ON THE REACTION $^{23}Na(p,\gamma)^{24}Mg$ AND THE ENERGY LEVELS OF ^{24}Mg

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Summary

The energies of at least 20 γ-rays emitted from the 302 kV resonance level of $^{23}Na(p,\gamma)^{24}Mg$ have been measured with sodium iodide crystals employed as (*a*) single crystal spectrometer, (*b*) scintillation pair spectrometer, (*c*) " cascade " spectrometer. A tentative decay scheme involving levels at 1·38, 4·25, 5·3, 5·8 or 6·2, 7·73, 8·57, 10·60, 11·23, 11·62, and 12·03 MeV is proposed for ^{24}Mg. The effect of isotopic spin on the transition probabilities is discussed and some spin and parity assignments made. The resonance concerned has been determined as being at $302\cdot2\pm0\cdot6$ kV, and is believed to be less than 50 V wide.

I. INTRODUCTION

Apart from the well-established levels at 1·38 and 4·14 MeV that are excited in the decay of ^{24}Na, the energy levels of ^{24}Mg have not received considerable attention. Other levels reported have been (Mandeville 1949) 0·83, 1·24, 1·66, 4·16, 7·70, and 8·64 MeV from the $^{23}Na(d,n)^{24}Mg$ reaction, and $1\cdot5\pm0\cdot2$, $4\cdot2\pm0\cdot2$, $5\cdot5\pm0\cdot3$, $7\cdot3\pm0\cdot3$, $8\cdot3\pm0\cdot4$ MeV from the scattering of 15 MeV protons (Fulbright and Bush 1948). In a more accurate scattering experiment, using 8 MeV protons, Hausman *et al.* (1952) have found levels at 1·38, 4·13, and 4·24 MeV.

The only published measurements of the energies of γ-radiation emitted from the reaction $^{23}Na(p,\gamma)^{24}Mg$ are those of Casson (1953). It would appear worth while supplementing this information with data obtained from experiments undertaken at the Clarendon Laboratory, Oxford, even though the work had to be terminated, some 12 months ago, before conclusive results were reached.

II. EXPERIMENTAL

(*a*) *Accelerator and Target Details*

A 1 MV Cockcroft-Walton generator, manufactured by Philips of Eindhoven, delivered a maximum analysed proton current of between about 50 and 150 μA, according to the particular conditions prevailing at the time of operation. The set was ripple suppressed by a phase controlled feedback system that eliminated the fundamental frequency, but left about 100 V peak to peak of second harmonic at 300 kV. As the potential drop across the ion source plasma was about 50 V (Thonemann *et al.* 1948), the beam energy spread was around 140 V at 300 kV. An automatic voltage control kept the mean voltage constant to within 250 V, and careful manual control could maintain the mean voltage within 100 V.

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For resonance measurements, a 3-photoelectric-cell voltage cutter accepted counts within any desired voltage range down to 160 V in width. For a given number of beam integrator counts at a fixed beam potential, counts were recorded from two end-window Geiger counters, arranged so as to eliminate fluctuations in beam position and current distribution within the beam. Thick targets of metallic sodium and calcium fluoride were used.

For the γ-energy measurements, targets of sodium chloride, 50–100 keV thick, were used. About $\frac{1}{8}$ in. of brass and copper intervened between the target and the sodium iodide crystals. To prevent carbon being deposited on the target, a liquid-air cold trap was inserted between the second defining diaphragm and the target chamber, whilst the main silicone oil diffusion pump was fitted with a glycol-refrigerated baffle.

(*b*) *Single Crystal Spectrometer*

A conventional scintillation spectrometer was constructed using a 1-in. cube of thalliated sodium iodide, an EMI 5311 photomultiplier of only 35 μA/lm, and either a single channel or a 25-channel pulse-height analyser. The crystal was sealed in a " Perspex " box painted with magnesium oxide and, together with the photomultiplier and cathode follower, was housed in an ebonite tube. Individual points of the single channel runs were made for some multiple of 10,000 monitor counts, the monitoring pulses being taken from the output of the main amplifier. This was considered to be more reliable than the use of a beam integrator, as it automatically corrects for target deterioration or beam scattering. Twelve single channel runs were made, covering the spectrum in three stages, and 18 multi-channel runs were made covering the spectrum above 1 MeV in four stages. In addition two multi-channel runs were made to cover the region below 1·5 MeV in two sections.

