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United Kingdom Atomic Energy Authority

RESEARCH GROUP

NUCLEAR PHYSICS DIVISION PROGRESS REPORT

For the period 1st May 1966 to 31st October 1966

Editor: C. F. COLEMAN

Nuclear Physics Division,
Atomic Energy Research Establishment,
Harwell, Berkshire.
1967

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Nuclear Physics - II and Nuclear Photo-effect

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5 MV Electrostatic Generator and Cockcroft-Walton HT set

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IBIS (3 MeV) pulsed Van de Graaff

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NUCLEAR DATA FOR FAST REACTORS

(IBIS 3 MV pulsed Van de Graaff accelerator: A. T. G. Ferguson)

Elastic and inelastic scattering of 1.0 to 2.0 MeV neutrons from chromium (B. W. Hooton and B. Lawergren)

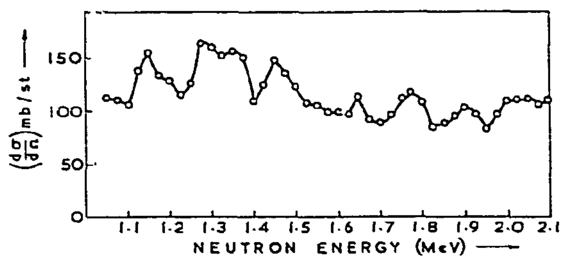

Fig. 1. Excitation functions for elastic scattering from chromium at 90°.

The elastic and inelastic scattering of 1.0 to 2.0 MeV neutrons from natural chromium have been studied using the IBIS time of flight system. The excitation function for elastic scattering at 90° taken with an energy resolution of 20 keV, shown in Fig. 1, displays fluctuations which have a width larger than the experimental energy resolution. The cross section measurements have a relative accuracy of about 5% and should have an absolute accuracy of 10% after multiple scattering corrections have been made.

GENERAL REACTOR TECHNOLOGIES AND STUDIES

GENERAL NUCLEAR DATA FOR REACTORS - I

(Nuclear Physics - I: M. J. Poole)

The fission cross section of ^{233}U from 1 eV to 25 keV (G. D. James and D. A. J. Endacott)

The fission cross section of ^{233}U has been measured by a time-of-flight experiment over the energy range 1 eV to 25 keV using the neutron booster source with 0.2 μs electron burst width, $\frac{1}{16}$ μs timing channel width and a 15 m flight path. A continuous-flow gas scintillation chamber was used to detect fission fragments from 40 mg of material containing 99.2% ^{233}U and 0.8% ^{234}U. Samples of cadmium and cobalt were kept permanently in the beam to prevent overlap of slow neutrons from one cycle to the next and to monitor the background at low energy and at 132 eV. The results, shown in Fig. 2 for $\frac{1}{4}$ μs channels, were normalised between 1 eV and 16 eV to the data of Moore et al.[1], which have a quoted error of 10%, but are the only low energy data available at present. A further error of 5% arises in the process of normalisation because the shape of the present results differs slightly from that of the data of Moore et al. over the energy range chosen for normalisation. For average values of the fission cross section over energy intervals E to 2E the statistical

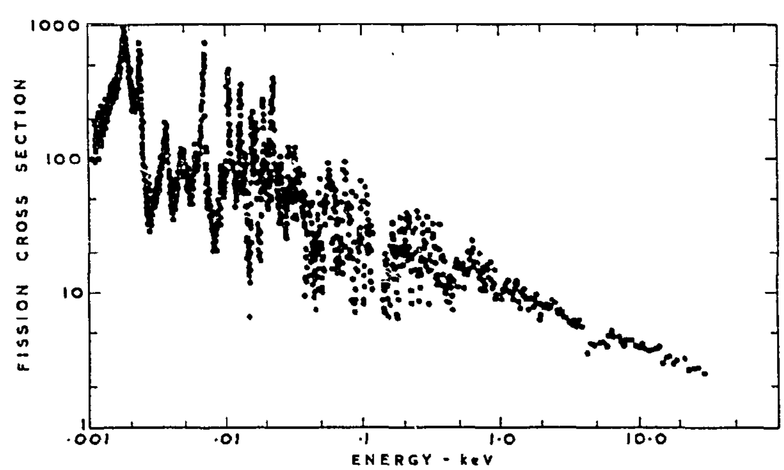

Fig. 2. Fission cross section of ^{238}U from 1 eV to 25 keV

(1) Moore M. S., Miller L. G. and Simpson O. D. Phys. Rev. 118, 714 (1960) and report IDO-16576 (unpublished).

accuracy is better than 1.2%. Above 7 keV, corrections, of 3% on average, have been made for the cobalt resonances. Between 4 keV and 6 keV the data have been suppressed because the corrections necessary exceed 10%.

Analysis of these data is incomplete but average values of the fission cross section above 1 keV have been compared with the data of Albert[2] and Bergen et al.[3]. Fig. 3 illustrates this comparison and shows that the present data agree well with the results of Albert below 4 keV and with the data of Bergen et al. above 6 keV. To avoid confusion in Fig. 3, results from different experiments referring to the same energy range have been plotted at slightly different energies. From the spread of the three measurements, the average error in the mean fission cross section over 1 keV intervals from 1 keV to 10 keV is 5.2%. At 23.89 keV the present data give a fission cross section of 2.73 ± 0.26 b compared with the value 2.73 ± 0.11 b measured by Perkin et al.[4] at 24 keV.

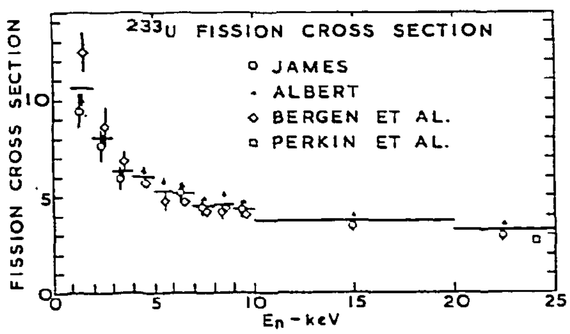

Fig. 3. Comparison of average fission cross section data between 1 keV and 25 keV. Horizontal lines represent the mean of the results of James, of Albert and of Bergen et al. Errors are given when quoted by the authors.

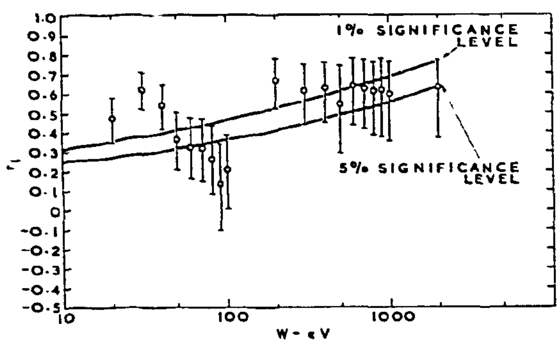

Fig. 4. First serial correlation coefficient as a function of energy interval for the fission cross section of ^{233}U.

A fluctuation analysis of the ^{233}U fission cross section has been carried out by the method previously described[5] and the results are shown in Fig. 4. Only the first serial correlation coefficient shows significantly high values and is above the 1% significance level for energy intervals W in the neighbourhood of 30 eV and 300 eV.

<u>Total neutron cross sections (C. A. Uttley, K. M. Diment and C. M. Newstead)</u>

<u>I - ^{10}B</u>

The total cross section of sintered samples of enriched boron has been measured over the energy range from 70 eV to 10 MeV on the 120 m and 300 m spectrometers[6]. Corrections for the impurities in

(2) Albert R. D. Phys. Rev. <u>142</u>, 778 (1966).

(3) Bergen D. W., Silbert M. G. and Perisho R. C. Report LADC-7622 (unpublished) and private communication.

(4) Perkin J. L., White P. H., Fieldhouse P., Axton E. J., Cross P. and Robertson J. C. J. Nuc. Energy A/B <u>19</u>, 423 (1965).

(5) James G. D. and Endacott D. A. J. Nuclear Physics Division Progress Report,AERE - PR/NP 10, p.2 (1966).

(6) Nuclear Physics Divisional Progress Report,AERE - PR/NP 10, p. 7 (1966).

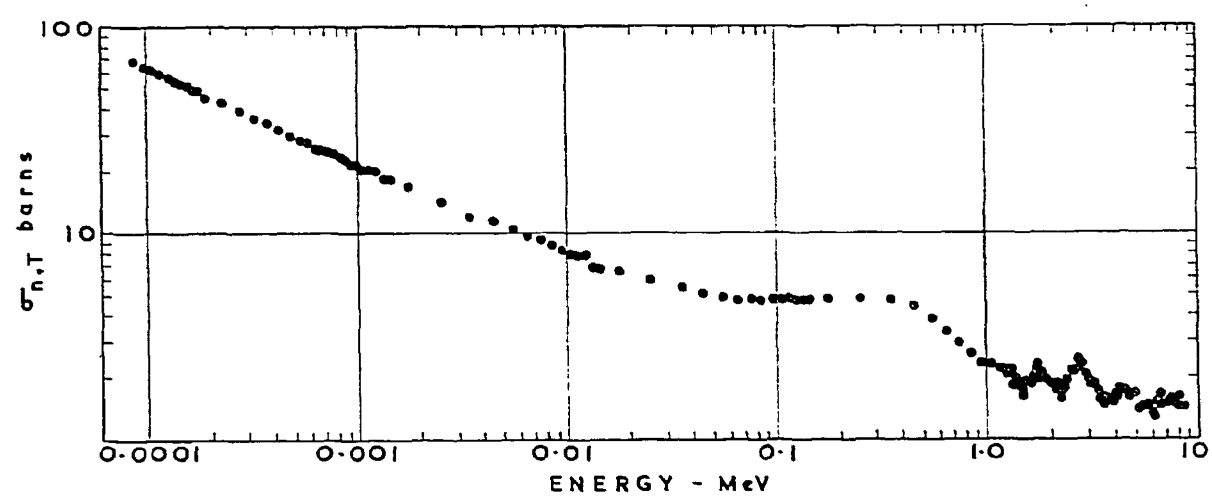

Fig. 5. The neutron total cross section of Boron 10.

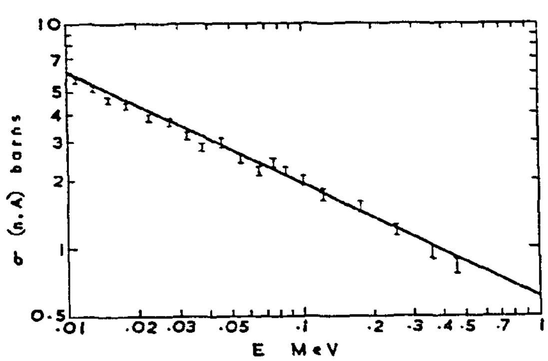

Fig. 6. The absorption cross section of Boron 10.

the samples have been made and the result is shown in Fig. 5. The measured data below 10 keV were fitted with a least squares programme to a curve of the form

$$\sigma_T = {}^{A}/\sqrt{E} + B$$

yielding values of 610.3 ± 3.1 and 1.95 ± 0.11 for A and B respectively if E is measured in electron volts and σ_T in barns. The constant term B represents the low energy potential scattering cross section which agrees well with the scattering cross section determined by Mooring[7], of 2.1 ± 0.2 barns at 11.5 keV. Above 10 keV Mooring finds that the scattering cross section begins to rise slowly, reaching a maximum of 3.8 barns at 350 keV. Subtraction of this scattering cross section from the present total cross section yields the value of the absorption cross section. Fig. 6 shows the variation of the absorption cross section above 10 keV together with the curve $\sigma = 610.3/\sqrt{E}$ obtained from the low energy data. It appears that the absorption cross section follows the $1/\sqrt{E}$ law to within about 5% up to at least 300 keV.

II - Strength function measurements

The average total cross sections of ^{98}Mo, ^{100}Mo and ^{232}Th have been analysed to determine the s and p-wave average resonance parameters. These results and similar data for ^{93}Nb, ^{103}Rh, ^{235}U and and ^{238}U were presented at the Paris Conference recently[8]. Total cross section measurements on ^{233}U, ^{239}Pu and ^{197}Au are almost complete.

Fission strength function theory (J. E. Lynn)

A model using a complex potential well in the space of the fission deformation parameter has been considered for calculating the mean ratio of fission width to level spacing in a single fission channel.

(7) Mooring F. P. Private communication.

(8) Uttley C. A., Newstead C. M. and Diment K. M. Conference on Nuclear Data, Paris, 1966, Paper CN-23/36.

The "weak coupling" version of this model (which introduces a small imaginary component of the potential) has the interesting property that it might be able to explain structure observed in the fast neutron fission cross sections of even nuclei. An account of this work is to be published in the Proceedings of the Conference on Nuclear Data held in Paris in October by the I.A.E.A.

GENERAL NUCLEAR DATA FOR REACTORS - II

(Nuclear Physics - II and Nuclear Photo-effect: E. R. Rae)

Cross section measurements on sodium (M. C. Moxon, N. J. Pattenden, V. S. Brown, J. E. Jolly and J. S. Pratt)

A knowledge of the radiative capture cross section of sodium over the energy range from 0.1 to 10 keV is required for fast reactor design[9]. The scattering cross sections are much larger than the capture cross sections, so that multiple scattering in the sample makes it very difficult to relate the observed capture γ-ray yields and their variation with neutron energy to the capture cross sections.

To calculate the multiple scattering correction by Monte Carlo methods one needs to know the transmission of the sample and the parameters of the 2.86 keV resonance. Hence to determine the capture cross section capture yields and transmissions must be measured over a wide energy range. In principle one can obtain the parameters E_R, Γ, Γ_n, l and J from the transmission measurements, and Γ_γ from the capture measurements. The true capture cross section can then be derived from the capture measurements.

Measurements of the capture yields (on the 32 m flight path) and transmission (on the 94 m flight path) of a range of samples have been started on the linac. A report on preliminary results was given to the Paris Conference on Nuclear Data[10].

The transmission measurements carried out so far give the following parameters for two resonances: (1) $E_R = 2860 \pm 25$ eV, $\Gamma_n = 424 \pm 13$ eV, $l = 0$, $J = 1$; (2) $E_R = 54 \pm 1$ keV, $g\Gamma_n = 750 \pm 40$ eV, $l = 1$, $J = 2$ (although the last value is not conclusive).

The capture measurements which have been carried out so far show (see Fig. 7) a high capture cross section on the low energy side of the 2.86 keV resonance. At present there appears to be no plausible explanation for this high cross section.

Because of the anomalously high capture cross section on the low energy side of the resonance, further transmission and capture measurements are being performed in order to confirm the values of the resonance parameters and to measure the potential scattering cross section.

Neutron cross sections of ^{107}Ag, ^{109}Ag and ^{181}Ta (A. Asami and M. C. Moxon)

Neutron scattering and capture measurements on ^{107}Ag, ^{109}Ag and ^{181}Ta have been completed and analysis of the data to determine resonance parameters is in progress.

Several modifications to the scattering detector have been undertaken during the past six months and it is hoped that they will decrease the background and improve the stability of the equipment. This will enable us to measure directly the potential scattering cross section of various elements and to perform measurements at higher energies than we can reach at present.

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(9) Pope A. L. and Story J. S. Unpublished information.

(10) Moxon M. C. and Pattenden N. J. Conference on Nuclear Data, Paris, Paper CN-23/27 (1966).

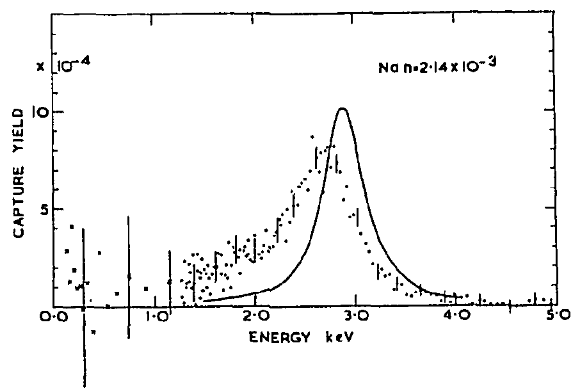

Fig. 7. The capture yield from a sodium sample ($n = 2.14 \times 10^{-3}$) versus neutron energy. The smooth curve was obtained from a Monte Carlo calculation assuming $J = 1$, $\Gamma_n = 410$ eV, and $\Gamma_\gamma = 0.5$ eV.

Total cross section measurements on barium isotopes (R. E. Van de Vijver and N. J. Pattenden)

The measurements described in the previous report[11] have been largely completed, and the analysis of the resonance data is proceeding. Resonances at the following energies (eV) have been observed in the different isotopes:

^{134}Ba

48.6, 102.4, 329, 502, 975, 1230, 1830, 4620, 8240, 9460.

^{135}Ba

24.4, 25.9, 81.0, 86.4, 104.5, 219, 224, 243, 283, 316, 378, 407, 435, 468, 655, 672, 724, 834, 884, 944, 1030, 1160, 1200, 1280 and 1400.

^{136}Ba

449, 513, 528, 2160, 2320, 3480, 4360 and 7310.

^{137}Ba

420, 578, 1050, 1200, 1350, 1740 and 3940.

Apart from those in the lower region in ^{135}Ba, most of the resonances have not been previously reported.

The measurement of alpha, eta and the neutron cross sections of ^{239}Pu (B. H. Patrick, M. G. Schomberg and M. G. Sowerby)

The measurements of eta and the fission and total cross sections of ^{239}Pu using the 35 m and 97 m flight paths have continued. In previous progress reports[12,13] the experiments on the two flight paths were described separately. All the necessary data have now been collected and the results are being calculated. Preliminary results were presented in a paper entitled "Measurements of Eta, Alpha and Neutron Cross Sections for ^{239}Pu on the Harwell Neutron Time-of-Flight Spectrometer" at the recent Conference on Nuclear Data in Paris. Figs. 8 and 9 (overleaf) show preliminary results for the fission cross section in the energy ranges 10 eV-50 eV and 50 eV-100 eV respectively. The regions of very low cross section between 20 eV and 40 eV are particularly interesting. These were first observed by Shunk et al.[14] and the present data verifies their results. In these regions, the cross section is too small to be measured and is estimated to be 0 ± 2 barns.

Of particular interest to the reactor designer is the quantity alpha, the ratio of the capture and fission cross sections. Integral measurements[15] in the 100 eV-1.5 keV energy range have produced

(11) Van de Vijver R. E. and Pattenden N. J. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 11 (1966).

(12) Schomberg M. G., Sowerby M. G. and Jolly J. E. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 11 (1966).

(13) Patrick B. H. and Pattenden N. J. Nuclear Physics Division Progress Reports, AERE - PR/NP 9, p. 5 (1966) and AERE - PR/NP 10, p. 7 (1966).

(14) Shunk E. R., Brown W. K. and La Bauve R. USAEC Rep. LA-DC-7620 (1966).

(15) Sampson J. B. and Molino D. F. KAPL-1793 (1957).

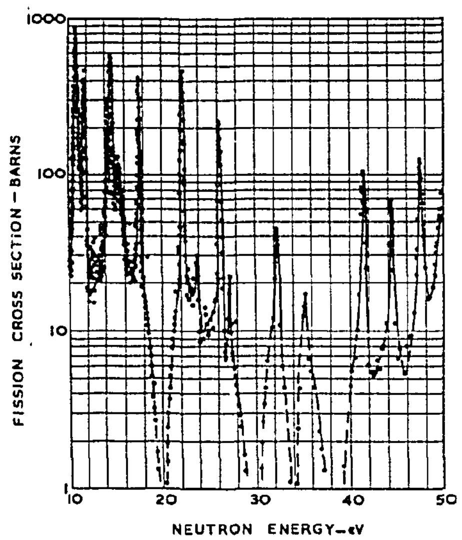

Fig. 8. Fission cross section of ^{239}Pu from 10 to 50 keV.

