STATES IN ^{27}Al AND ^{89}Y USING HIGH RESOLUTION SURFACE BARRIER COUNTERS

By G. M. Crawley,* D. L. Powell,* and B. V. Narasimha Rao*

[*Manuscript received July* 15, 1968]

Summary

The resolution of a solid state detector was investigated and a best value of about 16 keV was obtained after cooling. The energy levels of ^{89}Y and ^{27}Al were measured with this detector. New states were observed at around $3\cdot0$ and $3\cdot7$ MeV in ^{89}Y and over 20 new levels were noted in ^{27}Al.

I. Introduction

A number of recent papers have discussed the use of semiconductor counters with very good resolution over a range of incident proton energies up to 40 MeV (McCarthy and Crawley 1966; Andersson-Lindstroem 1967; Goulding, Landis, and Pehl 1967; Gruhn *et al.* 1968). Solid state counters have many advantages for charged particle detection, particularly the wide energy range of particles accepted and the immediate availability of the data for on-line appraisal and computer analysis. While the ultimate resolution of a solid state counter is probably not as good as that of a large magnet analysis system, there are situations where the intrinsic resolution of the magnet is not used. For example, when the counting rate is low the resolution is often limited by target thickness or kinematic broadening.

One application for a counter with very good resolution is the determination of nuclear energy levels especially when the spacing is small. Thus the energy levels of ^{89}Y have been the subject of a number of investigations (Awaya 1966; Shafroth *et al.* 1967; Stautberg, Kraushaar, and Ridley 1967), but there still remain inconsistencies in the region up to 4 MeV of excitation. It was therefore decided to measure these energy levels with a solid state counter of good resolution.

The various factors contributing to the resolution of a surface barrier counter were studied using a thin gold target on a carbon backing to attempt to reproduce the excellent resolution reported previously by Andersson-Lindstroem (1967).

A resolution of 16 keV full width at half maximum height (FWHM) was obtained for 10 MeV protons entering a cooled 1000 μ surface barrier detector. The main residual contribution at this point was the intrinsic detector noise.

In studying the ^{89}Y levels up to 4 MeV, a ^{27}Al target was used to calibrate the energy scale. From the calibration runs information on levels in ^{27}Al was obtained which confirmed the presence of some doubtful levels in the region 6–8 MeV and revealed a number of levels previously unreported.

* Department of Nuclear Physics, Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2600.

II. Detector Tests

The factors affecting the total energy resolution in a charged particle experiment are (1) statistics of the electron–hole production process; (2) energy resolution of the beam; (3) target thickness; (4) kinematic broadening, either from the angle subtended by the counter slits or from variation in the angle of the incoming beam; (5) electronic noise from the preamplifier and amplifier system, including the effect of cable and detector capacitance at the input to the preamplifier; (6) detector noise from reverse current in the diode and the surface barrier junction; (7) pile-up, both of positively charged particles and also of low energy electrons stripped from atoms in the target; (8) charge collection effects in the detector; and (9) stability of the electronics.

The first of these factors is seldom a limitation since the energy required to form an electron–hole pair in silicon is 3·66 eV and the Fano factor is about 0·15 (Goulding, Landis, and Pehl 1967). Thus, for a 10 MeV proton, the statistical limit on the resolution is less than 6 keV.

The effects (2), (3), and (4) are controllable in principle although, in any real experiment, counting-rate considerations may mean that one or other of them actually limits the resolution.

The test runs were made with an Ortec surface barrier counter (Model SBCJ-050-1000) with a specified noise of 14 keV FWHM. The 10 MeV proton beam from the Australian National University tandem accelerator was used to bombard a thin gold target on a carbon backing. The gold–carbon separation acted as an internal calibration and the resolution was then measured from the width of the gold peak. A pulser connected at the input of the preamplifier monitored the electronic noise. All slits were kept small enough to eliminate kinematic broadening. Cabling to the preamplifier, both inside and outside the chamber, was kept as short as possible to reduce the effect of stray capacitance on the electronic noise. An Ortec 109 FET preamplifier was coupled to an Ortec 410 main amplifier and the signals were passed through a biased amplifier and pulse stretcher before being analysed in an Intertechnique CA13 analogue to digital converter and stored in the IBM 1800 computer. The resolution both of a pulser peak and the gold peak was found to improve quite rapidly when the time constants of the 410 amplifier were increased to about 1 μsec, and then more slowly as they were further increased. A time constant of 1 μsec was chosen for all the following experiments.