(*c*) *Scintillation Pair Spectrometer*

The block diagram (Fig. 1) presents the salient features of this spectrometer. The centre crystal was a 1-in. cube, whilst the side crystals were 4 cm in diameter and 3 cm long. A dry box was used to wrap the freshly polished crystals in aluminium foil and then mount them in paraffin-filled thin duralumin containers with " Perspex " windows. The separation of the upper surfaces of the two side crystals was 5·3 cm. The two single channel pulse-height analysers selected pulses in the energy range of 0·3–0·55 MeV. The coincidence unit was usually set to 0·1 μsec resolving time and any coincident pulses opened the cathode follower type of gate with a 100 V, 5 μsec square pulse. Reasonable statistics were obtained for 12 runs varying from 200 to 700 μAh of proton bombardment.

(*d*) " *Cascade* " *Spectrometer*

A single channel pulse-height analyser, selecting a narrow band of the γ-spectrum formed in one crystal, opened a 1·7 μsec gate to allow pulses from a second crystal to operate a 25-channel pulse-height analyser. This enabled energy determinations to be made of the γ-rays in cascade with a selected γ-ray or group of γ-rays. Twenty runs from 100 to 500 μAh were made, the statistics of the shorter runs being rather poor.

(e) *Calibration*

Calibration was achieved with the use of ^{22}Na, ^{65}Zn, ^{24}Na, ThC″, and ^{9}Be(α,$n\gamma$) sources plus ^{19}F(p,γ) and ^{11}B(p,γ) reactions. Linearity was retained for all energies except for an indefinite 0·1–0·2 MeV "shift" at 11·7 MeV when using the pair spectrometer. This shift is attributed to the combined effect of electrons and bremsstrahlung radiation escaping from the crystal. (The apparent position of the pair peak for 17·6 MeV γ-rays was found to have shifted 2·5 MeV for a single 1-in. cube.) The possible presence of ^{19}F contamination was simply checked by comparing runs made above and below the ^{19}F 340 kV resonance.

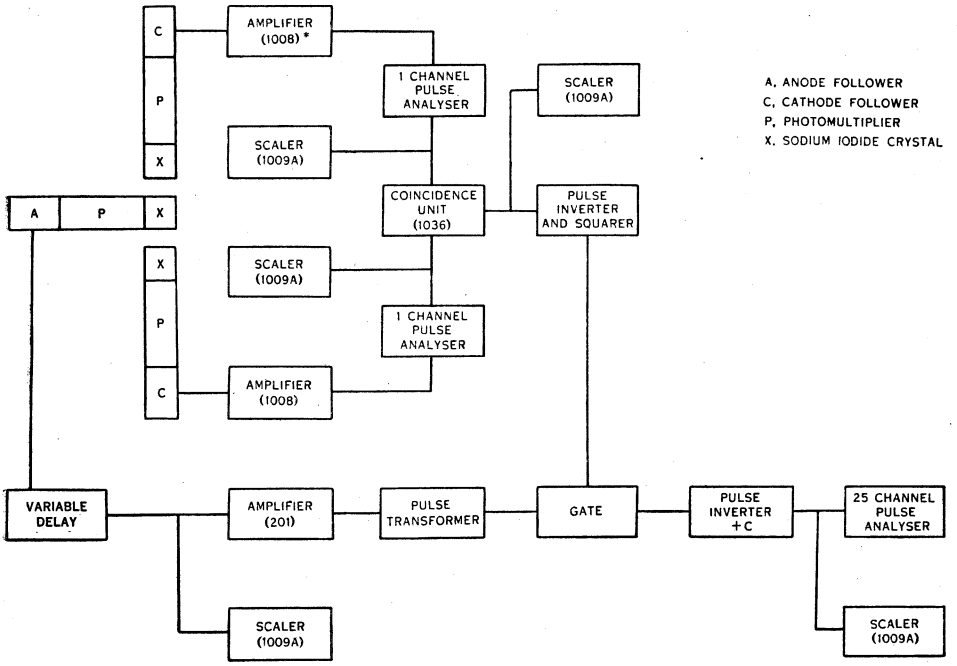

Fig. 1.—Block diagram for scintillation pair spectrometer.
*Electronic unit type numbers correspond to A.E.R.E. (Harwell) specifications.