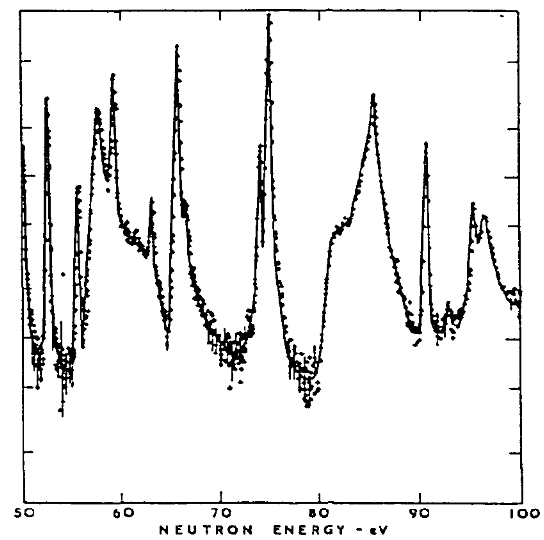

Fig. 9. Fission cross section of ^{239}Pu from 50 to 100 keV.

values for alpha ~ 0.7. Provisional values of alpha in the energy range 10 eV - 30 keV, deduced from the present experiments subject to the assumptions described below, indicate that alpha is ~ 1.0 between 100 eV and 600 eV and rises to higher values between 600 eV and 10 keV. Above 10 keV, alpha falls, until at 25 keV it has a value ~ 0.5, in reasonable agreement with the results of de Saussure et al.[16]. These results depend quite strongly on the values used for the scattering cross section. In ^{239}Pu the neutron width Γ_n is often as much as 20% of the total width Γ and the contribution of the resonant scattering to the total scattering cross section cannot be neglected. Now while the average total cross section falls off with energy approximately as $1/\sqrt{E}$, the average fission cross section has a sudden break at ~ 600 eV, where it falls to about half of the expected value. Since this change could be reflected in the behaviour of both scattering and capture cross sections, the scattering cross section might not be well behaved above 600 eV. In our initial calculations we have assumed that the scattering cross section is unaffected, with the result that high values of alpha are obtained.

Since the end of the Paris Conference, we have been examining the scattering data obtained by Asghar[17]. Preliminary results indicate that between 600 eV and 2 keV the scattering cross section is ~ 15% higher than assumed in our initial calculations. This will have the effect of reducing alpha but will still not give values as low at 0.7.

The analysis of these data is continuing and the corrections are being studied in greater detail.

Determination of ^{240}Pu resonance parameters (M. Asghar, M. C. Moxon, N. J. Pattenden, J. E. Jolly and J. S. Pratt)

The measurements previously reported[18] together with the resonance analyses have been largely completed, and a paper on the results was submitted to the Paris Conference on Nuclear Data[19].

(16) de Saussure G., Weston L. W., Gwin R., Ingle R. W., Todd J. H., Hockenbury R. W., Fullwood R. R. and Lottin A. Proc. I.A.E.A. Conf. on Nuclear Data, Paris (1966), Paper CN-23/48.

(17) Asghar M. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 9 (1966).

(18) Asghar M., Moxon M. C., Chaffey C. M., Pattenden N. J. and Pratt J. S. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 11 (1966).

(19) Asghar M., Moxon M. C. and Pattenden N. J. Conference on Nuclear Data, Paris, Paper CN- 23/31 (1966).

The transmission data were analysed by the area method to give Γ_n values for 40 resonances between 20 and 950 eV. The transmission, capture and scattering results were combined together to give Γ_n and Γ_γ values for 17 resonances between 20 and 290 eV. These parameters give the following mean values:

$$<\Gamma_\gamma> = (18.11 \pm 1.81) \text{ meV}$$

$$S_o = (0.93 \pm 0.25) \times 10^{-4}$$

This $<\Gamma_\gamma>$ value is considerably different from the accepted value for the 1.06 eV resonance of about (31 ± 3) meV. Hence further measurements and analyses are being performed on additional thicker samples to minimise the effect of possible errors in sample thickness.

PDP-4 data processor (E. M. Bowey, G. B. Dean and J. Wilbourne)

The computer has been in operation for 1670 hours during the period of this report.

Modifications have been made to the Shackman MK.3 auto-camera to give independent control of shutter and film transport mechanisms, allowing greater flexibility in programming display routines for graph plotting and 'page' printing with FORTRAN. The hardware for the revised computer logic is installed and working, and the modifications to the basic software have been made.

INTEGRAL DATA MEASUREMENTS

(Nuclear Spectra and Nuclear Physics - I: M. J. Poole)

The energy dependence of the $^6Li(n,\alpha)^3H$ cross section in the range 10 eV to 100 keV (M. S. Coates, K. M. Diment, D. B. Gayther, B. H. Patrick, M. G. Schomberg and M. G. Sowerby)

In the measurement of neutron reaction cross sections in the keV region the energy spectrum of the neutrons incident on the sample is usually determined by making use of detectors based on the $^{10}B(n,\alpha)^7Li$, $^{10}B(n,\alpha\gamma)^7Li$ and $^6Li(n,\alpha)^3H$ reactions. Recent measurements[20,21] have shown that the first two reactions follow a $^1/v$ energy dependence from thermal energies up to at least 50 keV to an accuracy of ± 5%, but Spaepen[22] and Bergstrom et al.[23] conclude that there is doubt that the $^1/v$ dependence of the $^6Li(n,\alpha)$ cross section extends up to the keV region. Because of this uncertainty we have studied the energy dependence of the $^6Li(n,\alpha)$ cross section with certain ^6Li glass detectors which have already been used to measure energy spectra. Three methods were used:

(a) In the energy range 10 eV to 1.2 keV the efficiency of a ^6Li glass detector (NE 905) 2½" in diameter and ⅛" thick[24] was compared to that of a "thin" BF_3 counter by the time of flight method, using the Neutron Project booster target as a neutron source.

(b) In the energy range 50 eV to 30 keV the efficiency of the ⅛" thick ^6Li glass detector was compared in the same way with the efficiency of a ^{10}B-plug detector[25].

(20) Diment K. M. and Uttley C. A. This progress report.

(21) Sowerby M. G. J. Nuclear Energy, A/B 20, 135 (1966).

(22) Spaepen. Proc. I.A.E.A. Conference on Nuclear Data, Paris (1966), Paper CN 23/119.

(23) Bergstom A., Schwartz S., Stromberg L. G. and Wallin L. CCDN-NW/3.

(24) Patrick B. H. and Pattenden N. J. Nuc. Phys. Div. Progress Report, AERE - PR/NP 10, p. 7 (1966).

(25) Rae E. R. and Bowey E. M. Proc. Phys. Soc. 66A, 1073 (1953).

(c) In the energy range 20 keV to 100 keV the efficiency of a 4⅞" diameter, ½" thick ^{6}Li glass detector (NE 905)[26] was compared with that of a calibrated long counter[27] using IBIS as a monoenergetic neutron source.

In methods (a) and (b) we assume that both the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha\gamma)$ cross sections have a $^1/v$ energy dependence. In (b) a Monte Carlo programme due to Lynn[28] was used to make a small correction (1-3%) for the effect of multiple scattering in the 'thin' ^{10}B plug. In (c) the efficiency of the thicker ^{6}Li glass detector is obtained from the long counter calibration[27], which in turn was obtained from the n-p scattering cross section. The efficiency of the lithium glass detectors can be written as,

$$\epsilon(E) = K[1 - \exp\{-\Sigma_t(E)\}] \cdot \frac{n\sigma_\alpha(E)}{\Sigma_t(E)} \cdot S(E)$$

where K is the factor which allows for the optical and electronic efficiencies for detecting α-events in the glass, $\Sigma_t(E)$ is the macroscopic total cross section of the glass, $\sigma_\alpha(E)$ is the $^6Li(n,\alpha)$ cross section, n is the number of ^{6}Li nuclei/cm^2 and S(E) is a factor which allows for the increase in efficiency due to multiple scattering in the detector. For a 'thin' detector in the present geometry $S(E) \to 1$ and $\epsilon(E) \propto \sigma_\alpha(E)$. This condition did not apply at all energies in the present measurements, the value of S(E) changing by $\sim 6\%$[28] and the factor $[1 - \exp\{-\Sigma_t(E)\}]/\Sigma_t(E)$ varying from 0.85 to 0.96. In Fig. 10 we show the ratio of the measured efficiencies to the efficiencies which would be obtained if $\sigma_\alpha(E)$ had a thermal value of 945 barns and a $^1/v$ dependence. The transmission factors for the calculated efficiencies were based on the cross sections in BNL 325 and S(E) was obtained from the Monte Carlo programme[28]. To a good approximation the deviation of the plotted ratio from a constant value shows the departure from $^1/v$ energy dependence of $\sigma_\alpha(E)$. It can be seen that within the accuracy of our measurements the $^6Li(n,\alpha)^3H$ cross section has a $^1/v$ energy dependence up to an energy of 20 keV.

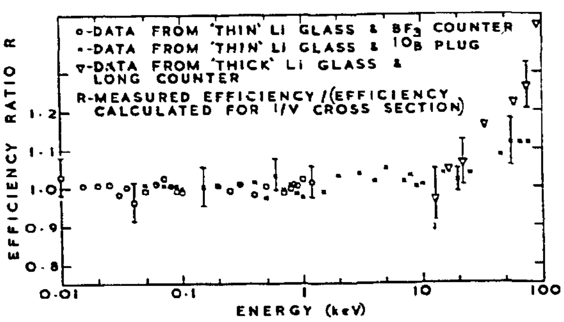

Fig. 10. Ratio of measured efficiency to efficiency calculated assuming a 1/V cross section.

The transmission of the ⅛" ^{6}Li glass detector has now been measured directly by time of flight and analysis of this measurement and further analysis of our IBIS measurements will allow us to deduce the relative value of $\sigma_\alpha(E)$ up to an energy of 400 keV.

<u>Time of flight neutron spectrum measurements on a sub-critical fast reactor assembly (M. S. Coates, D. B. Gayther, P. D. Goode and D. J. Tripp)</u>

The neutron spectrum near the centre of a sub-critical VERA fast reactor assembly has been measured by the pulsed source time of flight method using the 45 MeV electron linac. Reactor physics studies on a similar type of assembly are also in progress at AWRE, Aldermaston, using the VERA reactor facility[29] and the neutron spectrum in this reactor has been measured over a range of energies from 100 eV to several MeV. These AWRE measurements[30] employed three independent techniques to

(26) Coates M. S., Gayther D. B., Goode P. D. and Tripp D. J. Nucl. Phys. Div. Progress Report, AERE - PR/NP 10, p. 22 (1966).

(27) Allen W. D. and Ferguson A. T. G. Proc. Phys. Soc. <u>70A</u>, 639 (1957).

(28) Lynn J. E. Private communication.

(29) Weale J. W., McTaggart M. H., Goodfellow H., Paterson W. J. I.A.E.A. Symposium on Exponential and Critical Experiments (1963).

(30) Weale J. W., Benjamin P. W., Kemshall C. D., Paterson W. J. and Redfearn J. Neutron Spectrum Measurements in the Zero-power Fast Reactor VERA. Berkeley Conference on Radiation Measurements (1966).

cover this range, viz: proton recoil measurements in photographic emulsions (~ 500 keV → ~ 1 MeV) and in hydrogen filled proportional counters (~ 10 keV → ~ 5 MeV), and pulsed source time of flight measurements (~ 100 eV → ~ 50 keV). The first two measurements are made in the assembly core with the system critical, while the time of flight measurements require an extracted beam and a sub-critical system. The three sets of data were normalized absolutely using fission chamber monitors. This composite method of measuring a spectrum cannot yet be considered as reliably established and the prime object of the 45 MeV electron linac measurements to be described is to provide a comparison spectrum over the whole energy range using the pulsed source technique alone. (Source intensity considerations preclude extending the range of the time of flight measurements at AWRE). It is important that the spectrum determinations using the diverse techniques mentioned above should be brought into agreement in order to provide an accurate experimental spectrum against which to test the methods of calculation used in fast reactor systems.

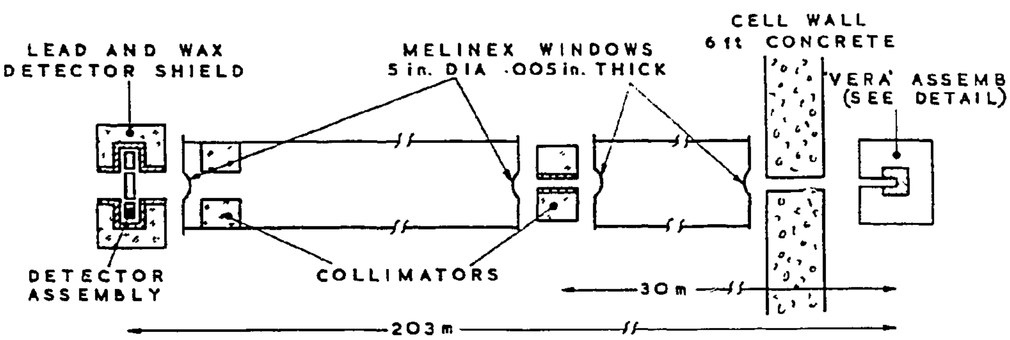

Fig. 11a. Experiment to measure spectrum from a subcritical VERA assembly.

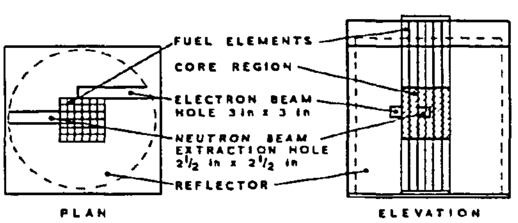

Fig. 11b. Detail. VERA assembly.

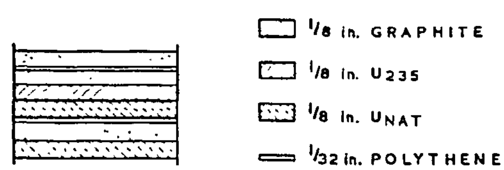

Fig. 12. Core region loading pattern in a VERA 7A fuel element.

The experimental arrangement for the linac experiment at Harwell is shown in Fig. 11. The sub-critical assembly (a VERA 7A type) comprises a central fuel element region surrounded by a reflector blanket of natural uranium rods. A fuel element consists of two stainless steel U-sections bolted together to form an unsealed can 4.65 cm square and 117 cm long with a wall thickness of of 0.122 cm, which is loaded with an arrangement of enriched uranium (93% U-235), natural uranium, graphite and polythene all in the form of thin tablets 4.32 cm square. The loading pattern is given in Fig. 12. The upper and lower sections of the tablet arrangement are natural uranium and act as part of the reflector while the central section forms part of the core region. Thirty six fuel elements are stacked vertically in a 6 x 6 array on a square pitch 4.68 cm between centres, being located at their lower ends by spigots fitting into a thick mild steel base plate and at their upper ends by bars attached to the mild steel supporting framework. The natural uranium reflector rods, each 2.92 cm in diameter and 109 cm high, are located in a similar manner. The total amount of U-235 in the assembly is 40 kg and the radial reflector thickness is 33 cm. The value of k_{eff} is $\simeq$ 0.8 corresponding to a neutron multiplication of $\sim$ 5. Special reflector rods and fuel elements form holes in the assembly to allow extraction of the neutron beam from near the core centre and to accommodate the natural uranium target which forms the neutron source. The extracted neutron beam is defined at the end of the first section of evacuated flight tube by a 60 cm long lead and nickel collimator with a 1.9 cm aperture. There are four 0.0127 cm thick Melinex windows and $\sim$ 6 m of air in the total flight path. Spectra were measured at flight paths of 200 m and 100 m using three 12.5 cm diameter detectors; a plastic proton recoil scintillation counter, a plug of ^{10}B mixed with vaseline, and a ^{6}Li glass scintillation counter. The calibration of the neutron sensitivity of these detectors was described in an earlier report[31].

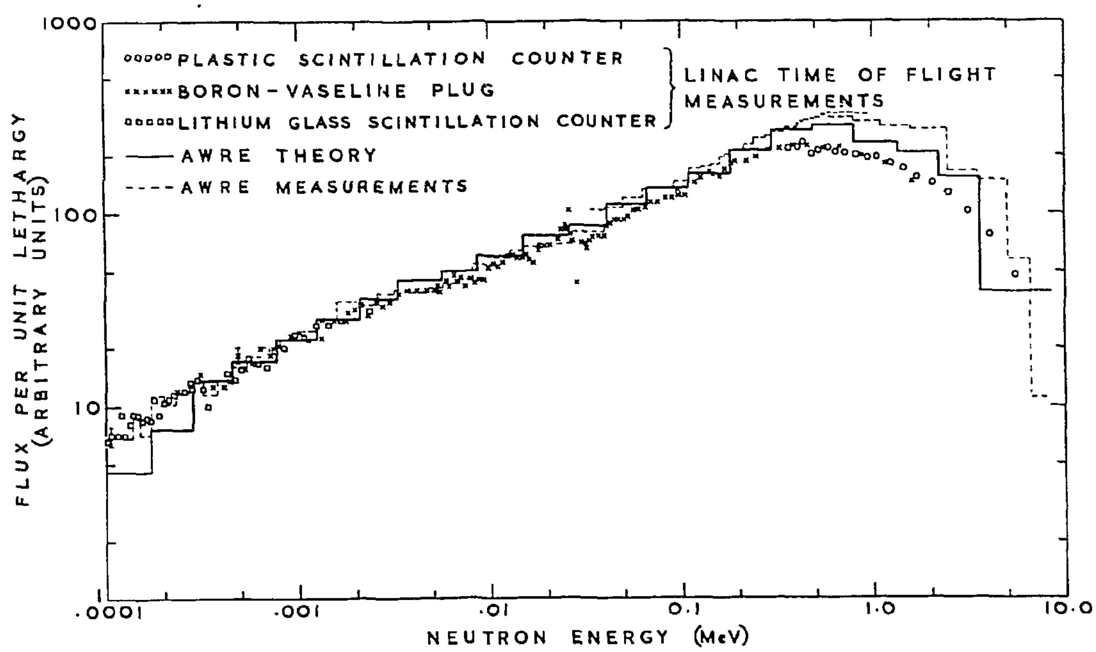

Fig. 13. Preliminary spectrum measurements on a VERA 7A assembly.

A preliminary spectrum is shown in Fig. 13. The measurements were made with an electron pulse of 0.5 μsec and the relaxation time of the neutron pulse in the assembly was 1.5 μs. The resolution correction, which is about 10% at 4 MeV and insignificant below 1 MeV, has not yet been applied. Also shown in Fig. 13 is a spectrum[30] measured on a similar core at AWRE, Aldermaston, together with a theoretical spectrum[30] calculated using the SWAN Diffusion Code with 35 group FD2(R) data. It will be seen that the linac measurement gives a softer spectrum than either the composite measurement or the theoretical calculation. The spectrum measured with the linac will appear slightly harder after the resolution correction has been applied, but the change will not be sufficient to alter this conclusion. The measured U-238/U-235 fission chamber ratio in the linac experiment is 0.0366, which is in reasonable agreement with similar measurements made at AWRE. If the three spectra in Fig. 13 are used to obtain this fission ratio by appropriate integration of the spectra over the fission cross sections, the U-238/U-235 ratio calculated from the linac spectrum (0.0381) is in better agreement with the experimentally determined value than either that derived from the composite technique spectrum (0.0522) or the theoretical spectrum (0.0439). A more complete analysis of the data will be presented later.

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(31) Coates M. S., Gayther D. B., Goode P. D. and Tripp D. J. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 20 (1966).

PULSED VAN DE GRAAFF ACCELERATOR (IBIS)

Neutron scattering at 6 MeV (W. M. Currie in collaboration with J. Martin and D. T. Stewart (University of Glasgow))

This work, preliminary notices of which have been given in Progress Reports PR/NP 8 and 9, has now been completed and is being prepared for publication. Elastic and inelastic differential cross sections have been measured for ^{27}Al (5 excited states), ^{28}Si (1 excited state), ^{31}P (2 excited states) and ^{32}S (4 excited states). Distributions for these transitions were also calculated using:-

(1) The non-local optical model, with the equivalent local potentials of Perey and Buck[32].

(2) The statistical model, using a programme by D. Wilmore which takes account of width fluctuations[33].

(3) A coupled channels programme, by A. Hill (Oxford)[34].