Pile-up of high energy charged particles in the detector can be improved by reducing the beam intensity or by the use of more sophisticated electronics. It was found that for the thin targets used in the present experiments this was unnecessary. However, another source of pile-up, which is not always recognized, is the large number of atomic electrons stripped off the target atoms, which produce low energy pulses in the detector and affect the resolution. Perhaps the most dramatic improvement in the resolution was obtained by the addition of a small (500 gauss) magnetic field in front of the antiscattering slit (Fig. 1) to prevent the low energy electrons from reaching the detector. This reduced the resolution from about 50 keV to 24 keV FWHM.

Both the resolution and the peak to valley ratio were improved when the detector was overbiased and, in general, it was run at 300 V bias rather than the 225 V required for full depletion. This presumably reflects the importance of higher charge collection efficiency in obtaining best resolution.

In order to reduce the intrinsic noise the detector was cooled to about $-70°C$ using a dry ice and alcohol eutectic mixture. The counter was mounted in a brass block thermally insulated by Lucite and cooled alcohol was circulated through the block. This gave rapid and efficient cooling of the detector, reducing the detector current from about $0\cdot 9$ μA to less than $0\cdot 05$ μA in about 5 min. The detector resolution decreased from a previous best value of 24 keV to 16 keV FWHM. At this stage, the electronic noise was measured as 7 keV. The cooling system has worked satisfactorily for up to eight detectors simultaneously. It also allows rapid warmup of the detectors since warm air or water can also be circulated through the block before opening the scattering chamber to air.

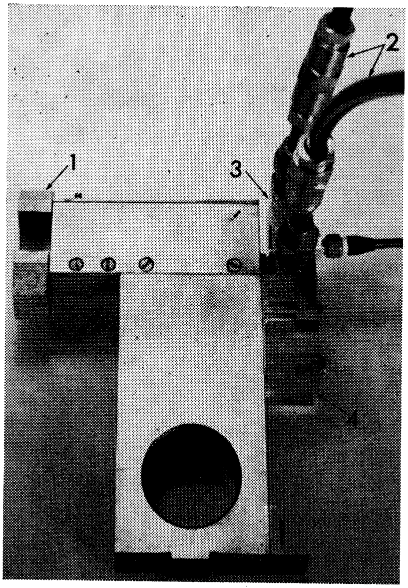

Fig. 1.—Experimental apparatus showing:
1, small magnet to deflect electrons
2, coolant tubes
3, brass detector block
4, Lucite insulating block

III. Calibration: Levels in ^{27}Al

In order to determine the positions of the levels in ^{89}Y with accuracy, it was necessary to calibrate the energy scale. Protons scattered from a thin ^{27}Al target provided such a calibration since the energies of the low lying levels of this nucleus are known to better than 1 keV. Spectra from the ^{27}Al target were taken before each ^{89}Y run at incident proton energies of 10 and 12 MeV.

All the spectra were analysed using a programme MIKIMAUS 4,* which makes a least squares fit of a cubic curve to the background, subtracts the background, and finds the centroid of each peak. The programme then generates both a linear and a

* MIKIMAUS 4 is derived from MIKIMAUS 3, which was made available by G. Berzins and J. Kolota of the Cyclotron Laboratory, Michigan State University, U.S.A.