III. Results

(a) *Resonance Values*

Assuming that the ^{19}F resonance is at 340·4±0·4 kV (Morrish 1949), then the lowest important ^{23}Na resonance was found to be 302·2±0·6 kV. The apparent width of this level was observed to be even less than the expected experimental width. The full width at half-height of the corrected resonance is believed to be less than 50 V. As the thick-target radiation below 302 kV is less than 1 per cent. of that above that energy, this needle-sharp resonance is ideal for a rapid check on the voltage calibration.

A single rough determination of the next intense level resulted in a value of 594·5±1·5 kV with a full width at half-height (or, more correctly, $\frac{3}{4}$–$\frac{1}{4}$ of

thick-target radiation increase) of 400 ± 150 V. Burling (1941) determined these resonances as being at 310 ± 10 and 598 ± 10 kV, whilst another level at 676 kV was misprinted as 576 kV. This misprint has been transferred to Alburger and Hafner (1950).

(*b*) *Energy Measurements*

The energies, E, of peaks in the spectra obtained from the various experiments are summarized in Table 1. The single crystal data are divided into two groups according as to whether the results were obtained from single channel or 25-

TABLE 1

γ-ENERGY AND INTENSITY

1 Channel		25 Channels		Pairs		Cascade		$E\gamma$ (MeV)	I
E (MeV)	No.	E (MeV)	No.	E (MeV)	No.	E (MeV)	No.		
		0·22	1						~25
		0·41	1					0·41±0·02	~15
0·51	2	0·51	2			0·51	2		~40
						0·63	6	0·63±0·03	≲30
0·81	2	0·8	1U			0·80	6	0·80±0·02	~50
1·0	2	1·0	1			1·1	3	(1·38)	
1·37	2	1·38	3			1·4	12	1·38±0·02	~70
1·85	1U			1·83	3	1·85	6	2·86±0·08	20
2·1	2U	2·1	4			2·2	7U		
2·35	4	2·5	2	2·40	3	2·5	2U	3·43±0·07	14
2·87	3	2·8	3	2·9	6	2·9	1	3·89±0·06	18
3·35	4	3·25	5	3·30	6	3·2	1	4·30±0·06	28
		3·55	7					(4·30)	
4·2	1U	4·25	4	4·3	3U			5·3 ±0·15	1–2
		4·7	3U	4·8	3U			5·8 ±0·15	2–3
5·13	3	5·1	3	5·16	3			6·15±0·10	4
5·73	4	5·65	9	5·75	3			6·75±0·15	3
6·15	3	6·1	6	6·2	3			7·18±0·12	6
6·75	7	6·71	9	6·71	7			7·73±0·06	44
7·4	3U	7·5	2U	7·5	2U			8·5 ±0·2	~1
8·15	5	8·2	4	8·25	4			9·22±0·10	13
8·8	4U	8·85	3U	8·85	3			9·85±0·15	7
9·5	7	9·6	3	9·6	4			10·60±0·12	13
				10·2	2U			11·2 ±0·2	4
10·8	4U			10·8	2			11·8 ±0·15	23

channel pulse-height analysers. The numbers in the column associated with each energy column represent the number of occasions that the particular peak was identified. If the peaks were not statistically significant, the letter U has been added. The energies of the γ-transitions believed to be responsible for the various peaks are listed under E_γ. They have been determined from the mean of all peak energies weighted according to the accuracy of the particular run. The errors are estimates derived from the statistical variation of the apparent peak position, and the extent to which it may be separated from other

peaks. Casson (1953) reported 11 peaks each of which may be identified with one of the peaks in Table 1, but his interpretation of some of these peaks differs slightly from the above.