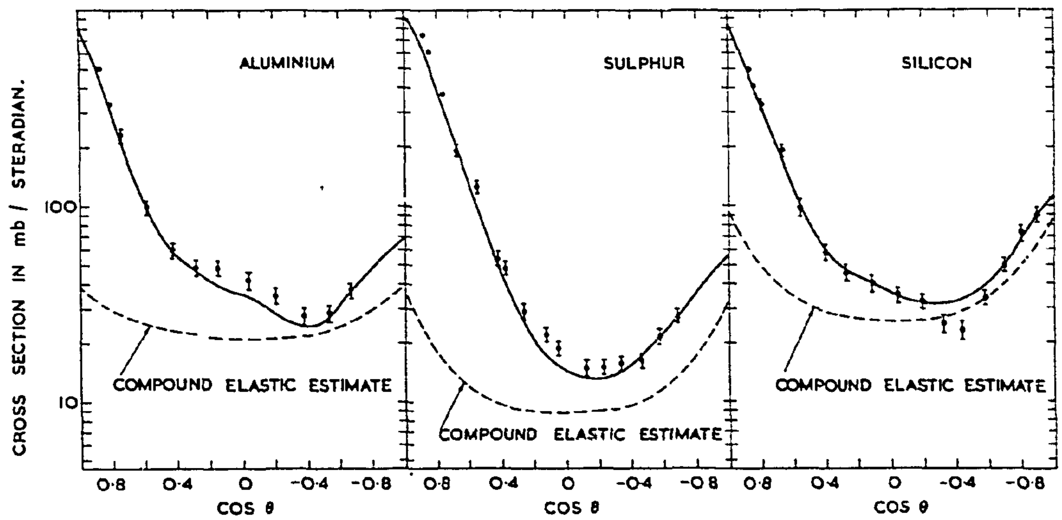

Fig. 14. Elastic scattering from sulphur, silicon and aluminium compared with the predictions of the optical model. The compound elastic estimate was obtained using the same potentials.

The agreement between the calculated distributions, which were obtained without recourse to parameter adjustments, and the experimental results is good for elastic scattering (see Fig. 14) and fair for inelastic scattering (see Fig. 15 (overleaf)), with inelastic scattering from ^{32}S showing the largest discrepancies encountered.

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(32) Perey F. G. and Buck B. Nuc. Phys. 32, 353 (1962), also Wilmore D. and Hodgson P. E. Nuc. Phys. 55, 673 (1964).

(33) Harwell Report No. R 5053.

(34) Report in preparation.

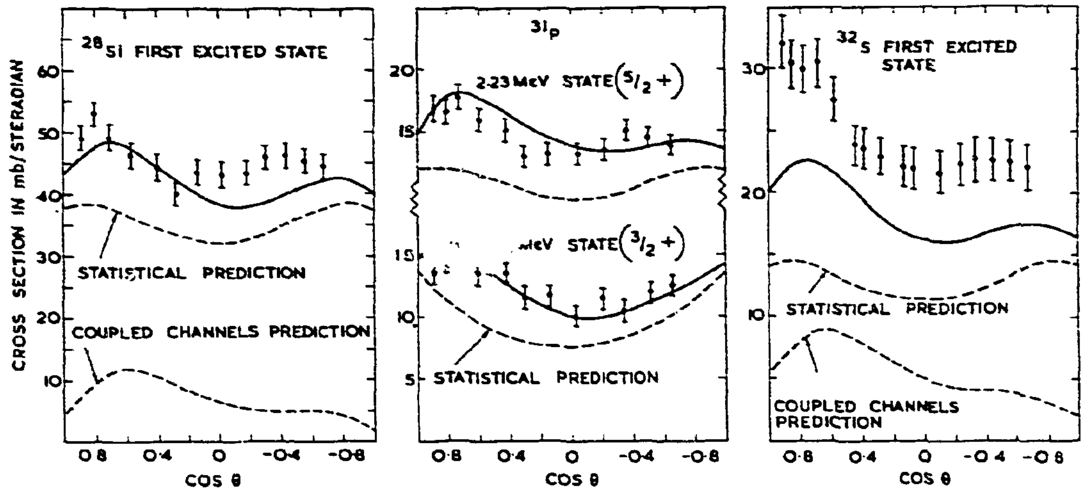

Fig. 15. Some results for inelastic scattering in ^{32}S, ^{28}Si and ^{31}P. The coupled channels and statistical predictions have been added to give the solid theoretical curve. No parameter adjustments were involved.

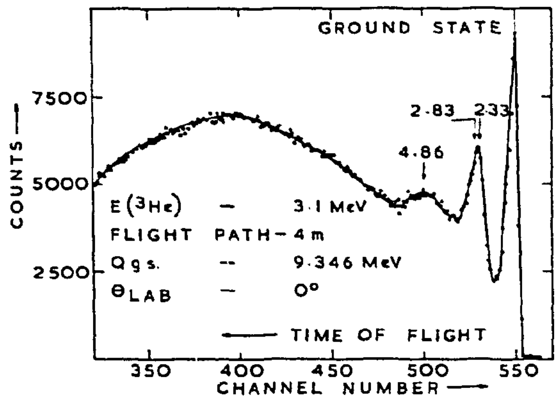

Fig. 16. Time of flight spectrum of neutrons from $^7Li(^3He,n)^9B$ at an incident energy of 3.1 MeV using a flight path of 4 metres.

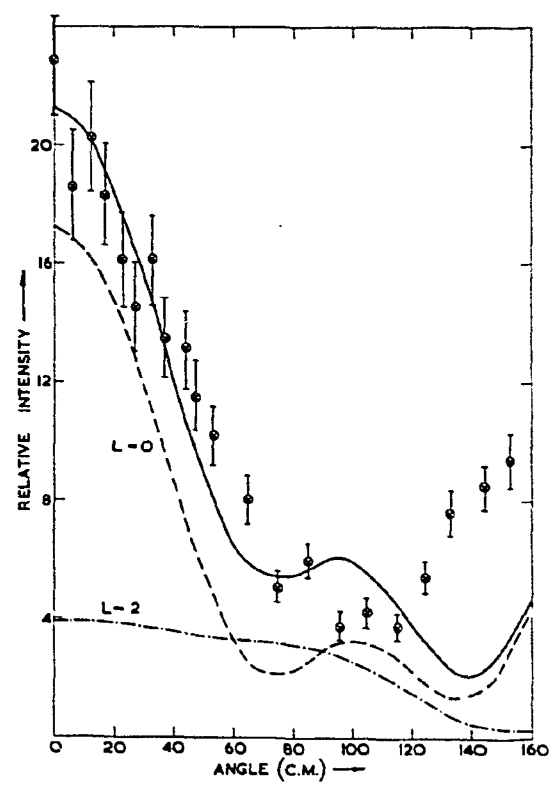

Fig. 17. Angular distribution of neutrons to the ground state of ^9B. The solid curve is obtained by assuming equal spectroscopic factors for $L = 0$ and $L = 2$.

$^{7}Li(^{3}He,n)^{9}B$ (B. H. Armitage, K. Gul and B. W. Hooton)

Angular distributions of neutrons from the $^{7}Li(^{3}He,n)^{9}B$ reaction have been measured using the IBIS time of flight system at an energy of 3.1 MeV. A time spectrum of neutrons is shown in Fig. 16. Neutron groups were observed corresponding to the ground state, unresolved excited states at 2.33 and 2.83 MeV and a broad level at 4.86 MeV. The continuum was attributed to three body break up. The angular distribution of neutrons to the ground state of ^{9}B is shown in Fig. 17. A reasonable distorted wave fit to the data appears to require an L = 0 component, which fixes the ground state spin as 3/2, the value to be expected by comparison with the mirror nucleus ^{9}Be. However compound nucleus formation and heavy particle stripping may also be important, and this perhaps accounts for the fact that Duggan et al.[35] were able to fit their 2.1 MeV measurements with a D.W.B.A. calculation using L = 2 only.

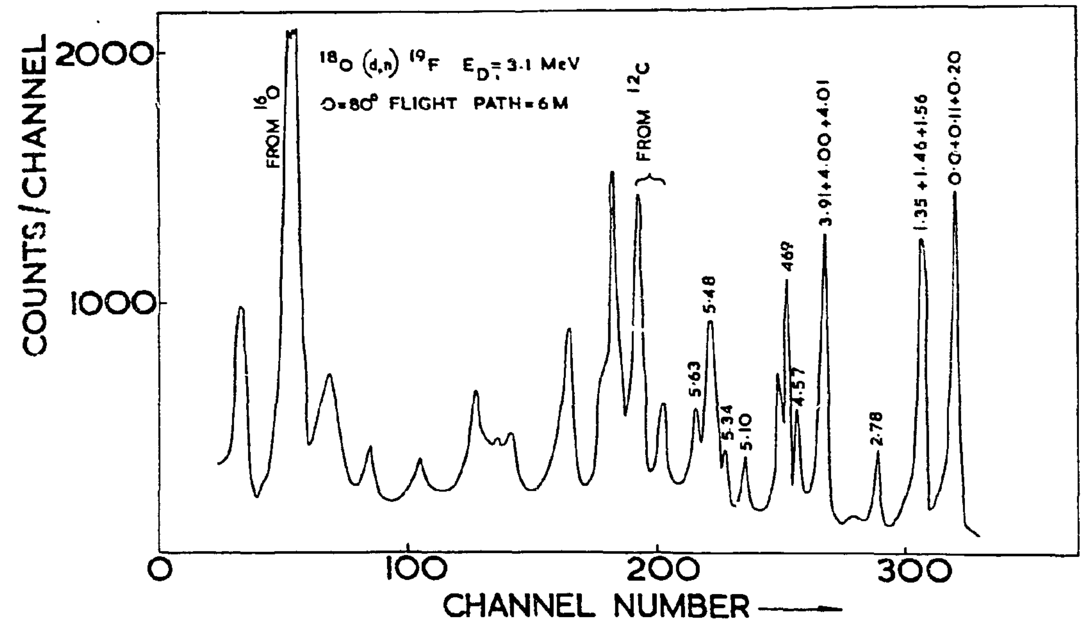

Fig. 18. $^{18}O(d,n)^{19}F$ time of flight spectrum over a flight path of 6 metres obtained with 3.1 MeV deuterons at an observation angle of 80°.

$^{18}O(d,n)^{19}F$ and $^{18}O(^{3}He,n)^{20}Ne$ (B. H. Armitage, K. Gul and B. W. Hooton)

Angular distributions of neutron groups in the $^{18}O(d,n)^{19}F$ and $^{18}O(^{3}He,n)^{20}Ne$ reactions have been measured with the IBIS accelerator, using WO_3 targets enriched to 99% in ^{18}O. A typical $^{18}O(d,n)^{19}F$ time of flight spectrum is shown in Fig. 18. It can be seen that significant contributions arise from ^{16}O and ^{12}C contamination and the former covers the expected position of the 7.40 MeV T = 3/2 state. Groups associated with established[36,37] low energy states in ^{19}F are labelled with the appropriate excitation energy in ^{19}F: the triplet of states including the ground state and the triplet of states near 1.5 MeV are not resolved.

The angular distributions from both reactions are being analyzed using D.W.B.A. theory.

(35) Duggan J. L., Miller P. D. and Gabbard R. F. Nuclear Physics 46, 336 (1963).

(36) Silbert M. G. and Jarmie N. Physical Review 123, 221 (1961).

(37) Ajzenberg F. and Lauritsen T. Nuclear Physics 11, 1 (1959).

5MV VAN DE GRAAFF GENERATOR

The channelling of protons in single crystals (G. Dearnaley and I. V. Mitchell with R. S. Nelson, Metallurgy Division, and Prof. M. W. Thompson and B. W. Farmery, University of Sussex)

The angular distribution of protons channelled through thin crystals has been further investigated, using the photographic technique described in the previous report. An explanation has been developed for the asymmetrical dark and light streaks observed in planar channelling near 0°. The effect appears over the range of angles for which channelling (anomalously high transmitted intensities along crystal planes) changes to blocking (relatively low scattered intensities along crystal planes). By extending an earlier model[38] of channelling to take account of the higher proton potential near atomic planes, Prof. Thompson has derived theoretical distributions similar in intensity and angular width to our experimental results.

Protons with incident energies between 2 and 4.5 MeV were passed through thin crystals of silicon and iron and the energy spectra of the emerging particles were studied in detail. Angular widths of the channelled component observed along certain low order directions and planes were measured at several energies. It was found that the streaks of high intensity observed in photographs of planar channelling showed enhanced intensities for both the channelled and normal energy-loss components.

The hypothesis of superposition (the idea that axial channelling can be explained as a linear superposition of contributions from the intersecting planes) has been tested and found to be at least a good first approximation. Some quantitative discrepancy at the <112> direction in silicon will be tested further.

An attempt has been made to find a spin polarization of protons channelled through magnetized single-crystal iron. A helium-filled polarimeter was constructed and used to measure the scattering to left and right of protons emerging with about 2 MeV energy from an iron crystal about 0.01 cm thick. A polarization of 3% would have been detectable, but no significant asymmetry was observed.

Analysis of analogue resonance data and evidence for internal mixing effects (C. H. Johnson*, R. L. Kernell* and S. Ramavataram)

Robson et al.[39] have analysed data on (p,n) excitation functions in the vicinity of analogue resonances by extending the original Robson theory of analogue resonances[40] under certain simplifying assumptions. In their theoretical treatment the following relationships are implied:

(a) the observed width Γ of the analogue state may be separated into two terms,

$$\Gamma = \Gamma_{op} + W^{(e)}$$

where Γ_{op} = observed partial width for entrance channel

$W^{(e)}$ = external spreading width

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*Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

(38) Nelson R. S. and Thompson M. W. Phil. Mag. 8, 1677 (1963).

(39) Robson D., Fox J. D., Richard P. and Moore C. F. Phys. Letters 18, 86 (1965).

(40) Robson D. Phys. Rev. 137, B 535 (1965).

(b) In addition, the resonance part of the cross section can be written as:

$$\sigma_{p,n}\,(\text{res}) = \sigma_{p,n}\,(\text{bkd}) \left[\frac{(E - E_0 - \Delta)^2}{(E - E_0)^2 + (\Gamma/2)^2} - 1 \right]$$

where E_0, Δ, Γ and $\sigma_{p,n}$ (bkd) are respectively the resonance energy, level shift, total width and non-resonant background cross section for a single proton channel. If neutron emission dominates the decay of the background $T_<$ states, $\sigma_{p,n}$ (bkd) is approximately equal to the $T_<$ reaction cross section. Estimates of the latter quantity may be obtained by choosing a suitable form of the optical potential.

Experimental $^{89}Y(p,n)^{89}Zr$ reaction cross sections[/] for proton energies ranging from 3.6 MeV to 5.1 MeV have been analysed to see whether they are consistent with the above expressions in the neighbourhood of the 3^- analogue resonance in ^{90}Zr.

The non-resonance background cross section was determined by using the form of proton optical potential suggested by Perey[(41)] to describe the absorption cross section and calculating the relative probability for decay by neutron emission from Hauser-Feshbach theory[(42)], using Wilmore's computer programme[(43)]. The input for the Hauser-Feshbach calculation included the first three levels in ^{89}Y and ^{89}Zr with the tentative[(44)] assignment of $\frac{1}{2}^-$ for the second excited state in ^{89}Zr. The neutron optical potential used was that suggested by Moldauer[(45)]. The proton optical model parameters required to give a satisfactory fit to the entire off-resonance excitation function were found to be essentially those recommended by Perey, except that we had to use an imaginary well depth W_D of 5 MeV. Shell effects may account for the fact that this value is lower than Perey's average estimate.

Having obtained the background curve we extracted the parameters of the 3^- analogue resonance and compared them with values calculated using the assumptions of Robson et al.[(39)]. We found that the calculated value of Γ was only half of the observed width, while estimates of the background cross section obtained by applying equation (b) to the observed cross section at the resonance peak amount to only 20-30% of the values given by the optical model for this particular exit channel.

Such discrepancies between theory and experiment clearly indicate that the existing theory is inadequate. In this particular situation the single channel assumption and the assumption that direct interaction contributions may be ignored are probably well justified. On the other hand internal mixing effects are ignored, and these should be included. A point worth noting is that the parameter Δ/Γ which characterises the asymmetry of the resonance would lose its significance if internal mixing effects are introduced by treating the background R-matrix as pure imaginary. A more general form for this part of the R-matrix would result in corrections due to internal mixing which include contributions to the shift factor as well as to the width.

/ Data obtained on the 5.5 MeV Van de Graaff at Oak Ridge National Laboratory, Tennessee, U.S.A.

(41) Perey F. G. Phys. Rev. 131, 745 (1963).

(42) Hauser W. and Feshbach H. Phys. Rev. 87, 366 (1952).

(43) Wilmore D. AERE - R 5053 (1966).

(44) Goodman C. D. et al. ORNL-3630, 21 (1963).

(45) Moldauer P. A. Phys. Rev. 135, B642 (1964).

Experiments relating to pure Fermi decays and to theories of weak interactions (J. M. Freeman, J. G. Jenkin and D. C. Robinson with G. Murray* and W. E. Burcham**)

Work is continuing[46] on experiments concerned with the discrepancy between the ft values for two of the transitions between $J = 0^+$, $T = 1$ isobars ($^{26}Al(\beta^+)^{26}Mg$ and $^{10}C(\beta^+)^{10}B^{**}$) and those for the six other pure Fermi decays which have been studied with an accuracy of better than 1%. These departures from the expected constant Fermi ft values are of importance in deriving a value for the weak interaction vector coupling constant G_V and the Cabibbo angle θ_V for non-strange particle decays.

A large volume Ge(Li) gamma-ray detector

In June the High Voltage Laboratory purchased from Princeton Gamma-Tech Inc. an encapsulated germanium detector with an active volume greater than 20 cc which had been lithium-drifted in coaxial geometry. Pulses from the detector were amplified by a Harwell made preamplifier using a development model of a commercial silicon tetrode, followed by a Tennelec TC 200 linear amplifier. With differentiation and integration time constants of 1.6 μsec the system has consistently given a resolution of 4.0 keV (fwhm) for 1332 keV gamma rays (^{60}Co source). The detector has an excellent reverse-bias characteristic curve; the leakage current remains below 3×10^{-11} amps until the bias voltage reaches 650 volts, after which it rises slowly to 6×10^{-11} amps at 800 volts. The detector is permanently encapsulated in a closed system containing a molecular sieve vacuum pump. On one occasion the sieve was successfully reactivated.

I - The ft value for the decay $^{10}C(\beta^+)^{10}B^{**}$

To determine this ft value the results of four experiments, which were described in previous Progress Reports[46], are required.

To reduce the uncertainties in the excitation energies of the first two states of ^{10}B and in the β^+ branching ratios for the decay of ^{10}C to excited states in ^{10}B much new data has been taken with the 20 cc Ge(Li) detector. This data is now being processed. It is hoped that a significant improvement can be made in the preliminary ft value quoted in the last Progress Report[46].

II - The ft value for the decay $^{14}O(\beta^+)^{14}N^*$

An accurate measurement of the ft value for this transition, made elsewhere in 1962[47], used a different method from that which has been used at Harwell to determine ft values for seven other pure Fermi decays. To compare these results directly with the ^{14}O case we have remeasured the β end point for this transition (the total half life and β branching ratios have been confirmed previously by several groups). Our $^{14}N(p,n)^{14}O$ threshold result is 6354.9 ± 2.2 keV. The excitation energy of the 0^+, first excited state in ^{14}N, found by comparing the double-escape peak from the de-excitation gamma ray with the accurately known ^{60}Co gamma ray peaks, is 2312.64 ± 0.10 keV. Thus the end point energy of the β transition to the first excited state is 1809.7 ± 2.1 keV, to be compared with the value 1812.6 ± 1.4 keV obtained by Bardin et al.[47].

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*University of Manchester.

**University of Birmingham.

(46) Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 28 (1966).

(47) Bardin, Barnes, Fowler and Seeger. Phys. Rev. 127, 583 (1962).