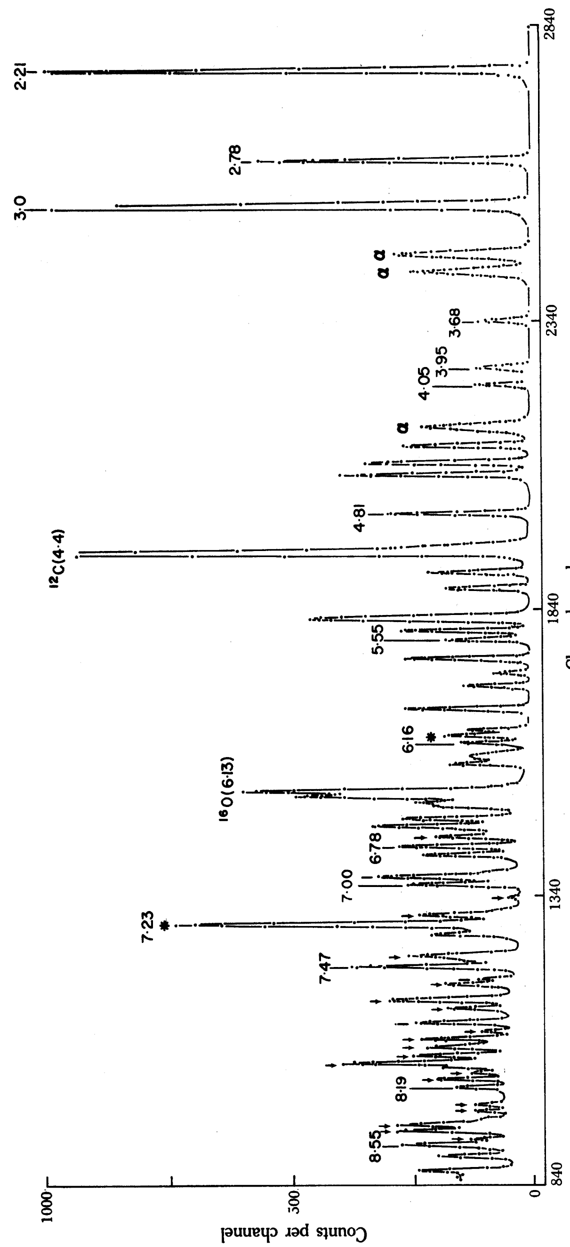

Fig. 2.—Spectrum of 12 MeV protons scattered at 70° from a thin aluminium target. The broader states marked **α** are from the ^{27}Al(p, α)^{24}Mg reaction. The levels marked with arrows have not been previously observed; those marked with an asterisk were previously uncertain. All energies shown are in MeV.

quadratic calibration curve from known peaks and calculates the Q value corresponding to any number of "unknown" peaks in this or following spectra.

Examination of the calibration spectra indicated a number of new levels especially in the region between 7·5 and 8·5 MeV. A spectrum of protons from ^{27}Al is shown in Figure 2. Only the levels above 2 MeV are shown so as to allow greater expansion of the region containing the unknown levels. Levels previously suspected and confirmed in this experiment are indicated by an asterisk while the new levels are marked by arrows.

The spectrum also contains peaks corresponding to α-particles from the ^{27}Al(p, α)^{24}Mg reaction but these were easily identified by their greater width and the kinematic shift that they show with change of angle.

The energy calibration below 7·5 MeV of excitation was readily obtained using levels in ^{27}Al whose energies are well determined. The levels used for the calibration are given in Table 1. In order to determine the energies of levels above 7·5 MeV the calibration was first extrapolated to a region above the ^{26}Mg plus proton threshold (8·271 MeV). A number of resonances have been observed in the ^{26}Mg(p, γ) reaction (Endt and Van der Leun 1967) and two of these at 292 and 338 keV were close to the energies of three levels in the inelastic spectrum obtained from the extrapolated calibration. Although one of the levels was consistently within about 25 keV of an energy corresponding to the 292 keV resonance, each of the three levels was matched to each of the two resonances and a complete new calibration was determined. The standard deviations for both a linear and a quadratic calibration curve were always smaller if one of the levels was set equal to 8·552 MeV corresponding to the 292 keV resonance.

Now it is possible that the (p, γ) reaction and the inelastic scattering process excite different states in ^{27}Al. In fact, the resonance at 392 keV does not appear to correspond to any strong level excited in (p, p′). Therefore, the matching of the level in the (p, p′) spectrum with the 292 keV resonance in ^{26}Mg(p, γ) may be accidental. There is thus the possibility of a systematic error in the energies of the levels above 7·5 MeV which increases with excitation energy and in the worst case is estimated to be about 30 keV. One check which suggests that such a systematic effect is not present is the agreement of the level observed at 8·194 MeV with a previously observed level at 8·200 MeV (Endt and Van der Leun 1967), although no error is assigned to this latter energy.

The average energies of levels above 4 MeV obtained from about six different angles are shown in Table 1, together with the mean deviation. The previously known levels from Endt and Van der Leun are given for comparison. In all cases, except for unresolved doublets, the energies match within the quoted errors. It should also be noted that six of the levels marked as "new" in Table 1 between 6·5 and 8 MeV are within 30 keV of levels observed recently in inelastic scattering at 17·5 MeV (Crawley and Garvey 1968). The lowest lying new level is the lower member of a close doublet at about 6·5 MeV with an energy of 6·514 MeV$\pm$5 keV. There is also evidence from the consistent broadening of the level at 7·674 MeV that this is also a close doublet with a separation of less than 20 keV. The previously suspected states at 6·119 and 7·231 MeV show up clearly at all angles and, in fact, the 7·231 MeV state is one of the levels above 3 MeV most strongly excited in this reaction (Fig. 2).