In each experiment, the spectrum had to be covered in at least three overlapping sections, usually with different degrees of amplification. It is therefore difficult to combine the various runs into a single curve unless no attempt is made to insert the original points on the curve. The pair spectrometer runs are readily correlated in terms of the number of side crystal coincidences, the total of which was 132,000. The amplifications, which varied from 4 analyser channels/MeV to 11 channels/MeV have been normalized to 5·5 channels/MeV for presentation in Figure 2. For comparison of peak shape, four calibration

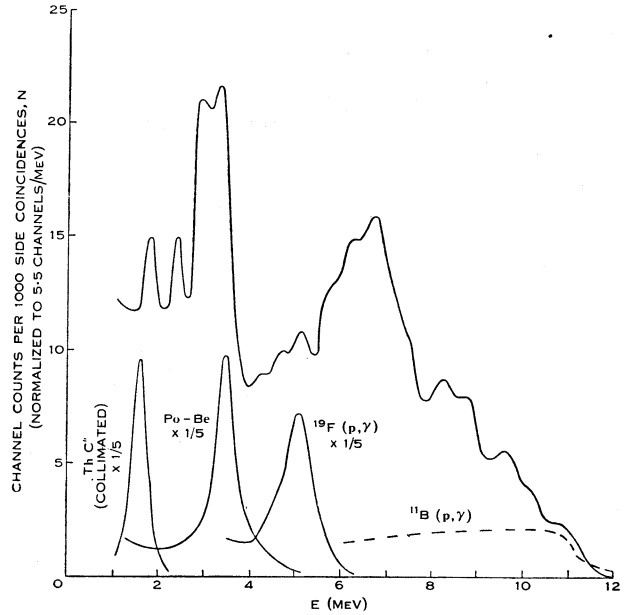

Fig. 2.—γ-Spectrum from $^{23}Na(p,\gamma)^{24}Mg$, using a pair spectrometer.

energies are also shown. It is noted that as the γ-ray energy increases, the change in slope of the lower energy side of the peak is increased, until at 12 MeV the peak virtually disappears. This is attributed to the escape of bremsstrahlung radiation from the crystal. The rise in the low energy tail of the peaks is attributed to the escape of electrons from the crystal, plus the detection of electrons emitted from the target backing. The pair spectrometer curve for 11·7 MeV radiation from $^{11}B(p,\gamma)^{12}C$ was found to be inferior to that from a single crystal, which still exhibited the remnant of a pair peak. This effect is considered to be due to bremsstrahlung radiation escaping from the centre crystal in sufficient quantities to be competitive with annihilation radiation in operating the coincidence gating circuit, thereby enhancing the detection of bremsstrahlung events. As a result, the apparent peak energy appears to be lowered by about 0·2 MeV for 12 MeV γ-rays.

Using the shape of the calibration curves as a basis for determining the contribution each γ-ray makes to the overall curve of Figure 2, values of $\int_0^E N\mathrm{d}E$ were estimated for each γ-ray, where N represents the number of channel counts per 1000 side coincidences and E the energy in MeV. The intensity was then taken to be $I=(10/\eta)\int_0^E N\mathrm{d}E$ where η is the per cent. efficiency of pair production plus escape of both annihilation quanta for a 1-in. cube of sodium iodide. Intensity values are listed in Table 1. In some instances, such as when two or more γ-rays are insufficiently resolved, these estimates may be in error by a factor of two or more. The intensities of γ-rays with energies less than 1·5 MeV have been estimated from photo-peaks obtained with single crystals. In these cases, η is the per cent. efficiency of photo-electron production plus capture of Compton scattered radiation. The calculated intensity values in this energy range are very approximate.

(*c*) *Energy Levels of* ^{24}Mg

As the Q value for the reaction at 302 kV is 12·03 MeV (Alburger and Hafner 1950), energy considerations alone would suggest the simple cascades 10·6+1·4 MeV and 7·7+4·3 MeV. Unfortunately, the results of the cascade experiment do not support such a suggestion. With the gating range set to cover any region between 12·0 and 9·4 (apparent) MeV, the only cascade γ-rays detected were 0·80 and 0·63 MeV. The 0·63 MeV peak is believed to be mainly a photo-peak, and not merely the Compton of the 0·8 MeV γ-ray. The two peaks have the same apparent height.

The 0·83 MeV level of Mandeville (1949) could be responsible for the 0·8 MeV γ-ray if an additional level at either 1·4 (not the 1·38) or 11·4 MeV is postulated. However, all recent proton scattering experiments (Gove and Hedgran 1952 ; Gove and Stoddart 1952 ; Hausman *et al.* 1952) indicate that the only level below 4·1 MeV is the 1·38 MeV level.