III - The decay $^{42}Sc(\beta^+)^{42}Ca$

We have obtained an accurate ft value for this decay, which is one example of a transition between analogue $J = 0^+$, $T = 1$ states. It has been assumed that for such transitions charge dependent effects produce a negligible (< 1%) reduction in the Fermi matrix element. Calculations[48] on similar transitions have suggested that this is true. The fact that the second excited state of ^{42}Ca at 1.84 MeV is also known to be 0^+, $T = 1$ suggests an experimental test of the extent of mixing into the ^{42}Ca ground state. The 20 cc Ge(Li) detector has been used to search for a 1.53 MeV gamma-ray resulting from the de-excitation of the 1.84 MeV state through the first excited state, following a possible weak beta decay branch from ^{42}Sc. Some slight evidence for such a gamma ray has been obtained, but an appreciable improvement both in the statistical accuracy and in the target will be required to obtain a satisfactory value of, or limit to, the intensity of the excited state beta branch.

A study of the levels in ^{29}Si and ^{31}Si using the (d,p) reaction (R. B. Taylor and R. B. Weinberg)

Isotopically enriched targets of ^{28}Si and ^{30}Si were bombarded with 11 MeV deuterons and the scattered protons from the (d,p) reaction were recorded on photographic plates in the broad range spectrograph. Angular distributions were measured from 0° to 145°. All exposures have been made and the plates have been read. At the moment the data is being reduced and analysed using a D.W.B.A. programme to extract reduced widths of as many levels as possible.

High resolution nuclear structure studies in some samarium and tellurium isotopes (R. K. Jolly, G. A. Jones and R. B. Taylor)

I - Samarium isotopes

These isotopes are suitable for studying the f-p $82 < N \leqslant 126$ neutron shell, since the lightest stable Sm isotope contains 82 neutrons. Spectroscopic studies of ^{145}Sm via (d,p) reactions have been recently completed by one of us[49] and studies of ^{149}Sm and ^{151}Sm are currently underway. Some isobaric analogue state studies using proton elastic scattering from ^{144}Sm, ^{148}Sm, ^{150}Sm, ^{152}Sm and ^{154}Sm targets have recently been completed[50], and it is of considerable interest to compare the results of the two types of experiment.

II - Tellurium isotopes

Nuclear structure studies on all the isotopes of Te for which stable targets were available were undertaken at the University of Pittsburgh[51] (U.S.A.) some years ago, but could not be brought to a satisfactory conclusion because the energy resolution (~ 40 keV) was inadequate, particularly for the lighter isotopes of Te. This work has now been restarted at Harwell. (d,p) reaction measurements on the target nuclei ^{122}Te and ^{124}Te have already been performed and measurements on ^{126}Te and ^{128}Te are contemplated in the near future. Isotopically separated Sm and Te targets were bombarded with 11.0 MeV deuterons from the Tandem Van de Graaff accelerator and the reaction products analysed in a Brown-Buechner spectrograph with an overall energy resolution of ~ 15 keV. The proton spectra were measured at eight angles between 10° and 70°.

The D.W.B.A. code "Export Julie"[52] has been recently acquired from the Oak Ridge National Laboratory and it is planned to use the code to calculate stripping cross sections so that we can determine l-values, spectroscopic factors and other related single particle parameters. We plan to check

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(48) Blin-Stoyle, Nair and Papageorgiou. Proc. Phys. Soc. 85, 477 (1965).

(49) Jolly R. K. Phys. Rev. 145, 918 (1966).

(50) Jolly R. K. and Moore C. F. (To be published).

(51) Jolly R. K. Phys. Rev. 136, B683 (1964).

(52) Bassel R. H., Drisko R. M. and Satchler G. R. Private communication.

some of our spin assignments by measuring the polarization of protons scattered from the isobaric analogue resonances as discussed elsewhere[53] in this report.

A study of the levels in ^{119}Sn and ^{121}Sn using the (d,p) reaction (D. L. Allan, G. A. Jones, R. B. Taylor and R. B. Weinberg)

As a result of the study of isobaric analogue resonances[54] in ^{119}Sb and ^{121}Sb it was decided to repeat the work of Cohen et al.[55] on the reactions $^{118}Sn(d,p)^{119}Sn$ and $^{120}Sn(d,p)^{121}Sn$ using much better resolution. The analogue work predicted many more levels than Cohen observed and it was of interest to see whether these predicted levels could be seen with the higher resolution. A beam of 11 MeV deuterons was used in conjunction with the Harwell broad range spectrograph. Angular distributions were measured on as many groups as possible. The data for $^{118}Sn(d,p)^{119}Sn$ has been extracted from the photographic plates and is being analysed. The $^{120}Sn(d,p)^{121}Sn$ data is still in the process of being obtained from the photographic plates. The initial data on the ^{121}Sn levels show many more levels than Cohen reports and the agreement with the analogue work appears reasonable.

Isobaric analogue states in ^{91}Nb (G. A. Jones, G. C. Morrison* and R. B. Taylor)

The reaction $^{90}Zr(p,p')^{90}Zr^*$ has been studied both directly by looking at the inelastic spectra using Si detectors, and indirectly by observing the subsequent decay of the 0.8 sec, 2.3 MeV isomeric state in ^{90}Zr. Excitation functions are given in Figs. 19 and 20. Since the isomeric state has $J^\pi = 5-$, it should be fed from both the (5–) and (4–) states, and the excitation function for its decay should correlate with the excitation functions for inelastic scattering to these two states. The proton groups to the (4–) and (3–) states are not resolved, but comparison of their combined excitation function with that for the isomeric state enables us to decide which of these two states are concerned at each resonance. The arrows in Fig. 20 indicate where isobaric analogue resonances corresponding to the levels of ^{91}Zr strongly excited in the stripping reaction $^{90}Zr(d,p)^{91}Zr$ are expected to appear. It will be seen that we are observing the analogues of many more states in ^{91}Zr than are revealed by the (d,p) reaction.

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*Now at Argonne National Laboratory.

(53) Jones G. A., Neilson G. C. and Jolly R. K. Ibid.

(54) Allan D. L., Jones G. A., Taylor R. B. and Weinberg R. B. Ibid.

(55) Schneid E. T., Prakash A. and Cohen B. L. (To be published).

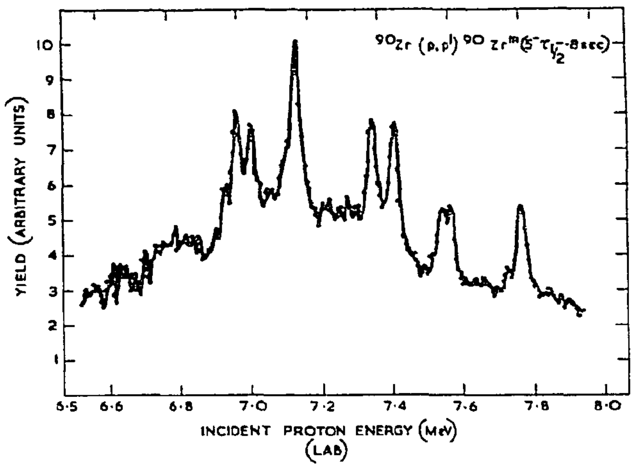

Fig. 19. $^{90}Zr(p,p')^{90}Zr^m(5, \tau_{1/2} = 0.8s)$. Excitation function for observation of delayed radiation from the isomeric state.

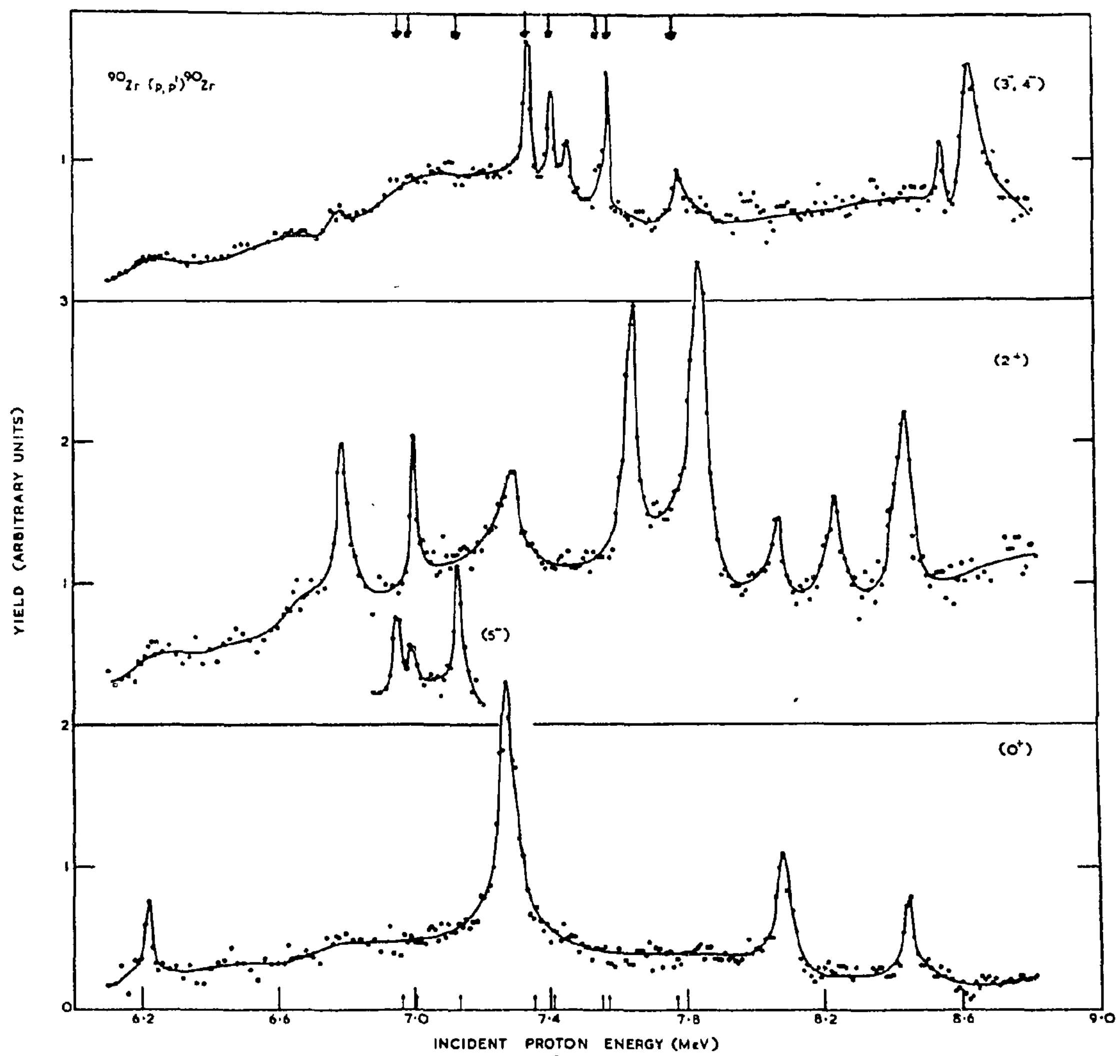

Fig. 20. $^{90}Zr(p,p')^{9}Zr^*$. Excitation functions for proton groups corresponding to transitions to the low lying excited states in ^{90}Zr.

A study of isobaric analogue states in the Sb isotopes (D. L. Allan, G. A. Jones, R. B. Taylor and R. B. Weinberg)

The study of isobaric analogue resonances in ^{119}Sb and ^{121}Sb which was previously reported[56,57,58] has now been completed. The previously reported work has been extended by making absolute cross section measurements, by measuring the elastic scattering cross sections at angles of 90° and 125° and by measuring a complete excitation function for the reaction $^{120}Sn(p,p')^{120}Sn^*$ (3^-, 2.39 MeV level). At the present moment the data are being analysed to extract the proton partial widths which are needed to determine whether the resonances are in the ingoing channel, the outgoing channel, or both. A comparison of the data for ^{119}Sb and ^{121}Sb shows far fewer resonances in ^{121}Sb. This phenomenon must be associated with the addition of two extra neutrons, but cannot at the moment be explained.

Polarization of protons elastically scattered from isobaric analogue resonances (R. K. Jolly, G. A. Jones and G. C. Neilson)

The recent work of Adams et al.[59] and Terrel et al.[60] has shown that the energy dependence of the polarization of protons elastically scattered via an isobaric analogue resonance uniquely determines the spin of the resonance. Robson et al. claim that the method is applicable even to resonances with partial widths as low as 5%-10% of the total width. If the above claims are valid, then this technique, as a supplement to stripping and pick up measurements on the target nucleus, provides a sure way of ascertaining spins of most low lying states of even-odd nuclei. However, polarization measurements are notoriously slow and tedious. Consequently a polarimeter was designed with the object of achieving an efficiency which would allow the present technique to be used for routine measurements.

The polarimeter fits inside the existing scattering chambers and can rotate around the target under vacuum. It uses a 20 mg/cm^2 carbon foil as an analyser. Under optimum conditions it is hoped to make one polarization measurement ($\sim$ 10% statistical accuracy) in approximately 5 hours.

Some successful test runs have already been made and more results are hoped for in the near future.

Lifetimes in ^{24}Mg measured by the Doppler-shift attenuation method (W. M. Currie and C. H. Johnson)

The doppler shift method described in the last progress report has been used to study the 1.37 and 4.23 MeV levels of ^{24}Mg, but the results have not yet been completely analysed. Computer programmes are being written to make geometrical corrections, and to estimate the effect of large angle nuclear scattering at low recoil velocities, using Blaugrund's[61] treatment for the mean nuclear scattering angle. The preliminary result for the lifetime of the 4.23 MeV level is 1.0×10^{-13} sec and the final result should not differ by more than 30% from this value. Thus it is likely to agree with the result of 1.2×10^{-13} sec obtained recently by the Chalk River group[62] using inelastic proton scattering and a Ge(Li) detector.

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(56) Allan D. L., Jones G. A., Morrison G. C., Taylor R. B. and Weinberg R. B. Phys. Lett. 17, 56 (1965).

(57) Allan D. L., Jones G. A., Morrison G. C., Taylor R. B. and Weinberg R. B. Phys. Lett. 21, 197 (1965).

(58) Allan D. L., Jones G. A., Morrison G. C., Taylor R. B. and Weinberg R. B. Nuclear Physics Division Progress Reports AERE - PR/NP 9 and AERE - PR/NP 10 (1966).

(59) Adams J. L., Thompson W. J. and Robson D. To be published.

(60) Terrel G., Moore C. F., Adams J. L. and Robson D. Conference on "Isobaric Spin in Nuclear Physics" - 1966 (page 333 - Academic Press Inc. N.Y.).

(61) Blaugrund A. E. To be published.

(62) Alexander T. K. et al. Submitted to The International Conference on Nuclear Physics, Gatlinburg (1966).

The lifetime of the first excited 2+ state (1.37 MeV) is already known to be 1.0×10^{-12} sec. The reduced transition probabilities for the decay of the first and second (4.23 MeV) 2+ states to the ground state therefore differ by a factor ~ 37. This difference is $2 \rightarrow 6$ times greater than the various possible ratios derived by Elliott and Harvey(63), whose calculations were based on an SU_3 classification of states and assumed an inert ^{16}O core.

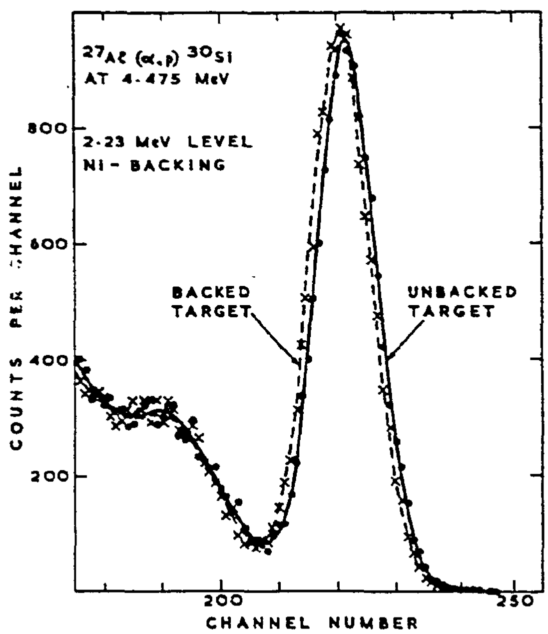

Fig. 21. Two photopeaks from the first excited state of ^{30}Si produced in the reaction $^{27}Al(\alpha, p\gamma)^{30}Si$. They were recorded simultaneously, one from an unbacked target, the other from a target on a Ni backing. The attenuated Doppler-shift observed here is 0.45%.

<u>Lifetimes in ^{30}Si and ^{34}S measured by the Doppler-shift attenuation method (W. M. Currie and A. K. Sen Gupta)</u>

The twin-target Doppler-shift technique described in the last progress report has been used with the ^4He beam from the 5 MeV Van de Graaff to populate the first two excited states of ^{30}Si and ^{34}S by way of the reactions $^{27}Al(\alpha,p)^{30}Si$ and $^{31}P(\alpha,p)^{34}S$. No B(E2) values are known for these nuclei.

Both singly and doubly charged ^4He ions were used. Backward going protons were detected in two annular detectors, forward going γ-rays in a 3 in. x 3 in. NaI(Tl) crystal. Measurements were made with two different backing materials for each of the recoil nuclei, Ni and Mg in the case of ^{30}Si, and Ni and C in the case of ^{34}S. Fig. 21 shows an example of the kind of spectra obtained.

The work is not yet completed. More measurements are being made and a detailed analysis of the data has to be carried out. At the moment only some crude first approximations to the lifetimes have been derived. These are: for the first excited state of $^{30}Si \sim 5 \times 10^{-13}$ sec, and for the first and second excited states of ^{34}S, $\sim 5 \times 10^{-13}$ sec and $\sim 2 \times 10^{-13}$ sec respectively.

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(63) Elliott J. P. and Harvey M. Proc. Roy. Soc. A272, 557 (1963).

45 MeV ELECTRON LINEAR ACCELERATOR
(Nuclear Physics - II and Nuclear Photo-effect: E. R. Rae)

Energy spectra of photoneutrons from heavy nuclei (D. B. McConnell*, B. H. Patrick and E. M. Bowey)

This experiment(64) has continued, but less time has been devoted to the collection of data. Two further elements, bismuth and gold, have now been studied. These elements too show an increasing "direct" component in the photoneutron spectrum as the excitation energy is increased.

The main object of the work has been to estimate the effects of neutron scattering on the spectra obtained from the heavy and ordinary water targets. It is thought that the corresponding corrections to the data from the two targets will be appreciably different, and will not cancel completely when the two sets are subtracted, so that the corrections will have to be made before we can proceed with the analysis of the data. A programme for the IBM 7030 computer is being written to calculate the corrections and this should be completed shortly.

50 MeV PROTON LINEAR ACCELERATOR (S.R.C.)
(Proton Physics Group: P. E. Cavanagh)

Study of the levels of the odd tin isotopes through the (p,d) reaction (P. E. Cavanagh and C. F. Coleman)

Earlier reports on this work appear in the Nuclear Physics Division Progress Reports PR/NP 9 and PR/NP 10. Our data have now been corrected for isotopic and chemical impurities in the targets and for a non-uniform continuous background associated with random coincidences between telescope and spark chamber events. The major single quasi-particle peaks appear at excitations up to about 1.5 MeV, minor peaks (some only partially resolved) at excitations up to about 3 MeV and a continuum of unresolved levels at higher excitations. The integrated intensity falls sharply over this range, in ^{115}Sn for example by a factor $\sim$ 20.

I - J dependence

The experimental determination of the 'j' values for the 'd' peaks from the angular distributions has been simplified by taking as a criterion of the stripping peak position the area ratio

$$R = \frac{0.5 \times \sigma(6°) + \sigma(7°) + \sigma(9°) + \sigma(11°) + \sigma(13°) + \sigma(15°)}{\sigma(17°) + \sigma(19°) + 1.5 \times \sigma(22°) + 1.5 \times \sigma(25°)}$$

By plotting R for the main $d_{3/2}$ and $d_{5/2}$ peaks, for which the J values are known, against Q one can find a and b such that

$$R' = R + a\Delta A + b\Delta Q$$

is almost independent of A and Q. Here ΔA and ΔQ are the amounts by which the particular target mass and Q value exceed 124 and 7.461 respectively. Values of R' for all the observed 'd' peaks are plotted against the corresponding Q values in Fig. 22, the main $d_{5/2}$ and $d_{3/2}$ levels being represented by filled circles and squares respectively. All but one of the main $d_{5/2}$ lines have R' values lying in the range $1.71 \pm .02$, whereas the values for the $d_{3/2}$ lines lie in the range $2.14 \pm .02$, except that for ^{113}Sn, which lies about halfway between the two. The full lines show the values of this ratio determined from our

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*Now at Physics Dept., University of Toronto, Ontario, Canada.