TABLE 1

STATES IN ^{27}Al FROM ^{27}Al(p, p′)^{27}Al

All energies are in keV

Present Experiment	Error	Endt and Van der Leun (1967)	Error	Present Experiment	Error	Endt and Van der Leun (1967)	Error
Calibration		3955·9	1·3				
4058·1	2·8	4054·8	1·4	6955·5	1·5	New*	
4409·9	2·0	4409·0	2·0	Calibration	—	6997	3
4511·6	1·6	4508	5	7079·1	3·3	New	
4582·6	1·7	4580	2	7178·8	1·3	New	
Calibration	—	4811	2	7231·0	1·3	(7226)*	3
5154·3	1·3	5155	3	7291·4	1·1	7285	3
5247·3	1·8	5246	2	7411·5	1·6	New*	
5431·8	2·5	{5410 5434	6 2	Calibration	—	7471	3
5499·3	2·9	5491	6	7548·3	2·0	New	
Calibration	—	5550	2	7577·4	1·1	New	
5665·9	2·0	5659	6	7673·5†	—	New*	
5751·9	2·3	5752	4	7724·7	2·0	New	
5826·7	1·5	5825	6	7807·5	1·7	New*	
5962·1	1·2	5955	6	7865·9	1·9	New	
6083·9	0·7	6082	2	7909·1	2·0	New	
6118·6	1·0	(6114)	4	7954·1	0·7	New	
Calibration	—	6160	2	8006·4	2·0	New*	
6287·5	3·8	6284	5	8057·9	1·6	New	
6480·1	1·7	{6466 6477	3 3	8109·2	0·5	New	
6534·4‡	—	6547	12	8148·1	1·8	New	
6612·1	3·2	6606	3	8194·4	2·5	8200	
6658·1	1·6	6653	3	8302·2	2·6	New	
6719·6	2·6	New		8345·6	1·3	New	
Calibration	—	6778	3	8424·1	2·4	New	
6825·5	1·5	{6815 6821	2 2	8470·8 8509·0	2·5 11·4	New New	
				Calibration	—	8552·0	1

* Levels observed by Crawley and Garvey (1968) at 6·94, 7·23, 7·44, 7·66, 7·79, and 7·99 MeV.

† Probably close doublet with about 20 keV separation.

‡ Probably doublet with energies 6514 and 6547 keV.

IV. STATES IN ^{89}Y

The yttrium target was prepared by vacuum evaporation of the metal (100% ^{89}Y) onto a carbon backing to obtain a thickness of 100 μg cm^{-2} of metal. The main impurities in the target were carbon, oxygen, and fluorine. This last impurity has excited states in the region of interest which can be identified by their kinematic shift with angie.

Spectra were obtained at 10 MeV and later 12 MeV at about six angles from 40° to 140°. A spectrum at 85° is shown in Figure 3. The states at 1·5 and 0·91 MeV are obscured by impurity peaks, indicating the necessity of running at a large

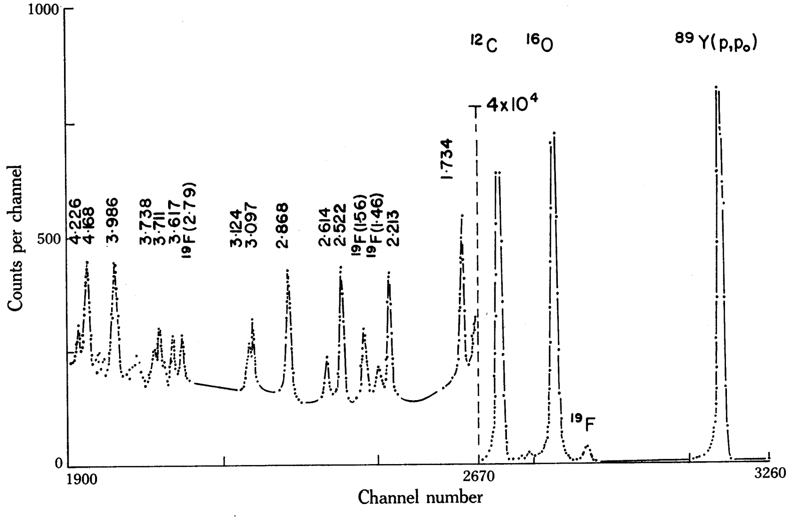

Fig. 3.—Spectrum of 12 MeV protons scattered at 85° from ^{89}Y. Protons scattered from the ^{19}F impurity target are also seen in this spectrum. All energies shown are in MeV.