In general, the available data are best represented by assuming that the levels concerned are at 10·60 and 11·23 MeV. In an effort to confirm the existence of an 11·2 MeV level, the proton energy was raised above the 595 kV resonance and a run taken with the gating range set to 9·5–10·5 MeV. It was found that the 0·8 MeV γ-ray was replaced by either a 1·1 MeV γ-ray in the presence of a 1·4 MeV line or otherwise completely to 1·4 MeV. This suggests the possibility that the direct transition to the 1·38 MeV level which appears to be forbidden for the 302 kV resonance is permitted at 595 kV.

With the gating range set to any part of the pair peak energy region of 7·8–9·3 MeV, the cascade spectrum is found to include peaks at 1·4 and 1·1 in addition to 0·8 and 0·6 MeV. This means that the introduction of the 9·2 and 9·8 MeV γ-rays into the gate has added a 1·4 MeV γ-ray to the cascade. Apparently these two γ-rays represent transitions to the 1·38 MeV level from the 10·6 and 11·2 MeV levels respectively.

The next region investigated was in the gating range 6·2–7·5 MeV which introduces the 7·2, 7·7, and 8·5 MeV γ-rays. The cascade peaks were found to

be 1·4, 1·85, 2·9, and 3·2 MeV, with somewhat indefinite subsidiary peaks at 2·2 and 2·5 MeV which could at least partly be accounted for by the contribution from 2·85 and 3·9 MeV γ-rays. The 3·2 MeV peak, which was smaller than the 2·9 MeV peak, may be due entirely to a 3·9 MeV γ-ray, or there may be a contribution from the 4·3 MeV γ-ray. As the cascade spectrum was not investigated below 0·5 MeV, it is also possible that the 0·41 MeV γ-ray was also present. It is tempting to consider the transition 0·4+3·9+7·7 MeV. Such a transition could proceed through levels at about 4·3 and 3·9 MeV, but for reasons similar to those advanced against the existence of 0·8 and 1·7 MeV levels, a 3·9 MeV level is not favoured. However, a level in the vicinity of

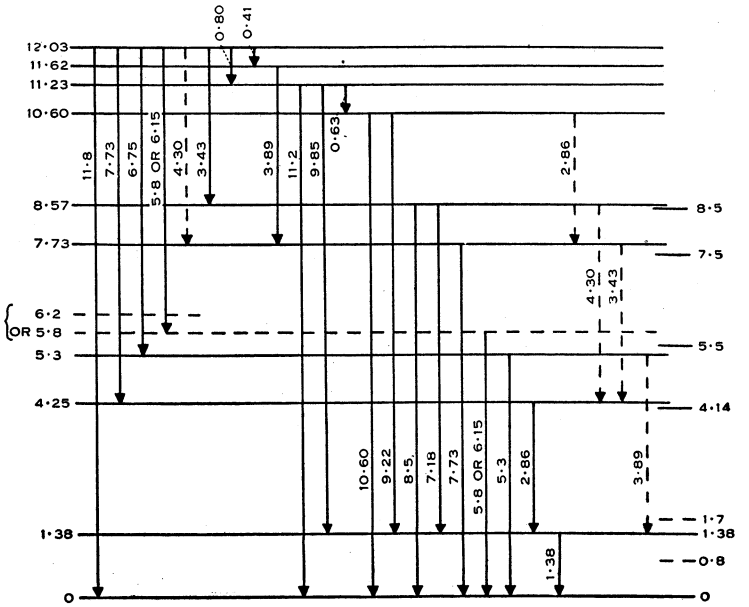

Fig. 3.—Proposed decay scheme for the 302 kV resonance of $^{23}Na(p,\gamma)^{24}Mg$. Level energies on the right are from Alburger and Hafner (1950). All energies are in MeV.

7·7 MeV has been reported and would suggest that this is the required level, in which case one has to choose between additional levels at either 8·1 or 11·6 MeV. The latter is favoured because (i) it is near the continuum, (ii) it lies in a region not previously investigated, (iii) the 8·1 MeV region has been covered without locating a level.