(64) McConnell D. B., Patrick B. H. and Bowey E. M. Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 37 (1966).

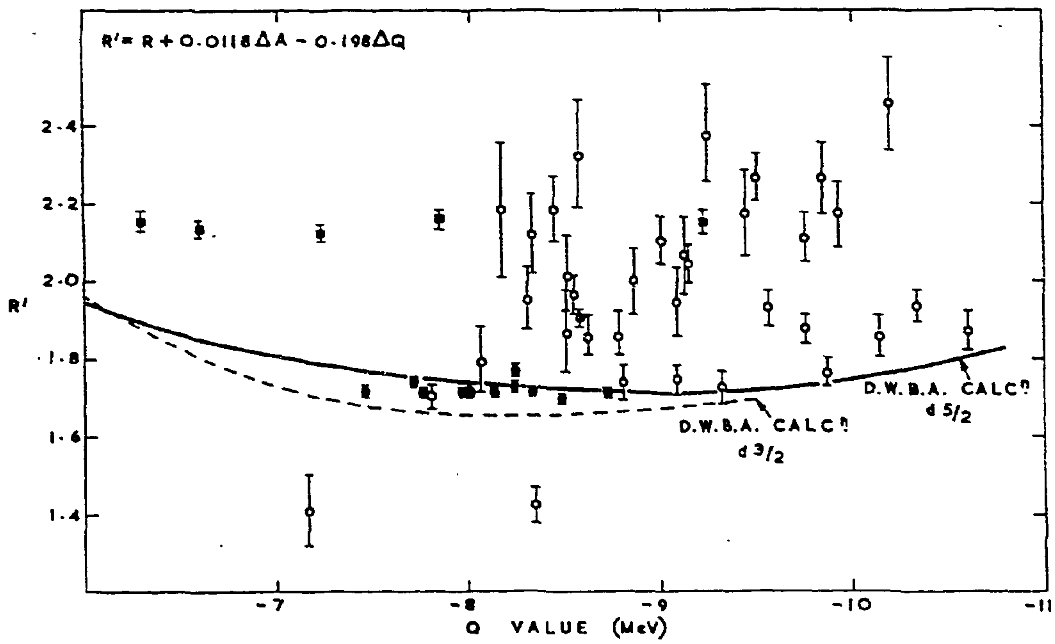

Fig. 22. Values of R′ for all the 'd' levels observed in the tin isotopes.

D.W.B.A. calculations. They follow the $d_{5/2}$ data fairly closely, but give no indication of the $d_{5/2}$, $d_{3/2}$ separation, even though a spin orbit term is used for the neutron bound state potential. The trend from Q = − 8 to − 9 MeV of the points for a group of weak levels which we have some grounds for interpreting as $d_{3/2}$ suggests that the anomalous ^{113}Sn point may lie in a rather sharp dip in the $d_{3/2}$ locus. Even in this region the R′ value is usually enough to determine the value of 'j'.

<u>II - 'Weak' loci</u>

The angular distributions of all the lines observed in ^{115}Sn are shown in Fig. 23 (overleaf). Over the range of isotopes, most of the weaker lines are 'd' lines, a few have rather indeterminate angular distributions, and the rest include a number of 's' and some unmistakable 'p' lines. When the Q values for the various lines are plotted against the mass numbers (Fig. 24 (see page 25)) two sequences of 's' and 'p' lines appear to lie on smooth curves. Their excitations are a few hundred keV below those to be expected in the weak coupling approximation from the configurations $(d_{5/2}, \lambda_2 = 1)_{1/2+}$ and $(g_{7/2}, \lambda_3 = 1)_{1/2, 3/2-}$, and are so far removed from the one quasiparticle $s_{1/2}$, $p_{1/2}$ and $p_{3/2}$ levels that mixing between the configurations is unlikely to explain the appearance of transitions to these levels in a pick-up spectrum. Alternative possibilities are excitation through four quasiparticle admixtures to the ground state wave functions of the even targets, and two stage excitation (coulomb excitation combined with pick-up). The $(g_{7/2}, \lambda_2 = 1)_{3/2+}$ configuration may be represented by small groups of $3/2+$ levels which appear at appropriate excitations, while the $(s_{1/2}, \lambda_2 = 1)_{5/2+}$ configuration appears for mass 117 and above, dropping progressively further below the main $d_{5/2}$ levels as the mass number increases. Over the mass range from 111 to 123 the excitation and composition of the lowest observed $5/2+$ levels change in a way qualitatively similar to that calculated by Kuo, Baranger and Baranger(65), who use realistic form of residual interaction, but adjust the parameters to match the observed positions of the low lying one quasiparticle states.

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(65) Kuo T. T. S., Baranger E. U. and Baranger M. Nuclear Physics <u>79</u>, 513 (1966).

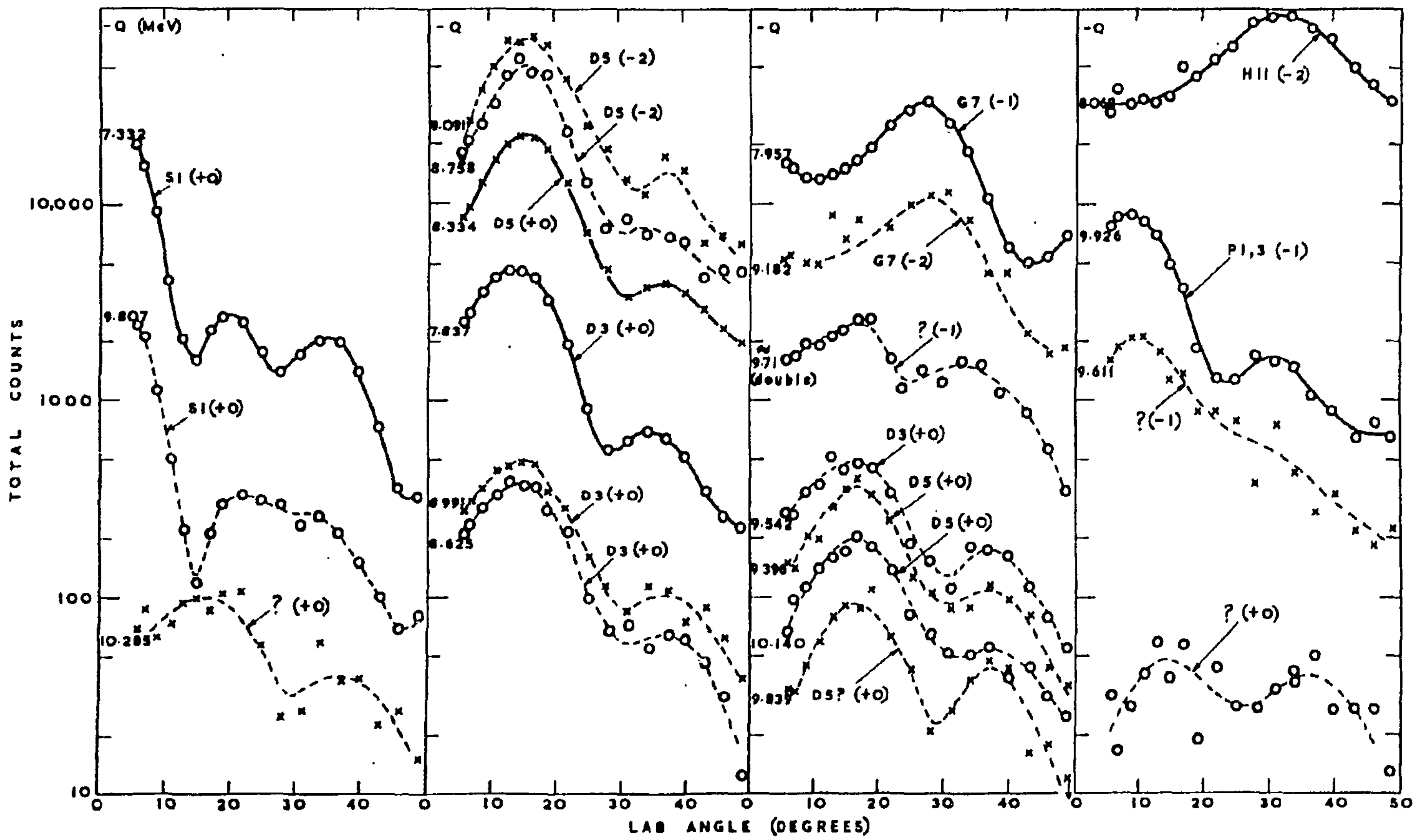

Fig. 23. Angular distributions of transitions to all the levels observed in ^{115}Sn. The numbers in brackets are the powers of 10 by which the right hand scale should be multiplied.

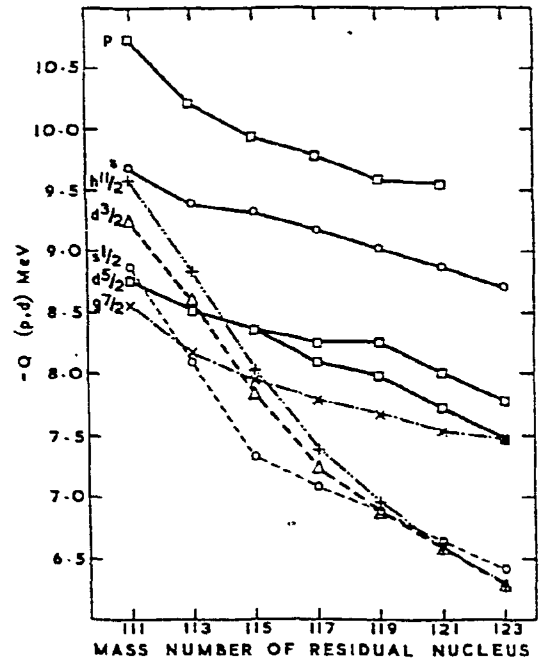

Fig. 24. Q values as a function of mass numbers for the major levels and certain minor level sequences in the tin isotopes.

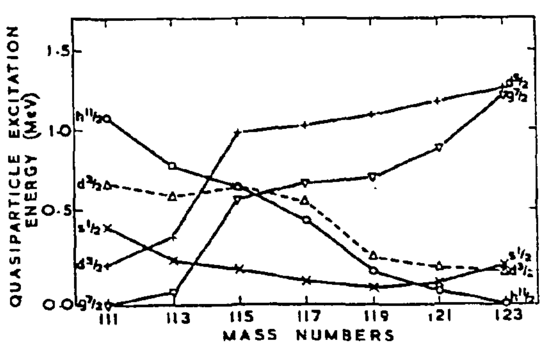

Fig. 25. Experimental quasiparticle energies (referred to ground state energies) for the odd mass tin isotopes.

III - Occupation numbers and quasiparticle energies

On the simple pairing model the quasiparticle energy E_j and the occupation number V_j^2 for the orbit with total angular momentum 'j' are related to the shell model energy E_j, the chemical potential λ and the energy gap Δ by

$$E_j = \sqrt{(\epsilon_j - \lambda)^2 + \Delta^2}$$
$$V_j^2 = \tfrac{1}{2}(1 \pm \sqrt{1 - \Delta^2/E_j^2})$$

If the configuration is split into a number of levels at excitations E_{ji} which have peak cross sections σ_{ji} in the (p,d) reaction, and if the corresponding single particle cross sections are $(\sigma_{ji})_T$, then Yoshida[66] showed that in the presence of the phonon couplings the sum rule

$$V_j^2 = \sum_i \sigma_{ji}/(\sigma_{ji})_T$$

holds good, so that the V_j^2 can be found if reliable D.W.B.A. calculations of the $(\sigma_{ji})_T$ are available. One can also calculate the E_j's, and thus the V_j^2's from

$$E_j = \sum_i E_{ji}\,\sigma_{ji}/\sum_i \sigma_{ji}$$

This is approximate, since Yoshida's calculations show that certain interference terms should be added on the right hand side, but the systematics of the experimental $\sigma_{ji}(p,d)/\sigma_{ji}(d,p)$ ratios suggest that these terms are a good deal smaller than Yoshida's calculated values. The experimental E_j values calculated from this formula are shown in Fig. 25. The sudden drop in $E_{1/2}$ near A = 115 is believed to result from the fact that in this mass region no shell model levels of high statistical weight lie near the Fermi surface, so that Δ becomes unusually small, and $E_{1/2}$ falls because $\epsilon_{1/2}$ is near the Fermi surface. This appears to account for the binding energy irregularities quoted as evidence for a weak shell closure at A = 114. $E_{5/2}$ rises surprisingly slowly above A = 119, since a mean rise of 150 keV/unit mass is required to cover the gap between the 50 and 82 particle neutron shell s, while the actual value of $E_{5/2}$ is rather high, since taken in conjunction with the value of Δ it implies that $U_j^2 \sim .07$, whereas Cohen's (d,p) results[67] require $U_j^2 \sim .15$. The calculations of Yoshida and of Kuo et al. both predict a spreading of the $d_{5/2}$ reaction strength in the heavier isotopes which is several times larger than the splitting we observe.

(66) Yoshida S. Nuclear Physics 38, 380 (1962).

(67) Cohen B. H. BNL 948, vol. I, p. 269 (1965).

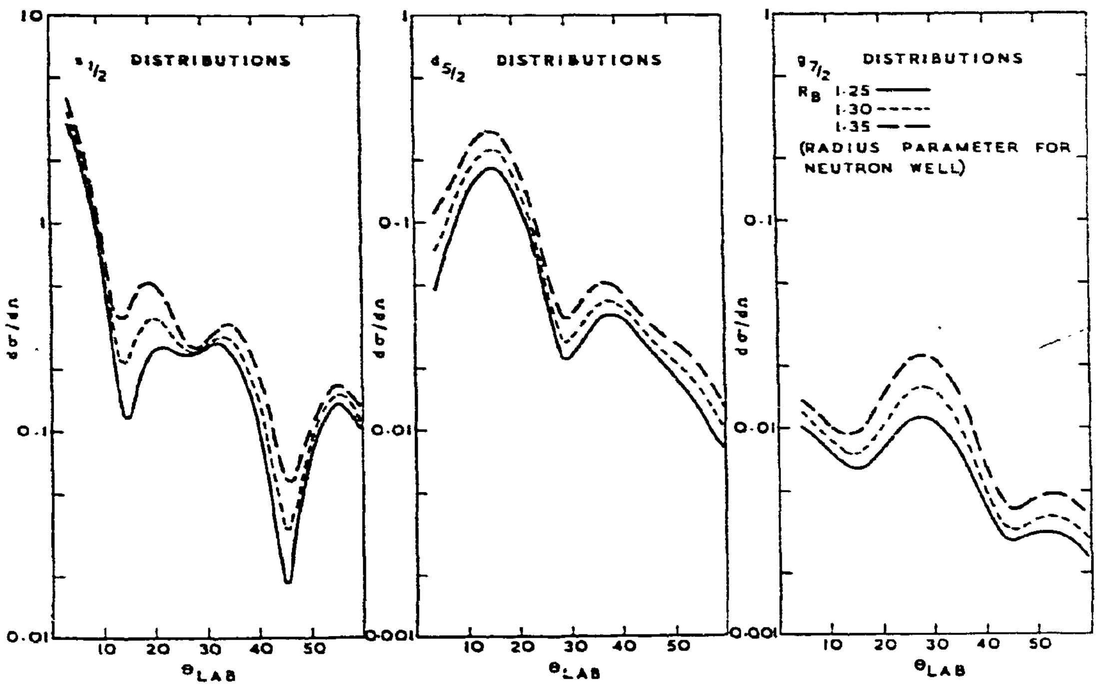

Fig. 26. DWBA angular distributions for $s_{1/2}$, $d_{5/2}$, $g_{7/2}$ pick-up from $^{118}Sn(p,d)$.

D.W.B.A. analysis of (p,d) reactions on tin isotopes
(P. E. Cavanagh)

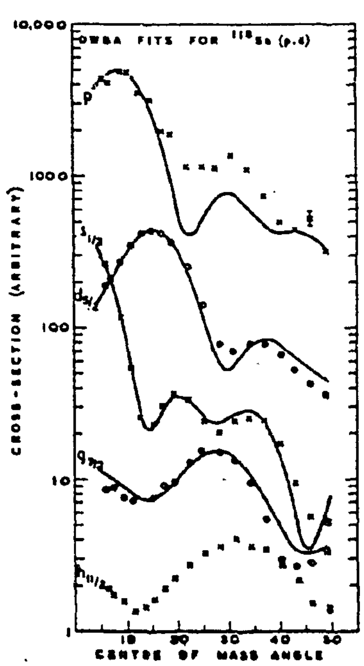

***Fig. 27.** DWBA fits to experimental angular distributions for $s_{1/2}$, $d_{5/2}$ and $g_{7/2}$ pick-up from $^{118}Sn(p,d)$.*

It was noted in the last progress report that a rather wide range of deuteron parameters (consistent with elastic scattering data) would give reasonable fits to the observed $d_{5/2}$ angular distribution when used in D.W.B.A. calculations, provided that the bound state potential radius parameters were chosen accordingly, but that these fits gave rise to a correspondingly wide range of spectroscopic factors. While the shapes and amplitudes of calculated $S_{1/2}$ distributions at forward angles are rather insensitive to the choice of parameters, the reverse is true of the double maximum that appears in the experimental distributions between 20° and 50°. The details of the calculated shape here depend critically on the value of the real radius parameter for the deuteron potential, R_d, and on the difference between R_d and the corresponding parameter for the bound neutron potential, R_b. Fig. 26 shows how changes in R_b affect the calculated angular distributions for $S_{1/2}$, $d_{5/2}$ and $g_{7/2}$ pickup from ^{118}Sn. The effects on the shapes of the calculated angular distributions diminish as the l value increases. A good fit to the experimental $S_{1/2}$ angular distribution requires radius parameters of 1.07 and 1.30 fermi for the deuteron and bound neutron wells respectively, and is sensitive to changes in these values of 0.02 fermi. The same set of parameters provides an excellent fit to the $d_{5/2}$ distribution, and a reasonable fit to the $g_{7/2}$ distribution, as shown in Fig. 27. It should be noted that the cut-off parameter for the radial integrations was set to zero for all these calculations. Similar parameters provide an excellent fit to the $S_{1/2}$

distributions for $^{120} \rightarrow {}^{124}$Sn, but to fit the ^{112}Sn data it was found necessary to increase R_b to 1.34 fermi, with intermediate values for intermediate masses. This is not surprising, since the $s_{1/2}$ configuration is filling strongly between ^{112}Sn and ^{118}Sn. Since the $s_{1/2}$, $d_{5/2}$ and $g_{7/2}$ configurations are all substantially full for $A \geq 120$, one would expect little variation of R_b over this mass range. However the best fit to the $d_{5/2}$ distribution for ^{124}Sn requires $R_b = 1.26$ fermi, which is not consistent with this viewpoint.