Table 2

ENERGY LEVELS OF ^{89}Y

All energies are in keV

Awaya (1966)	Stautberg, Krausharr, and Ridley (1967)	Long and Fox (1968)	Present Work
0	0	0	0
$894\pm^{20}_{10}$	910	897 ± 8	$910\cdot4\pm3\cdot8$
1502 ± 12	1490	1499 ± 8	$1503\cdot5\pm3\cdot5$
1730 ± 12	1740	1736 ± 8	$1733\cdot9\pm1\cdot6$
2207 ± 15	2220	2219 ± 8	$2212\cdot6\pm4\cdot6$
2518 ± 13	2520		$2522\cdot0\pm3\cdot4$
2605 ± 15			$2613\cdot8\pm3\cdot5$
2862 ± 11	2870		$2868\cdot3\pm2\cdot7$
			$3096\cdot7\pm1\cdot0$
3115 ± 12	3120		$3123\cdot8\pm1\cdot5$
3622 ± 13	3620		$3616\cdot7\pm1\cdot3$
3719 ± 12			$3711\cdot4\pm2\cdot5$
	3750		$3737\cdot9\pm2\cdot6$
			$(3851\ \pm5)$
3992 ± 12	3990		$3986\cdot0\pm2\cdot4$
4163 ± 13	4180		$4167\cdot8\pm1\cdot1$
			$(4226\ \pm5)$

number of angles. The energy levels up to 4 MeV are given in Table 2 together with previously published values. Again the errors in the present results reflect the standard deviation of the mean of the energies obtained at different angles. In addition to these random errors in determining the peak position, a small systematic error is possible because of the uncertainty in the laboratory angle of the counter. Using the ^{27}Al states as a calibration therefore involves an error because of the different masses of ^{27}Al and ^{89}Y. In the worst case this may introduce an uncertainty of about 5 keV into the level position. Since this effect is angle dependent it should lead to a systematic change of excitation energy with angle. No such systematic effects were observed.

The present values agree with the recent results on the levels up to 2 MeV of Long and Fox (1968). A doublet was observed near to 3·0 MeV but no evidence was found for a third level near this energy referred to by Shafroth *et al.* (1967). The second, close, doublet seen at around 3·7 MeV has not been reported previously. The levels at 3·851 and 4·226 MeV indicated in parentheses were observed at only a few angles and with poor statistics, and their energy is not well determined.

V. Conclusions

Care in reducing pile-up effects and electronic noise and the use of a simple cooling system allows a resolution of less than 20 keV to be obtained with a solid state counter. This has proved to be a useful technique for determining the positions of nuclear energy levels. The energy levels of ^{89}Y have been investigated up to 4 MeV and some new levels have been found. Many new levels in ^{27}Al have been observed up to the region of the proton threshold.

VI. Acknowledgment

One of the authors (G.M.C.) would like to acknowledge financial assistance from the Queen Elizabeth II Fellowships Committee during this work.

VII. References

Andersson-Lindstroem, G. (1967).—*Nucl. Instrum. Meth.* **56**, 309.

Awaya, Y. (1966).—*Phys. Lett.* **21**, 75.

Crawley, G. M., and Garvey, G. T. (1968).—*Phys. Rev.* **167**, 1070.

Endt, P. M., and Van der Leun, C. (1967).—*Nucl. Phys.* A **105**, 1.

Goulding, F. S., Landis, D. A., and Pehl, R. H. (1967).—Univ. California Radiation Lab. Rep. No. UCRL 17556.

Gruhn, C. R., Kuo, T., Maggiore, C., Preedom, B., Samuelson, L., and Chander, J. (1968).—Lithium drifted germanium for charged particle spectroscopy. *IEEE Trans. nucl. Sci.* (in press).

Long, D. D., and Fox, J. D. (1968).—*Phys. Rev.* **167**, 1131.

McCarthy, A. L., and Crawley, G. M. (1966).—*Phys. Rev.* **150**, 935.

Shafroth, S. M., Ainrichsen, P. F., Horoshko, R. N., and Van Patter, D. M. (1967).—*Bull. Am. phys. Soc.* **11**, 511.

Stautberg, M. M., Krausharr, J. J., and Ridley, B. W. (1967).—*Phys. Rev.* **157**, 977.