The other transition involving 7·7 MeV indicated by the cascade results was 7·75+2·85+1·4 MeV. The errors are insufficiently large to suggest that this is in reality a 7·9 MeV γ-ray proceeding to the well-known 4·14 MeV level. Instead, the best fit was for a transition to a level at about 4·25 MeV, which could be a 0+ vibrational level expected from the α-particle model to be at about 4–5 MeV. A level at 4·24±0·02 MeV has since been found by Hausman

et al. (1952). If this level is 0+, then any 4·3 MeV radiation that may be in cascade with the 7·7 MeV γ-ray would have to be to the 7·73 MeV level.

The 7·2 and 8·5 MeV γ-rays included in the 6·2–7·5 MeV gating range may be associated with the 2·5 MeV peak which could include the pair peak from the 3·43 MeV γ-ray. As a level is known to exist around 8·5 MeV, it appears reasonable to assume that the transitions 3·4+8·5 and 3·4+7·2+1·4 occur through a level somewhere between 8·55 and 8·60 MeV. As the 5·3 and 6·75 MeV γ-rays add up to the Q value and a level is known to be near 5·5 MeV, a simple cascade through a 5·3 MeV level is assumed. The remaining γ-rays of 5·8 and 6·15 MeV probably also form a direct cascade through a level in the region of 5·8 or 6·2 MeV.

The above conclusions are presented in Figure 3 as the best representation of the existing data. On the right-hand side are the levels given by Alburger and Hafner (1950). The dotted transitions on the right represent possible additional γ-rays whose energies approximately coincide with γ-rays selected in the main decay scheme. In particular, the possible 4·3 MeV transition from the 8·57 to the 4·25 MeV level is wanted to partly fulfil the intensity requirements. Even then the intensity of the 4·3 MeV transition is insufficiently satisfied.

IV. Discussion

Using the formulae for approximate γ-transition probabilities given by Blatt and Weisskopf (1952), even though the formulae are based on a single particle model, a 12 MeV E2 transition is about four times more probable than a 0·8 MeV E1 transition. As the discrepancy between theoretical and experimental lifetimes may be as great as two or three orders of magnitude, it is seen that if the 0·4, 0·6, and 0·8 MeV γ-rays are E1 transitions, then they could successfully compete with the higher energy γ-rays provided that the latter were E2, or higher forbidden, transitions.

It is of interest to invoke the question of isotopic spin. The level of ^{24}Mg corresponding to the ground states of ^{24}Na and ^{24}Al (Birge 1952) is expected to be at about 10 MeV. As the ground state of ^{24}Na has a spin of 4 units (Smith 1951) it is unlikely that the corresponding state in ^{24}Mg is the 10·6 MeV level as it has a direct transition to the ground state. The energy levels of ^{24}Na as determined by Sperduto and Buechner (1952) are compared with the higher levels of ^{24}Mg (Alburger and Hafner 1950) in Figure 4. The position of the ground state of ^{24}Na relative to the ^{24}Mg levels has been deliberately adjusted to indicate the possibility of the 10·60 and 12·03 levels having $T=1$ and the 11·23 and 11·62 MeV levels having $T=0$. If this should be true, then the 0·4, 0·6, and 0·8 MeV γ-rays would be unaffected by the isotopic spin selection rule that forbids electric dipole transitions between two pure $T=0$ states (Radicati 1952). However, in practice there is usually a slight mixing of $T=0$ and $T=1$ states (Radicati 1953; Wilkinson and Jones 1953) so that E1 transitions between two nominally $T=0$ states are inhibited rather than prohibited.

If the 12·03 MeV level is really a $T=1$ state, then an interesting consequence results. Electric dipole transitions would then be allowed to any level below

10 MeV (being $T=0$ states), but apart from the 1·38 MeV transition no γ-ray has been found with an intensity considerably greater than the 0·8 MeV γ-ray, so one is forced to conclude that E1 transitions do not occur for energies greater than 0·8 MeV. As the ground state, 1·38, and 4·14 MeV levels are known to be 0+, 2+, and 4+ respectively, then the 12·03 MeV level cannot have odd parity (unless $J>5$) and must have even parity. The 302 kV resonance is then