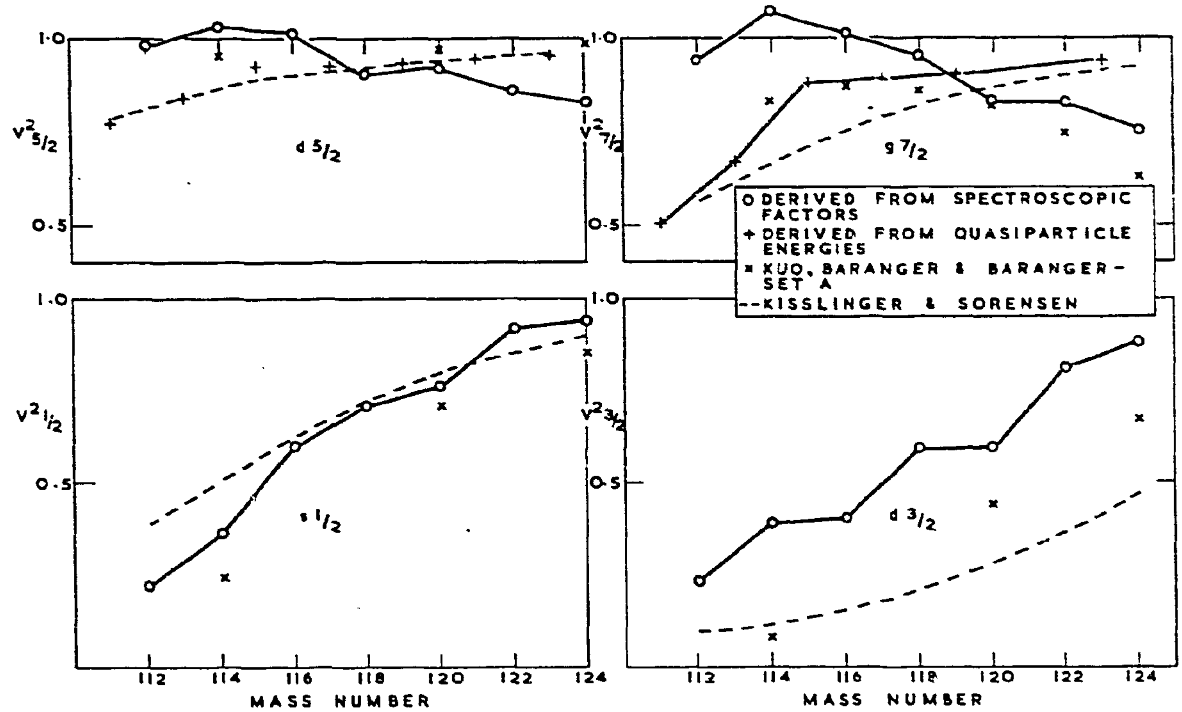

Fig. 28. Occupation numbers in the tin isotopes.

The D.W.B.A. calculation uses a local, zero-range interaction, and a spin-orbit term is included in the bound state potential only. These approximations will introduce some inaccuracy into the estimated spectroscopic factors. Fig. 28 shows, plotted against the mass number A, the occupation numbers V_j^2 for the $s_{1/2}$, $d_{5/2}$ and $g_{7/2}$ configurations derived from these spectroscopic factors, taking R_b constant and equal to 1.30 fermi for $A \geq 118$. For the three highest masses the spectroscopic factors are evidently correct to within about 20%, which is as good as can be expected from any current calculations. However the occupation numbers are expected to increase monotonically with A. $V_{1/2}^2$ behaves in the expected manner, but $V_{5/2}^2$ and $V_{7/2}^2$ take their maximum values near ^{116}Sn, and fall to about 80% of the peak values at ^{124}Sn. If R_b is decreased as A rises from 118 to 124 so as to optimise the fits to the $d_{5/2}$ distributions, $V_{5/2}$ remains approximately constant over this range, in better agreement with the expected behaviour, and with the trend of Cohen's (d,p) measurements[67]. Cohen's angular distributions are fitted very reasonably by calculations using the optical parameters discussed above, suitably modified to take account of the different reaction energies.

<u>Optical model research programme: elastic and inelastic scattering of 50 MeV protons (A. G. Hardacre and J. F. Turner)</u>

To provide new data for investigating the energy dependence of the optical model potential we measured differential cross sections for the elastic scattering of 50 MeV protons from ^{40}Ca, ^{56}Fe, ^{59}Co, ^{58}Ni, ^{60}Ni, ^{64}Ni, ^{120}Sn and ^{208}Pb. Our 30 MeV observations on these nuclei have already been published[68].

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(68) Ridley B. W. and Turner J. F. Nuclear Physics <u>58</u>, 497 (1964).

For the 50 MeV measurements we made use of the R.H.E.L. double focussing magnetic spectrograph with sonic spark chamber particle detection. Elastic scattering data were collected at intervals of not more than 4° over the angular range 6° to 144°, with an angular resolution of ± ½°. Inelastic scattering data over a similar range of angles have been accumulated for the even nuclei. The range of excitations includes the low lying 2+ and 3– collective states, and the data are intended for use in coupled channel analyses.

The analysis of the experimental data is not yet complete.

SYNCHROCYCLOTRON
(A. E. Taylor)

Neutron-proton total cross section (A. Langsford, P. H. Bowen, G. C. Cox and P. J. Clements, Nuclear Physics Laboratory, Oxford)

There is considerable interest in a high precision measurement of the n-p total cross section in the energy range 400 keV to 5 MeV. First, the hydrogen cross section offers the most satisfactory basis for neutron flux measurements in this energy range. Secondly, Noyes(69) has drawn attention to the discrepancy between the value of the singlet effective range calculated from the most accurate measurement of the n-p total cross section(70) and the value expected on the hypothesis of charge-independence. This measurement(70) at a neutron energy of 0.4926 MeV yields a total cross section of 6.202 ± 0.011 barns. Noyes claims that this result has 'less than a 5% chance of being consistent with the charge-independent prediction .....' and urges '..... that new high precision measurements of the n-p total cross section below 5 MeV be attempted'.

The neutron evaporation spectrum obtained from the interaction of 140 MeV protons with a heavy nucleus is peaked at 1 MeV, and in the energy range 300 keV to 5 MeV there is an adequate intensity for a high precision measurement of the total cross sections. The n-p total cross section is determined from the relative transmission of different hydrocarbon liquids, each liquid sample presenting the same surface density of carbon atoms to the neutron beam. The liquids, of ~ 99.95% purity, are toluene, cyclohexane and 2, 2, 4 trimethyl pentane. A resonance filter of boric oxide is used to help determine backgrounds. As a check on systematic uncertainties, we are measuring the cross section using three sets of matched absorbers, whose thicknesses vary in the ratio 1 : 2 : 4.

The aim of the measurement is to achieve a statistical accuracy of 0.2% in each of 80 energy bands in the range 300 keV to 5 MeV, and to keep the systematic uncertainties, which would affect all the data equally, less than 0.1%. At present we have taken sufficient data to obtain an accuracy of 0.5% per band considering counting statistics alone. This is comparable with the accuracy of the 10 or so high precision measurements in this range. In the present experiment systematic uncertainties in the region above 1 MeV are ~ 0.3%. Below 1 MeV the systematic uncertainties increase with decreasing neutron energy and we are uncertain of their value to ~ 0.6%. After-pulses in photomultiplier tubes, which occur 1 or 2 μs after a large pulse, appear to be the major source of this increased uncertainty. We are therefore trying to eliminate the after pulsing by proper choice of the photomultiplier tube and its operating conditions. We should then be able to time more than one neutron per beam pulse, and with the resulting 8 fold increase in counting rate the desired accuracy could be achieved with a further 300-400 hours of data taking.

During the previous six months we have also calibrated a neutron counter over the range 2 MeV to 110 MeV for a Chalk River/Birmingham University experiment.

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(69) Noyes H. P. Nuclear Physics 74, 508 (1965).

(70) Engelke C. E., Benenson R. E., Melkonian E. and Lebowitz J. M. Phys. Rev. 122, 324 (1963).

Proton-proton scattering at 98 MeV (J. P. Scanlon, M. R. Wigan (University of Oxford), P. J. Martin (University of Grenoble))

Some difficulty has been experienced in using a beam energy degrader at the face of the cyclotron tank to produce polarized and unpolarized beams of 100 MeV. Adequate beam spots could be obtained in the experimental area, but control of beam alignment proved to be difficult and preliminary measurements of polarizations in p-C scattering at 100 MeV yielded anomalous results. This was traced to a low energy tail in the energy spectrum of the beam. It was decided to delay the experiment until a liquid hydrogen degrader was available and experiments will be resumed in November.

Polarization analysers have been designed for a measurement of D in p-p scattering, and it is hoped that some measurements of this parameter at ~ 100 MeV will also be obtained before the September 1967 shutdown.

Study of the luminescent properties of meteoritic materials under proton bombardment (J. M. Blair in collaboration with J. A. Edgington (Queen Mary College, London)

Following the report(71) that some 5-10% of the light coming from the moon cannot be attributed to reflected sunlight, it has been suggested that this residual light arises from luminescence of the moon's surface under the bombardment of protons in the solar wind. Furthermore, transient luminous effects have been observed(72) which can be related in time with solar flares. Since 140 MeV is a typical energy for protons from solar flares, we are preparing an experiment to study the luminescent properties of various stony meteoritic materials (which might reasonably be expected to cover the moon's surface) bombarded by 140 MeV protons. If the connection between these transient luminous effects and solar protons can be established, the flux of high energy protons on the moon's surface during periods of solar activity can be estimated.

The samples are mounted at 45° to the beam, and are viewed by an EMI 9558 photomultiplier tube chosen for its enhanced red response) through a succession of broad band interference filters. As luminescent spectra do not have sharp features, this technique is preferable to the use of a high resolution spectrometer, as it provides a larger solid angle for light collection. Hence a smaller flux of protons is needed to produce an observable effect. This reduces the possibility of radiation damage to the sample, which caused difficulties in previous experiments(73) at lower energies. A proving run using commercial phosphors has been performed and the results were most encouraging.

NIMROD EXPERIMENTS

Investigation of the decay of the f^{0}-meson (C. Whitehead and L. Bird in collaboration with groups from Southampton University, University College, London and the Rutherford Laboratory)

In July and August data were taken for 680 hours. During this time the spark chambers were fired half a million times and 10^9 bits of information were passed through the data handling equipment to the DDP-224 computer and thence to ORION. On-line analysis of the data by the DDP-224 indicated that the equipment operated stably for much the greater part of the running time. Analysis by ORION indicated the following:-

(i) Reconstruction of events from the chambers around the hydrogen target allowed a vertex position consisting of one ingoing charged particle and two outgoing charged particles to be specified within a sphere of radius 1-2 mm.

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(71) Dubois J. Obs. Univ. Bordeaux, Ser. A, No. 13 (1959).

(72) Kopal Z. and Rackham T. W. Icarus 2, 481 (1963).

(73) Derham C. J. and Geake J. E. Nature 201, 62 (1964).

(ii) Kinematic analysis showed that the majority of coplanar events also fitted the hypothesis that the decay products were pions.

(iii) An enhancement at a missing mass of $\sim$ 1250 MeV (the f^o) is observed for final states where one pi-meson is moving strongly forward in the laboratory system, $\sim 3^\circ$ to 9°.

(iv) Evidence is observed for a small fraction of the events fitting a final state of one neutron plus two K-mesons.

This preliminary analysis was carried out during the experiment and before the ORION computer was dismantled. This analysis program is now being refined and modified for use on ATLAS and a comprehensive analysis of the data should begin shortly.

A study of nucleon isobar production in proton-proton collisions (I. M. Blair, A. E. Taylor and J. L. Watkins in collaboration with members of Queen Mary College, London, and the Rutherford Laboratory)

We have measured the momentum spectrum of protons scattered at small angles in high energy proton-proton collisions. The experiment was performed at incident momenta of 2.85, 4.55, 6.06 and 7.88 GeV/c, and protons were momentum-analysed at various scattering angles in the range 22 to 144 milliradians. In the reaction

$$p + p \rightarrow p + X$$

knowledge of the incoming and outgoing proton momenta and the scattering angle determines the invariant mass of the recoiling system X. Peaks in the momentum spectrum of the detected proton may be caused by resonant behaviour of the group X. Experiments of this type have previously been carried out at various energies and angles at Brookhaven, CERN and Berkeley. In the present experiment the use of several incident momenta, together with a range of scattering angles for each, allowed us to investigate systematically the production of various nucleon isobars as functions of the kinematical variables s and t in a relatively unexplored region. The squared total centre of mass energy, s, varied from 7.3 $(GeV)^2$ to 16.7 $(GeV)^2$, and the squared four momentum transfer, $-$ t, varied from 0.03 to 0.8 $(GeV)^2$.

An extracted beam from Nimrod containing 10^9 to 10^{10} protons per pulse was focussed onto a 10 cm liquid hydrogen target. Scintillation counter telescopes and a magnetic spectrometer analysed the fast scattered protons. The spectrometer was calibrated using a floating wire technique. The incident proton beam intensity was recorded by an ionisation chamber which was calibrated using the reaction $^{27}Al(p,3pn)^{24}Na$ in an aluminium foil activation.

The principal results of the experiment were:-

(i) the confirmation of the existence of the 1410 MeV isobar, with a mass of 1410 ± 15 MeV and width 125 ± 20 MeV, produce with a strongly t dependent differential cross section,

(ii) the discovery of a previously unsuspected s dependence of the total cross section of the 1518 MeV isobar production as shown in Fig. 29, and

(iii) the accumulation of a large body of data on the production of the 1236, 1410, 1518 and 1688 isobars as a function of s and t.

This experiment has now been completed, and the results were published in Physical Review Letters 17, 789 (1966).

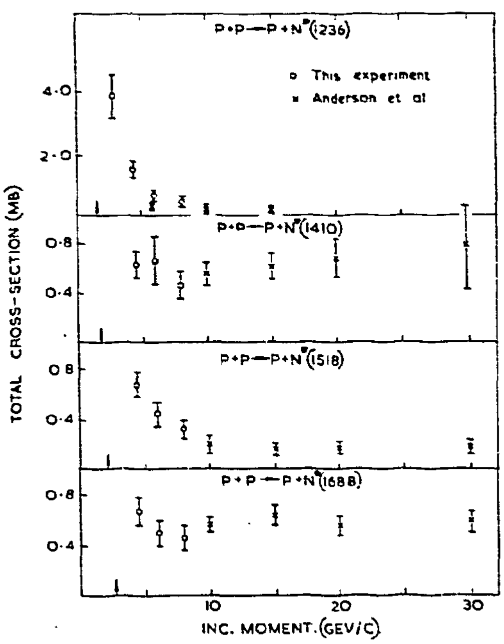

Fig. 29. Total cross sections for the reaction $p + p \rightarrow p + N^*$ expressed as millibarns against incident momentum in GeV/c.

<u>A study of Σ^- beta decay (I. M. Blair, A. E. Taylor and I. L. Watkins in collaboration with members of Queen Mary College, London, Oxford University and the Rutherford Laboratory)</u>

We are preparing to measure the electron – Σ^- spin correlation parameter in the decay process

$$\Sigma^- \rightarrow n + e^- + \nu .$$

This parameter is very sensitive to the magnitude and sign of the ratio of the axial vector and vector contributions to the interaction, in a way analogous to that of the parameter characterising the decay of polarized neutrons. However, current theories of weak interactions predict that the sign of the ratio for Σ^- beta decay should be opposite to that for neutron decay and for most other weak processes. This experiment, therefore, is a crucial test of the theory.

The Σ^- will be produced in the reaction

$$\pi^- + p \rightarrow \Sigma^- + K^+$$

at an incident pion momentum of 1130 MeV/c. The production reaction will be identified by the detection of a K^+ meson via its time delayed relativistic decay products. The electrons from the Σ^- beta decay process will be detected in an atmospheric pressure Isceon 12 Cerenkov counter. All the components of the apparatus have been thoroughly tested and have been shown to perform satisfactorily. We are at present mounting the final assembly and hope to take data early next year. The expected event rate is about 15 per day, and we require about 500 events to give a conclusive result.

As a subsidiary experiment we are preparing to measure the polarization of the Σ^- by studying the production process on a polarized proton target in collaboration with the resident group (J. J. Thresher et al.) at the Rutherford Laboratory. In this measurement the Σ^- polarisation manifests itself through an angular asymmetry of the K^+ mesons produced. The design is well advanced, and we hope to be taking data on this experiment also early next year.

CERN PROTON SYNCHROTRON EXPERIMENTS

(High Energy Physics Group: W. Galbraith)

<u>Decay of long lived neutral K-meson into two neutral pions (W. Galbraith+, A. G. Parham*, P. H. Sharp* and A. C. Sherwood in collaboration with staff of Rutherford Laboratory, CERN and Aachen Technische Hochschule)</u>

Details of the experimental arrangement at the CERN PS machine and preliminary data from this experiment have been discussed in previous reports[74].

+Now at Department of Physics, University of Sheffield.

*Now at Rutherford Laboratory, S.R.C., Chilton.

(74) Nuclear Physics Division Progress Reports PR/NP 9, 39 (1966) and PR/NP 10, 45 (1966).

During the period covered by the present report, data analysis has proceeded by hand, and details of the experiment and results have been published(75). Only a brief summary of the results, which show clearly that the $K^o{}_L$ decays via the two neutral pion mode, are given here. These decay events afford further evidence for the violation of CP invariance in $K^o{}_L$ decay.

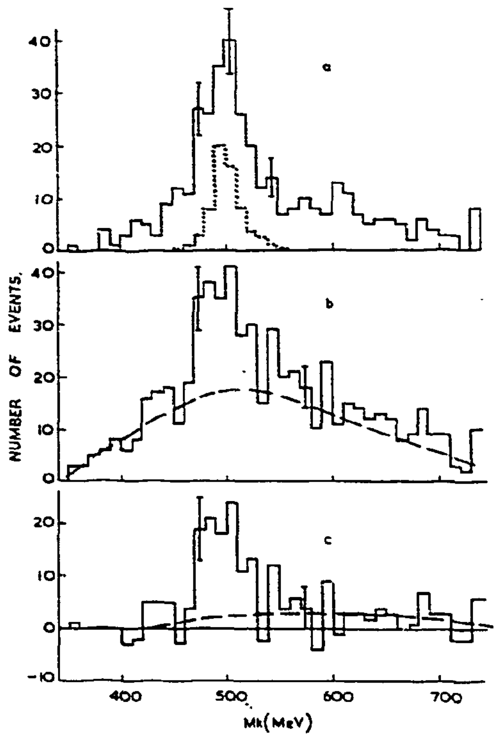

Fig. 30. (a) Experimental mass distribution for regenerated events. The dotted spectrum is the 2π spectrum shape calculated with the Monte Carlo program; (b) Experimental mass distribution for free decay events. The dashed line is the background spectrum shape for $3\pi^o$ decays calculated with an appropriate Monte Carlo program; (c) Experimental mass distribution with the Monte Carlo spectrum subtracted. The dashed line is a fit by eye to the residual background.

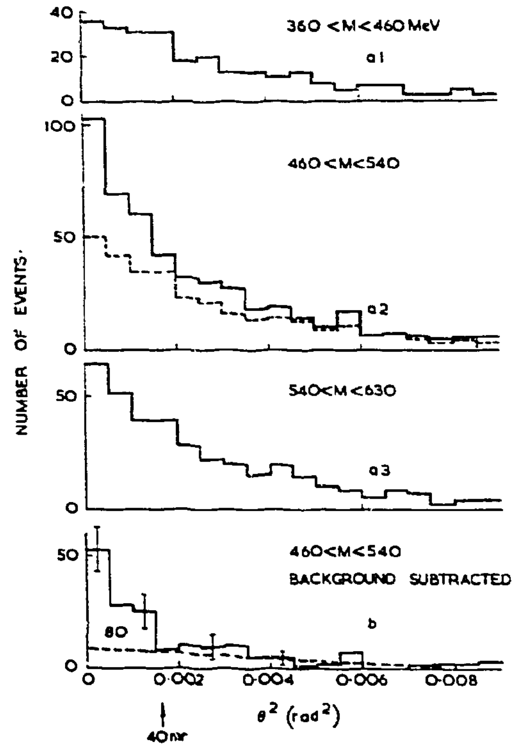

Fig. 31. (a) θ^2 plot in three mass ranges. In range a2 the dashed line shows the average of the observed distributions for high and low masses; (b) The observed distribution with the background subtracted. The dotted line is a fit by eye to the residual background.

