MeV γ-ray, leaving the intensity of the 4·237 MeV transition.

The present work (together with that of Meyer *et al.*) cannot account for 30 ± 20 % of the decay of the 8·36 MeV level. A careful search for other transitions was made; the upper limits are displayed in Tables 3 and 4.

Table 5. Comparison of results with previous work

The present results for branching ratios are compared with those of Meyer *et al.* (1972) and Ollerhead *et al.* (1968)

Bound level E_i (MeV)	E_f (MeV)	Branching ratios (%) Present	Meyer	Ollerhead
8·36	1·37	<11	48±5	Yes
	4·12	34±10	—	Maybe
	5·24	20±6	17±5	Yes
	6·01	16±3	6±5	Yes
	Unknown	30	29	—
8·437	1·37	60±13	69±5	53
($J^\pi = 4^+$)	4·12	34±13	23±5	47
	4·24	6±3	(8±5)	—
8·438	0	82±5	80±10	>70^A
($J^\pi = 1^-$)	1·37	18±5	(20)	<23^A
	4·24	<13	<10	<7^A
10·58a	4·12	<27	70±15	—
(from E_p = 1416 keV)	4·24	43±18	—	—
	5·24	57±18	30±15	—
10·58b	4·12	<10	70±15	—
(from E_p = 1747 keV)	5·24	28±10	30±15	—
	6·01	13±4	—	—
	7·62	(11)±4	—	—
	8·437	<25^B	—	—
	9·52	34±12	—	—

^{A} Definite decays, but the intensities were uncertain.
^{B} This transition possibly exists, but was not resolved from other spectral components.

Doublet at 8·44 MeV

The present work established the existence of an 18% branch to the 1·37 MeV level from the $J^\pi = 1^-$ level of the 8·44 MeV doublet, confirming the tentative 20% branch proposed by Meyer *et al.* (1972). There is no support in our work for the branch from this level to the 4·24 MeV level proposed by Ollerhead *et al.* (1968), of strength <7%, though the upper limit on this transition is not inconsistent with such a branch. The branching ratios for this $J^\pi = 1^-$ level were derived solely from the spectrum obtained at the 872 keV ($J^\pi = 1^+$) resonance, to ensure that the 8·44 MeV level with $J^\pi = 4^+$ was not excited at the same time. The results of the present work for the $J^{\pi} = 4^{+}$ member of the doublet agree with those of Meyer *et al.* and confirm the branch to the 4·24 MeV level proposed tentatively by them.

Bound Levels at 10·58 MeV

A level of this energy was excited at both the 1416 and 1748 keV resonances, but decayed quite differently in the two cases, as may be seen in Table 5. A doublet is therefore proposed at this energy, labelled 10·58a and 10·58b MeV. The results of Meyer *et al.* (1972) do not agree with either proposed scheme of decay.

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