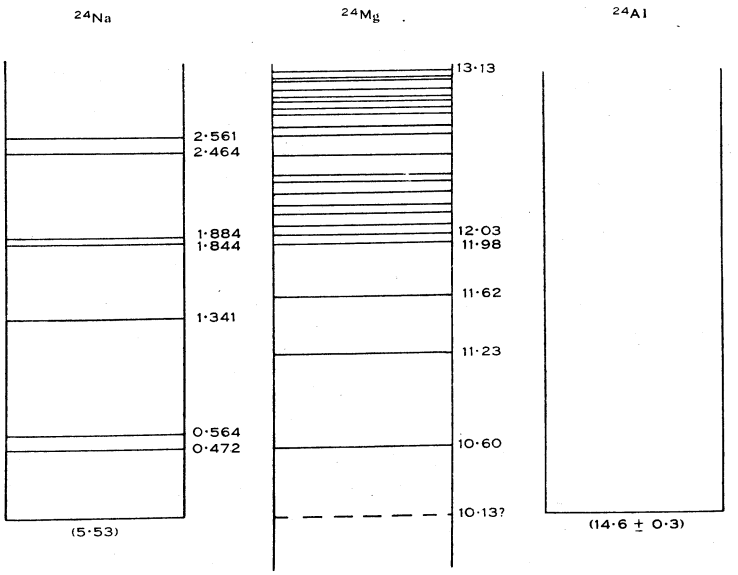

Fig. 4.—Comparison of the known energy levels of the isobaric nuclei ^{24}Na, ^{24}Mg, ^{24}Al over a 3 MeV region.

apparently due to a P proton wave. This agrees with that expected from the narrowness of the level (Christy and Latter 1948). This resonance level may then be a 1+, 2+, or 3+ state. The 3+ state is unlikely as it would require an M3 transition to the ground state to be much faster than M1, E2 admixtures to the 1·38 and 4·14 MeV levels. The possible total angular momentum, J, and parity assignments for all levels are given in Table 2.

TABLE 2

TOTAL ANGULAR MOMENTUM AND PARITY ASSIGNMENTS

E (MeV)	0·0	1·38	4·14	4·25	5·3	5·8	7·73	8·57	10·60	11·23	11·62	12·03
J, parity	0+	2+	4+	0, 1, 2, 3+	1, 2+	1, 2+	1, 2+	1, 2+	1, 2+	1, 2—	0, 1, 2—	1, 2+

Following Wilkinson and Jones (1953), an estimate of the proportion of $T=1$ in the 11·2 MeV level may be made from the measured intensities of the 11·2 and 9·8 MeV γ-rays. If the level were to be 1—, then the E1 11·2 MeV γ-ray has its intensity relative to the E1 0·63 MeV γ-ray reduced by a factor of about 40,000 and the E1+M2 9·8 MeV γ-ray by about 15,000. If the level

were a 2-state, then the M2 11·2 MeV γ-ray should be one-seventh of the intensity of the E1 0·63 MeV γ-ray, which happens to be about the ratio of experimental intensities. As about half of the 9·8 MeV γ-rays may be accounted for by an M2 transition, the E1 reduction is of the order of 30,000. In either case, therefore, about 0·5 per cent. $T=1$ mixed with the nominal $T=0$ state would account for the transition intensities from the 11·2 MeV level.

The validity of the proposed decay scheme appears to be not incompatible with known transition probabilities. However, it is quite expected that other levels and other transitions are yet to be found, and that some of the transitions suggested are actually incorrect. There remains, for example, an outstanding difficulty that is not readily explained in terms of spin changes, isotopic or otherwise, and that is the lack of a transition from 12·03 MeV to 1·38 MeV.

Repeating this experiment at higher resonance levels should assist considerably in determining whether the cascades indicated are in the correct sequence. It could also resolve some of the possibly duplicated γ-rays. The pair spectrometer that was used followed the principle of Johansson (1950, 1952) in having the side crystals larger than the central crystal. However, it is believed that at high energies a substantial improvement in the resolution of a pair spectrometer would be achieved if the side crystals were smaller than the centre crystal (preferably by about 2 cm). This would tend to reduce the number of events recorded that involve either electron escape from the crystal or electrons emitted from the target backing. The effect of bremsstrahlung escape can only be reduced by increasing the separation of the side crystals. There appears to be an upper limit of usefulness of a pair spectrometer at around 12 MeV.

V. Acknowledgments

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