The results to date, based upon the analysis of 30,000 spark chamber photographs (about ⅙ of total), are presented in Fig. 30. For each 4γ event the mass M of the decaying particle, its momentum, and the angle θ between its direction of travel and the direction of the incoming $K^o{}_L$ beam were determined, assuming that the 4 γ's arose from an unknown neutral particle of this mass. Details of the procedure have been given(75). Fig. 31(a) shows the experimental mass distribution for $K^o{}_S \rightarrow 2\pi^o$ events. The $K^o{}_S$ particles were regenerated by passing the $K^o{}_L$ beam through a carbon absorber placed at various positions within the fiducial volume selected for the free decay events, $K^o{}_L \rightarrow 2\pi^o$. The dotted

(75) Gaillard J. M., Krienen F., Galbraith W., Hussri A., Jane M. R., Lipman N. H., Manning G., Ratcliffe T., Day P., Parham A. G., Payne B. T., Sherwood A. C., Faissner H. and Reithler H. H. Phys. Rev. Letters (in press, Nov. 1966).

histogram is the $K^o{}_S \to 2\pi^o$ mass distribution calculated from a Monte-Carlo programme simulating these decays. $K^o{}_S \to 2\pi^o$ events are clearly recognizable in the experimental histogram. Fig. 31(b) shows the experimental mass plot for free $K^o{}_L$ decay events together with (dashed line) Monte-Carlo predictions for the background from the predominant (normal) neutral decay of $K^o{}_L$ into three neutral pions when two γ's are undetected, and the remaining four are analysed as if they arise from the decay $K \to 2\pi^o$. The excess of events in the mass region $460 < M < 540$ is clear evidence for the decay $K^o{}_L \to 2\pi^o$. Fig. 31(c) contains the same data as Fig. 31(b) with the background subtraction made.

Fig. 32 presents the data in the form of an angular distribution about the initial beam direction $\theta = 0$. It is again seen that there is an excess of events above background (Figs. 32(a2) and (b)) in the mass range $460 < M < 540$.

The following conclusions can be drawn from the results of this experiment:-

(a) The observation of 87 ± 22 examples of the free decay $K^o{}_L \to 2\pi^o$ is a further proof of CP violation in K^o decay. Under CP conservation $K^o{}_L \to \pi^o + \pi^o$ would be forbidden even if pions did *not* obey Bose statistics[76,77].

(b) Following Wu and Yang[78] and Wolfenstein[79] the transition rates $K^o{}_L \to \pi^+ + \pi^-$ and $K^o{}_L \to \pi^o + \pi^o$ can be expressed in terms of the parameters $\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}}$ and $\eta_{oo} = |\eta_{oo}| e^{i\phi_{oo}}$ where the η's are given in terms of the parameters ϵ, ϵ' by

$$\eta_{+-} = \frac{\text{Amplitude } K^o{}_L \to \pi^+ + \pi^-}{\text{Amplitude } K^o{}_S \to \pi^+ + \pi^-} = \tfrac{1}{2}(\epsilon + \epsilon') \; ;$$

$$\eta_{oo} = \frac{\text{Amplitude } K^o{}_L \to \pi^o + \pi^o}{\text{Amplitude } K^o{}_S \to \pi^o + \pi^o} = \tfrac{1}{2}(\epsilon - 2\epsilon') \; .$$

If ϵ' is zero (i.e. pure $\Delta I = \tfrac{1}{2}$ amplitudes) $\phi_{oo} = \phi_{+-}$. In this experiment η_{oo} is determined by direct comparison of the observed decay rate for the free $K^o{}_L$ with the decay rate observed for $K^o{}_S$ particles regenerated in carbon. The magnitude of the interference between the decay of the $K^o{}_L$ and of the regenerated $K^o{}_S$ depends upon $\phi = \phi_f$, which is the phase change due to regeneration. Several other experiments have measured ϕ for copper and carbon regenerators, and the results are reviewed by Rubbia and Steinberger[80]. A reasonable value of ϕ for a carbon regenerator and an average momentum of 2.1 GeV/c is $\sim 80°$. For the present experiment the assumption $\phi_{oo} = \phi_{+-}$ gives rise to constructive interference and results in a value of

$$\eta_{oo} = (4.8 \,{}^{+1.2}_{-0.9}) \times 10^{-3}$$

A change in ϕ of $\pm 10°$ about $80°$ produces a relative change in η_{oo} of only ± 1 per cent. This value of η_{oo} is 3 standard deviations greater than the value[81] $\eta_{+-} = (1.98 \pm 0.06)$. 10^{-3} which is incompatible with the assumption of pure $\Delta I = \tfrac{1}{2}$ amplitude and the superweak

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(76) Messiah A. M. L. and Greenberg O. W. Phys. Rev. 136, B248 (1964).

(77) Bludman S. A. Phys. Rev. 138, B213 (1965).

(78) Wu T. T. and Yang C. N. Phys. Rev. Letters 13, 380 (1964).

(79) Wolfenstein L. Nuovo Cimento 42, 17 (1966).

(80) Rubbia C. and Steinberger J. Phys. Letters 23, 562 (1966).

(81) Trilling G. H. U.C.R.L. report 16473 (1965).

theory of Wolfenstein[82]. A possible solution in terms of ϵ, ϵ' indicates that the CP violation could be due to a $\Delta I \geqslant 3/2$ amplitude[83,84].

MISCELLANEOUS STUDIES IN PHYSICS

Mössbauer effect (T. E. Cranshaw, G. Lang, M. S. Ridout, C. E. Johnson (S.S.P.), R. S. Preston (att.), A. P. Jain (T.R.A.) and M. Winter (Oxford))

I - Experiments with ^{119}Sn (C. E. Johnson, T. E. Cranshaw and A. P. Jain)

A programme has been started in which we will attempt to use the Mössbauer nucleus ^{119}Sn in tracer quantities as an indicator of conduction electron polarisation in magnetically ordered materials.

The results, which have not yet been completely analysed, are very surprising. For example, in the alloy (Cu, 3-6% Mn), which shows strong magnetic ordering at 4°K, the ^{119}Sn spectrum shows splittings corresponding to hyperfine fields of less than 10 kOe, whereas in (Au, 10% Fe) at the same temperature the observed splittings correspond to hyperfine fields of about 80 kOe, as large as in pure iron. Moreover, although broadening of the lines indicates that there is a distribution of fields at the Sn sites, very few of the Sn nuclei lie in weak fields.

The behaviour of ^{119}Sn in Co is complicated by its low solubility, and by the possible occurrence of different phases. A sample quenched from 1000°C shows what appears to be a simple spectrum corresponding to a unique field of about 20 kOe. However this field has an anomalous temperature dependence, falling by about 25% between 0°K and 300°K. The temperature dependence of the field experienced by ^{119}Sn nuclei dissolved in Fe is normal.

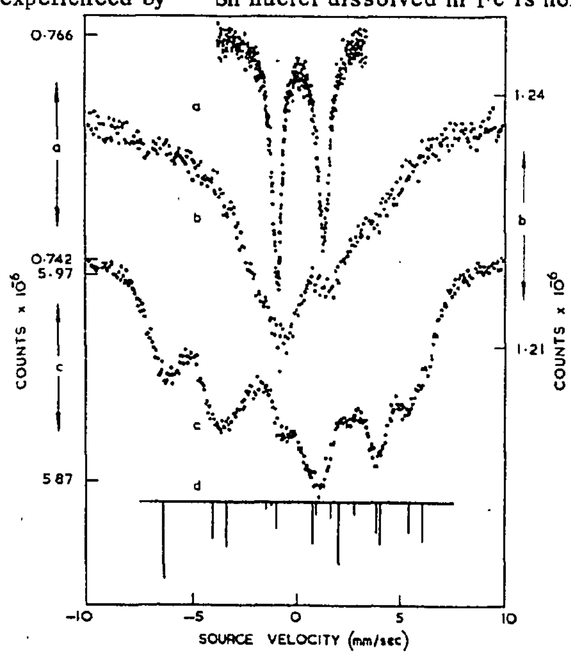

Fig. 32. Mössbauer spectra of haemoglobin azide at (a) 195°K, (b) 77°K and (c) 4°K. At (d) are shown predicted positions and intensities of absorption lines. No free parameters are used, the ground state wave function having been deduced from ESR data, and the size of the Fermi contact interaction constant having been taken from the haemoglobin fluoride result.

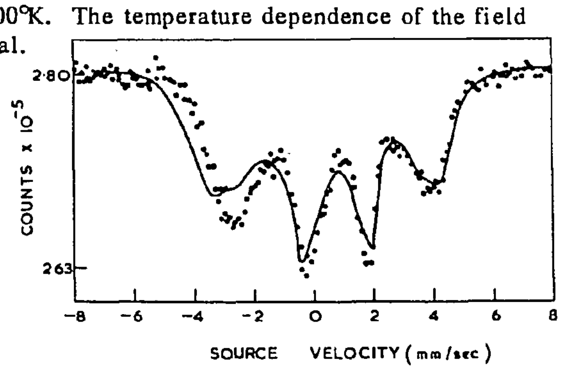

Fig. 33. Mössbauer spectrum of Haemoglobin azide at 4°K in an applied field of about 0.7 kilogauss. The solid line is derived from a calculation which averages over angle, the result having been folded with a Lorentzian of fwhm = 0.6 mm/sec in order to suppress the granularity introduced by the calculation and to represent in an approximate way the effects of relaxation.

(82) Wolfenstein L. Phys. Rev. Letters 13, 562 (1964).
(83) Truong T. N. Phys. Rev. Letters 13, 358 (1964) and 17, 153 (1966).
(84) Bowen T. Phys. Rev. Letters 16, 112 (1966).

II - Haemoblobin (G. Lang, C. Johnson and M. Winter (Inorganic Chem. Lab., Oxford))

Earlier low temperature measurements on low spin ferric haemoglobin compounds (haemoglobin cyanide and azide) yielded spectra showing gross magnetic splitting. These spectra were accounted for in terms of spin orbit coupling and the two crystal field splittings of the t_{2g} levels. More recently the spectra in small ($\sim$ 0.5 kOe) applied magnetic fields have been found to be less widely split, with fewer discernible lines. These small fields are strong enough to decouple the nuclear and electronic spins. A program has been written to compute the spectrum in polycrystalline absorbers when g is anisotropic. The agreement of the calculated results, which involve no new parameters, with the data confirms the validity of the theoretical interpretation (see Figs. 32 and 33).

The Mössbauer spectra of haemoglobin fluoride ($S = \frac{5}{2}$), cyanide ($S = \frac{1}{2}$) and azide ($S = \frac{1}{2}$) now are reasonably well understood. Theoretical work is continuing on the nitric oxide, acid methaemoglobin and hydroxide compounds. Measurements have recently been made on the imidazole compound, and measurements on the acetate and formate are planned.

Radio pulses associated with extensive air showers (W. N. Charman, J. H. Fruin and J. V. Jelley with R. A. Porter and F. Graham-Smith (Jodrell Bank)

(a) Analysis of last winter's experiment at Jodrell Bank

The analysis of the experiment described in the last report, a search for radio pulses from air showers which arrive at a low elevation to the horizon, has now been completed. Details of this experiment, the analysis, and the conclusions, can be found elsewhere[85]. The main results are displayed in the accompanying figures. Fig. 34 shows the integrated radio signal amplitudes, at 0.25 μs intervals, for recordings taken with three types of trigger. Fig. 35 (overleaf) shows the distribution of the positions and heights of all bandwidth-limited pulses the amplitudes of which are at least 1.5 times greater than those of any other pulses on the same trace.

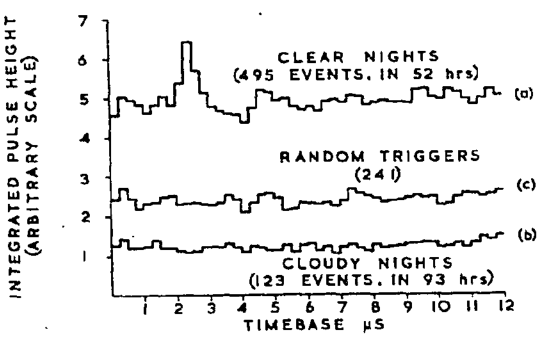

Fig. 34. Histogram for three types of trigger of the radio signal amplitudes integrated over 0.25 μs intervals and summed over all appropriate oscillograph recordings.

We conclude that most light pulses which initiate triggers arise from showers developing at great distances, that radio pulses accompanying such showers can be observed at low elevation, and that for a given antenna beam width and receiver sensitivity, the rate of detection of such radio pulses at an elevation of 15° is approximately 17 times greater than that at the zenith, in reasonable agreement with simplified theory.

(b) The installation at A.E.R.E.

The last six months have been occupied in the design, construction, and setting-up of the installation of antennas, receivers and electronics for the coincidence experiment outlined in the last progress report PR/NP 10. Arrays at A.E.R.E. and W.R.L. will define the 12 km base line. The A.E.R.E. array includes a wide field light receiver for shower identification, a 7.5 m high 60° triangle backed by a reflector to cover the 10-20 Mc/s band, and two antennas in the form of 90° corner reflectors[86] 4.6 m high and 6.1 in side dimension enclosing end fed triangular broad-band unipoles[87] to cover the

(85) Charman W. N., Fruin J. H., Jelley J. V., Porter R. A. and Smith F. G. Harwell Report No. R 5322 (also to be published elsewhere).

(86) Jasik H. Antenna Engineering Handbook. McGraw-Hill. Ch.11 (1961).

(87) Brown G. H. and Woodward O.M. R.C.A. Rev. 13, 425 (1952).

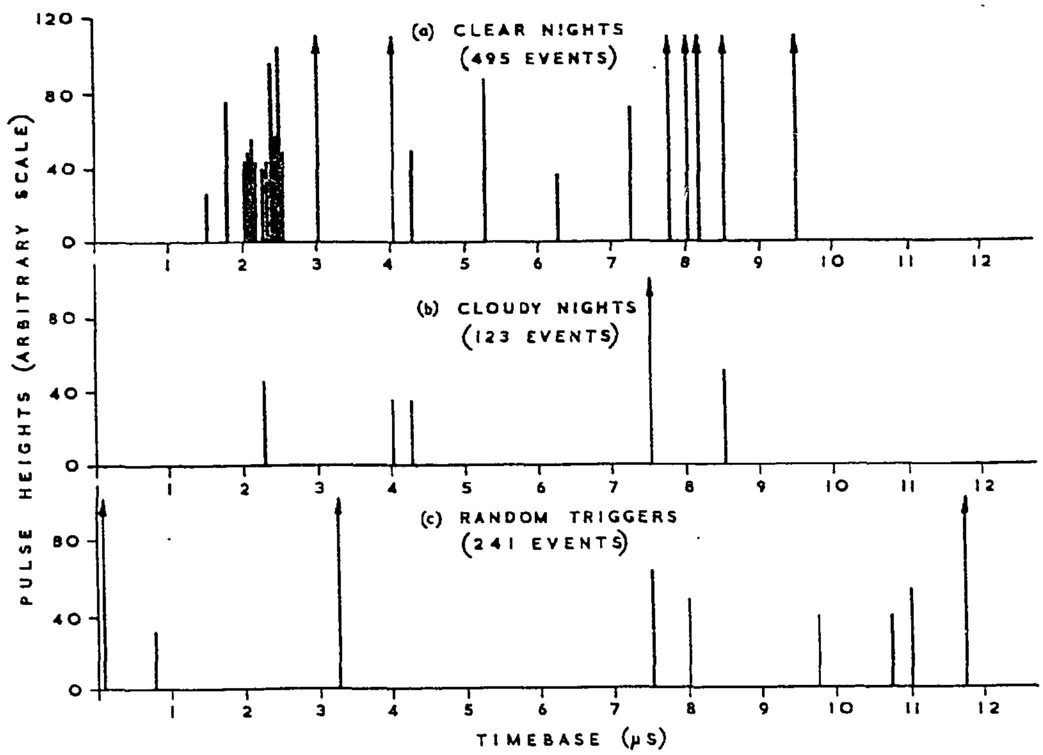

Fig. 35. The positions and amplitudes of bandwidth-limited radio pulses with amplitudes which exceed 1.5 times those of any other pulses occurring on the same trace. (An arrow denotes an off-scale pulse).

40-80 Mc/s band. These two antennas are 130 m apart and are coupled to a coincidence system with a resolving time of 0.1 μs. Interference from the pulsed air navigation beacon mentioned in PR/NP 10 forced us to incorporate an anticoincidence channel operated from a narrow band receiver. T.V. interference restricts observations to the night period from 00.00-07.00 hours. B.B.C. FM signals at 88 Mc/s, which continue till 02.00 hours, have been successfully filtered out.

Cherenkov radiation in the atmosphere

(a) U.V. experiments (W. N. Charman)

During the summer months, which give poor viewing, the three 60 cm mirrors and their associated equipment have been moved to a new site on Mease Hill plantation. Preparations for the experiments continue.

(b) Servo systems for light receivers (J. H. Fruin and J. V. Jelley)

In γ-ray astronomy[88] and other applications of the atmospheric Cherenkov effect a number of types of electronic servo systems are used to compensate for fluctuations in the brightness of the night sky. The characteristics of four such systems are currently under study.

The absorption of high energy γ-rays in astrophysical environments (J. V. Jelley)

Calculations of the effects of photon-photon pair production show that this process may lead to significant absorption of the high energy γ-rays emitted from some discrete radio sources within these

(88) Jelley J. V. and Porter N. A. Quarterly Journ. of the Roy. Astron. Soc. 4, 275 (1963).

sources themselves[89]. Absorption between the sources and the earth was considered earlier[90].

A cooled image-intensifier system for astronomical spectroscopy (W. N. Charman, J. H. Fruin and A. V. Hewitt)

The moving plate camera for the system has now been completed and tested. A new intensifier has been installed which is free from the thorium-contaminated phosphor which marred the intensifier used in the astronomical tests at Oxford Observatory. The complete system is undergoing final tests in preparation for an observing programme at the Coudé-focus of the 30" telescope at the Royal Greenwich Observatory, Herstmonceux this winter. A study of the absolute luminosities of early-type stars in the Orion association will be undertaken, using observations of H_γ line profiles.

MISCELLANEOUS TECHNIQUES

The preparation of lithium-drifted germanium detectors for gamma-rays (G. Dearnaley, Mrs. D. W. Lang, I. V. Mitchell and B. D. Rogers)

In view of the short term need for large volume detectors in the Division work has been concentrated on the co-axial technique, drifting in a liquid with evaporative cooling. The aim has been to set up drifting equipment from which all groups of N.P. Division could be supplied with lithium drifted detectors. With some help by J. Jolly and J. Down of the E.L.A. Group, a start was made and ten sets of lithium-drift equipment are now nearing completion.

The technique is a combination of the lithium diffusion from molten LiCl-KCl eutectic, electrolysed at 450° (developed at McMaster University[91]) with co-axial ion drift in boiling pentane (developed at Ispra[92]). Good diode characteristics and good drift rates have so far been achieved. Various types of contact were assessed, and the best was found to be nickel electro-plated on to the germanium. A double open-ended geometry has been chosen to give best uniformity of collection paths and minimal pulse rise-times.

The first detector prepared by the technique outlined above has a volume of about 28 cc. At 500 v. bias the leakage current is at present 2×10^{-9} A and falling; the energy resolution for ^{60}Co gamma-rays is not worse than 7 keV.

The preparation of lithium-drifted germanium particle detectors (G. Dearnaley, B. W. Hooton and B. D. Rogers)

Lithium-drifted germanium offers the possibility of detectors with good energy resolution for high energy protons (up to 160 MeV). At the higher energies it is arranged that the particles travel parallel to the junction in a planar slab, which may be up to 6 cm in length. At the lower energies it is better to allow the protons to enter normal to the junction, but in many cases it is necessary to devise a structure in which the dead layer at the surface is shallow (less than 5 microns). Since lithium diffusion results in dead layers usually 500 microns in thickness it is not possible to use a lithium diffused front contact. Instead, we have suggested ion implantation of a thin p-type contact to which lithium is drifted from a diffused layer on the opposite face. Gallium ions, implanted at 40 keV energy into germanium have a range (without channelling) of less than 0.1 micron. Annealing of the radiation damage which accompanies the implantation is accomplished during the lithium diffusion (20 minutes at 400°C). P-type layers of good electrical conductivity have been prepared in this way and the lithium has been

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(89) Jelley J. V. Nature 211, No. 5048, 472 (1966).

(90) Jelley J. V. Phys. Rev. Lett. 16, 479 (1966), also AERE Report R 5121.

(91) Fiedler H. J. et al. Nucl. Instr. & Methods 40, 229 (1966).

(92) Restelli G. B. et al. Private communication.

drifted across into the layer with no untoward results. The first device is shortly to be tested at 77°K as a particle detector, as soon as a cryostat is complete. R. Ellis, of A.W.R.E. (who is also following our suggested technique) has just reported to us that his first detectors have good characteristics.

One difficulty which can be foreseen results from dust on the crystal surface during implantation. This could lead to 'pipes' of low gallium concentration extending up to the surface; these could become compensated by lithium and lead to a poor contact in the finished device. A double implantation with an intermediate wash should minimise this possibility.

The preparation of silicon surface-barrier detectors (M. M. Aslam (Pakistan A.E.C.) and G. Dearnaley)

Equipment has been constructed for the preparation and mounting of a batch of about sixty detectors, by a variety of methods. This should enable an assessment to be made of a number of contact procedures. Parameters to be varied are: (i) the metal for the evaporated rear contact; (ii) the temperature during vacuum deposition; (iii) the applied voltage after forming the contact; (iv) the presence of an oxide protecting mask around the junction.

Ion implantation in semiconductors (G. Dearnaley and M. A. Wilkins)

The ranges and profiles of radioactive ^{32}P implanted in single-crystal silicon have been studied, using the technique described in the last report. The technique has, however, been simplified so that radiochemical processing of the stripped solutions is no longer necessary. Accidental contamination is thus rendered unlikely.

The thickness of silicon removed when an anodic oxide layer which shows the first order interference colour is stripped has been determined by weighing to be 300 ± 15 Å.

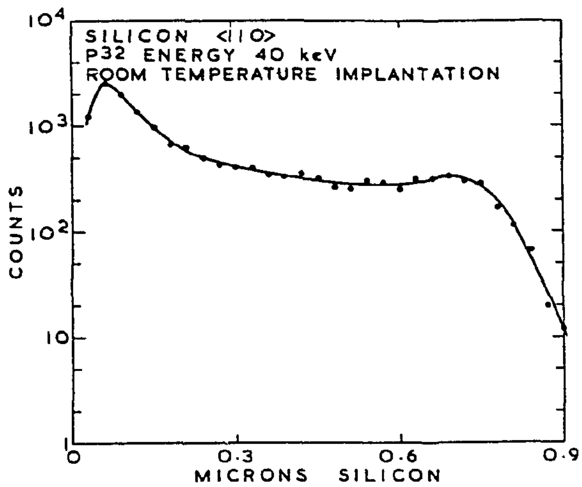

Fig. 36. Profile of 40 keV ^{32}P ions implanted at room temperature along the <110> direction in silicon.

Fig. 36 shows the profile of ^{32}P implanted with 40 keV energy along the <110> direction in silicon held at room temperature. The channelled range is 0.7 micron, about twelve times the normal mean range of 0.06 micron. The profile shows an almost horizontal saddle with a slight but significant rise in concentration towards the end of the range.

Studies have begun of the penetration of ^{32}P through oxide films. Twenty-five per cent of ^{32}P ions implanted at 40 keV penetrate a 0.10 micron thick oxide layer. This result is relevant to the use of oxide masking films during implantation.

A programme to study the electrical behaviour of impurities implanted in silicon has been initiated, in collaboration with Reading University. The work, to be carried out partly at A.E.R.E. and partly at Reading, is funded by an E.M.R. contract.

Position-sensitive counters for charged particle spectrograph (D. L. Allan, G. V. Ansell and R. B. Taylor)

Eleven position-sensitive silicon surface barrier counters are now available for experiments in the broad range charged particle spectrograph: 5 were manufactured by Nuclear Diodes Inc. (Illinois, U.S.A.), 5 were produced by the Electronics and Applied Physics Division (A.E.R.E.) and one was made at A.W.R.E., Aldermaston. All have lengths of 50 mm. The A.E.R.E. counters have maximum depletion layer depths ~ 1 mm, the other counters, ~ 100 μ.

Most of the tests carried out with the spectrograph so far have been made on the A.E.R.E. counters. The resolution (full width at half maximum) for 10 MeV protons varied a little from counter to counter within the range 1.2 mm to 1.8 mm, which corresponds to an energy resolution of 15 → 23 keV. The depletion layer depth was entirely adequate for protons of this energy; in fact the resolution showed no signs of deterioration until the bias voltage had been reduced to below half the recommended maximum value.

A new spectrograph camera box has been designed and manufactured. In the design provision was made for accommodating the existing photographic plate holder, but the emphasis was placed on providing ready access to the counters and ample space for F.E.T. pre-amplification stages, which we hope to install when they become available. An additional temporary holder which has been built for immediate use in the existing camera box will permit up to 5 position-sensitive counters to be operated simultaneously, each accurately located in the focal plane of the spectrograph.

Construction of a large scale aluminising plant (I. M. Blair, P. G. Davies, D. D. Hunt, H. Newman and J. H. Stevens in collaboration with B. W. Davies (Queen Mary College, London) and D. Axen (Rutherford Laboratory))

It has always been difficult to aluminise large objects because vacuum-tight vessels large enough to accommodate the object together with the necessary processing equipment have not been available. The synchrocyclotron vacuum testing tank has been adapted to this task and two 62" diameter parabolic mirrors have been successfully aluminised. These mirrors, which are 26 inch focal length ex-searchlight mirrors, are to be used in gas Cerenkov counters in the Σ beta decay experiment to be performed on Nimrod by the AERE/QMC/RHEL collaboration. Some mirrors have also been aluminised for a group at the Daresbury Nuclear Physics Laboratory.

ACCELERATOR OPERATION AND MAINTENANCE

Cockcroft-Walton 0.5 MV generator (G. A. Jones, F. D. Pilling, S. Waring and E. W. Sparrow)

Total running hours May to October 1966 = 604

Harwell usage 38% (chiefly Analytical Sciences)

Outside usage 62% (Exeter University)

3 MV pulsed Van de Graaff generator (D. R. Porter and E. Gove)

Analysis of machine running	Hours
Running time possible	3695
Time taken by maintenance	1238
Experimental time available	2457
Experimental time used	1339

Machine availability 66%

Experimental usage 55%

Fault Analysis	Hours Lost
Ion source changes and terminal equipment faults	299
Accelerator tube replacement and conditioning	133
Cooling circuits	252
Machine alignment	476
Electronic faults	47
Vacuum faults	23
General maintenance	9

During this period the possible running time per week was reduced from seven twenty-four hour days to five twenty-four hour days plus two eight hour days.

Ion sources were changed every two hundred to three hundred hours, but a reduction in expenditure was made by a reconditioning service.

The accelerator tube used during this period, which had also been reconditioned, ran for a total of 3,300 hours, most of the time at an energy of 3 MeV. Failure was due to severe spark erosion of the first glass insulator, which normally suffers severe X-ray browning. A major shutdown occurred in June, when extra control rods were fitted for future development and provision was made for installing another target line.

A number of running hours were lost due to a fault in the gas feed to the ion source which allowed tank gas to leak into the source gas. The fault was traced to a batch of defective source gas containers.

Frequent stoppages occurred in August because of water flow failures in various parts of the accelerator. Blockages of pumps and small pipes became frequent and investigation revealed a growth identified as fusarium penicillium around the cooling coils in the main water tank. Ethylene glycol was considered to be the nutrient and sodium panicide has since been added to the cooling water.

5 MV Van de Graaff generator (G. A. Jones, F. D. Pilling, S. Waring, E. W. Sparrow)

Total running hours May to October 1966 = 1920

equivalent to 74 hours per week

Harwell usage 87% (37% Nuclear Physics, the remainder shared between Metallurgy, H.P. & Medical, Analytical Sciences, Chemistry and Electronics)

Outside usage 13% (taken up by S.R.C.., Birmingham University, Exeter University, Sussex University and K.C.H. London)

Modification (G. A. Jones, K. C. Knox, F. D. Pilling and S. Waring)

Orders have now been placed for most of the component parts. The two major components, the magnet and the pressure vessel, are due in July and September 1967. It is anticipated that all other components will have arrived before then and that the new top terminal will have been completed. The machine will then be shut down for modifications. It is hoped that those will be completed within a further three months.

12 MV Tandem generator (J. M. Freeman, P. Humphries and F. D. Pilling)

Analysis of machine running

In the six-month period from 1st May 1966 to 31st October 1966 the tandem experimental hours have been 2064, of which 68% were used by Nuclear Physics Division, 16% by Universities (Bradford, Exeter, Manchester), 8% by other Harwell Divisions (Solid State Physics, Chemistry, Metallurgy) and 8% by other external organisations (M.R.C. and R.S.R.S. Slough). About 12% of the available time was taken up by routine maintenance and machine development work. During the period covered by this report the stripper foils were changed twice.

Accelerator tube behaviour

Beams of protons, deuterons, oxygen and sulphur ions have been accelerated. The accelerator tubes have now run for a total of 19,300 hours. By August of this year there were clear indications that the accelerator tubes were beginning to deteriorate and it was decided that the machine should be shut down at the beginning of 1967 for the installation of new accelerator tubes and other new or modified components.

Machine modifications

New ion beam deflector and focus units have been installed in the target lines. These give improved beam stability and easier control, and reduce the loss of machine time in changing from one target line to another.

A new radiation interlock system for the machine and target areas has been installed and is operating satisfactorily.

Preparatory work for the installation of a magnetic quadrupole lens at the lower end of the machine and an ion-pump at the high voltage terminal has been carried out.

A special target line is being constructed in an attempt to eliminate the carbon deposits that appear on some experimental targets. This target line will use only ion pumps, sorption pumps and viton 'O' ring seals.

Ion-source development for the tandem (R. H. M. V. Dawton and P. Humphries)

Two ion sources are to be provided. The first to be installed (referred to in future as ion source 1) will be a mercury-pool source which should increase the available beam currents of H^-, C^-, O^- and S^-. The second (ion source 2) will be developed to give an He^- beam of ½ μA. The layout of ion source 1 has now been settled. The pressure vessel will have a flat lid in order to improve the ion source beam optics and to allow sufficient room for alternative injection systems if these should be required at a future date. A preliminary computer examination of the lens aberrations indicates that changes in the size of the flight tube at distances of up to 2 lens diameters away from the lens noticeably affect the focal length and may possibly affect the aberrations. One important result is that any change from a circular to a rectangular flight tube, e.g. a magnet bend, must be made at least 2 diameters away from any neighbouring lens. Manufacturing drawings for the main ion source structure and flight line components are now being prepared. For ion source 2 an experimental duoplasmatron source is being assembled. At the same time a rig is being constructed for handling cesium vapour since it has recently been reported that cesium vapour used as a donor target gives a very high yield of He^-.

45 MeV electron linear accelerator (M. J. Poole and B. Clear)

From 1st May 1966 to 31st October 1966, the accelerator ran for a total of 3506 hours, i.e. 86.5% of the scheduled operational time and 79.4% of the whole period (4416 hours).

The analysis of the time is as follows:-

	Hours	%
Total length of period under review	4416	100
Scheduled shut-down time (maintenance only)	361	8.2
Scheduled operational time	4055	91.8
Machine utilisation:		
Users:		
N.P. Division	3452	85.2
Other users	54	1.3
Total time operational	3506	86.5
Lost time:		
(1) Machine faults and optimising	434	10.7
(2) Experimental requirements and users' requests	115	2.8
Total	4055	100.0

The utilisation of the Cell III/Cell IV facilities was rather less, being as follows:-

Scheduled operational time	3041	68.9
Cell utilisation:		
Fully operational	2211	72.7
Lost time:		
(1) Machine faults	369	12.1
(2) Optimising	54	1.8
(3) Users, etc.	407	13.4
Total	3041	100.0

The following engineering work has been carried out on the machine during this period:-

(i) A new ^{235}U brem core was installed in the booster on 4th July 1966, and the machine successfully run up to full power during the following week. The booster has since run continuously without trouble.

(ii) New stabilised power supplies for Cell I (Booster) deflectors and quadrupole lenses were installed.

(iii) A specially developed high stability power supply for the accelerator first section focussing solenoid, first installed in 1965, was modified to prevent 50 c/s pickup due to large earth currents and is now working satisfactorily, ripple level being now less than 0.01% and overall stability 0.1%.

(iv) New klystron focus supplies using silicon controlled rectifiers, were fitted to all seven klystron units.

Klystrons: There are now three types of klystron in use in the accelerator - K352, K211 and K390 (8 MW). Average lives of K352 and K211 types were 5232 and 3007 hours respectively, five K352 and two K211 valves being replaced. There have been no failures of the type K390 so far - two are now in service, the first one installed having run 5000 hours approximately.

Synchrocyclotron (P. G. Davies)

Analysis of machine running

		hrs.		%
Hours in period		4416		100
Scheduled maintenance and installation work	1094		24.8	
Holidays, visitors	84		1.9	
	1178		26.7	
Scheduled hours		3238		73.3
Machine not available owing to faults		50		1.1
Available hours		3188		72.2

The available hours break down into the following categories:

	hrs.	%
Machine in use	1090	34.2
Machine not required	1284	40.3
Machine development work (ion source)	310	9.7
User setting up	278	8.7
Pumping down the vacuum system	138	4.3
Running up and closing down	88	2.8
	3188	100

Machine serviceability was 97.4%.

The above analysis is based on a 24 hours scheduled day. In fact during this period demands for machine time were light and running did not normally exceed a fourteen hour day. This largely explains the high ratio of "not required" to "used" time.

The preliminary shut down for the Improvement Project occupied the whole of the period from 22nd September onwards, and was mainly responsible for the large time allotted to maintenance and installation work.

Machine users

The following hours were available to individual experimental groups:-

		hrs.	%
1.	A. Langsford et al. (time of flight)	1183	37.1
2.	M. Wigan	737	23.1
3.	E. Wood, J. P. Scanlon (ion source)	310	9.7
4.	Imperial College, London	252	7.9
5.	I. M. Blair and A. J. Edgington	62	1.9
6.	Irradiations for R.C.C. Amersham	29	1.0
7.	Miscellaneous irradiations	15	0.5
8.	Spare	600	18.8
		3188	100.0

Machine faults

The condenser oil seals failed on 18th July 1966 after standing idle for a prolonged period while shielding wall installation and ion source development work were carried out; hours run were 879.

In July some days of unstable running resulted from a poor vacuum in the tank. This was attributed to outgassing of the upper liner following removal of the cooling in order to clear an area around the vertical hole to be drilled in the magnet yoke.

Improvement project progress

Programme (P. G. Davies)

Critical path methods have been used to programme the project. The current programme calls for a shut-down in September 1967 to install the new R.F. system and ion source, and the improved machine should be ready for experimenters in February 1968.

Modulator (M. J. Lee, P. G. Davies and G. B. Huxtable)

Construction of the new modulator and power supply by Physics and Electronics Support Group is well advanced. Testing will start within one month.

Vertical hole in magnet (P. G. Davies)

Studies of methods for producing a vertical hole through the main magnet to admit the improved ion source resulted in the choice of one suggested by the main Workshops, Hangar 9. They proposed to trepan a five inch diameter hole and then to bore this out to the finished diameter of 8.5 inches. At the time of writing the work is nearly completion.

R.F. system (P. E. Dolley, G. B. Huxtable, D. Tripp with D. Colven (sandwich-course student from Brighton Tech.))

The R.F. test resonator (which was transferred from the V.E.C. group) has been brought into action, driven by our new power oscillator, and has been used to test components for the new R.F.

system and ion source. These are realistic checks because they reproduce the combinations of R.F. currents and vacuum environment.

Mock-up shorting switch elements have been tested to failure at over twice the expected operating current density: electrically the results are satisfactory but the switch design is being changed to make the contacts mechanically more robust.

Tests of R.F. sparking between the blades of the rotating condenser indicate that a dee voltage of 30 kV (peak) will be achieved.

An alumina insulator for supporting the new ion-source puller has been tested up to 35 kV: this was found to be satisfactory after suitable end-caps had been added, but the tests were limited in duration by troubles with some resonator components. The test programme is continuing, but has been delayed by difficulties in obtaining suitable replacements for these components.

We have collaborated with R. Bint of Engineering Division in working on some of the mechanical and electrical design problems of the new R.F. system. This is now being built by Engineering Division: major components should be ready to test by March, and testing of the complete R.F. system should start in June.

Frequency discriminator

The improved cyclotron will have a much faster frequency-sweep rate than at present (up to 1600 sweeps per second instead of 200). Timing pulses must be derived from the R.F. to operate extraction equipment, counter gates, neutron pulse timing equipment, etc. For the time of appearance of these pulses to be sufficiently closely related to the mean radius of the proton beam, the time at which the dee frequency passes through the selected value will have to be determined to within 1 microsecond, corresponding to a change in relative phase between the dee signal and the reference signal of only 10°. A circuit is being developed to meet this stringent requirement.

Slow extraction coils

Kim[93] has suggested that a cee electrode for slow particle extraction could be replaced by a coil which produces a time-varying azimuthal field bump at large radii. This bump should be used to induce coherent radial oscillations in the particle orbits so as to transport the particles into a regenerative extraction system; this would be done slowly to give a good duty cycle. The main advantage over a 'cee' electrode is that the extraction takes place over a time when there is no R.F. acceleration of the particles, so the energy spread is due to phase oscillations alone.

The electrical design of such a system is being studied. A trial pair of coils and driver stage are ready for making field measurements on the cyclotron.

Ion source (J. P. Scanlon, E. Wood, P. Robinson, W. H. Holland and D. Whatley)

It was decided that the ion source should be inserted through an axial hole in the upper pole face and yoke of the cyclotron magnet. The design of the ion source positioning mechanism is based on the types used on the Berkeley 88" cyclotron and the Harwell V.E.C. Some simplifications have been possible because the synchrocyclotron is a fixed energy machine, and less elaborate arrangements are needed to shim the central magnetic field.

The bottom 18" of the hole, sleeved to 8" diameter, will be taken up by rotatable plugs, which will allow a 2" hole containing the ion source feed tube to be moved over a range of positions in the central region. An eccentrically placed 5" diameter hole through the 8" plug will take a 5" diameter plug which contains an eccentric 2" diameter hole for the feed tube. By suitable gearing of the motor drives to each plug separate radial and azimuthal movements of the source may be obtained. The vertical location of

(93) Kim H., I.E.E.E. Trans. Nuc. Sci. 13, 4, p. 58 (1966).

the ion source will be preset, and the final central field shimming will be done in situ. A motor drive cut-out will prevent the source from colliding with the dee or dummy dee. The basic design is completed and detailing has begun.

Work on the ion source is less advanced. The principles of operation of calutron ion sources are well established and no great difficulty is anticipated. Tests are being carried out to determine whether the puller electrode can be mounted by means of a high grade insulator on the body of the ion source itself. To our knowledge this method, which has the great advantage that a separate mounting and positioning system for the puller is not required, has not been used before. In general it should not be necessary, once the optimum running conditions of the ion source are established, to adjust the puller position with respect to the ion source slit.

Work is in progress on the dee configuration for the machine centre. The requirement that particles must be accelerated in either direction around the cyclotron places some restrictions on the type of electrode configurations which may be used. Measurements for one design have been made using an electrolytic tank at Culham. The resulting electrical potential distributions will be analysed and particle orbits calculated using a computer program CYCLEWHEEL.

Magnetic field measurements using a ¼ scale model of the machine centre are being made to determine what degree of field shimming will be required.

Radial oscillations (J. P. Scanlon)

It has been established that the cut-back dee proposed for the modified cyclotron will give rise to appreciable radial oscillations. It is worth exerting some considerable effort to find those parameters which determine the amplitudes of the radial oscillations so generated, and to find means of reducing these oscillations to a minimum, since the efficiency of the beam extraction system, the quality of the external charged particle beam and the size of the neutron source for T.o.F. measurements are all adversely affected by the presence of such oscillations.

A computer program WALKABOUT has been written and used to investigate how the particle orbit centre moves during acceleration. The program is essentially a "paper cyclotron" and enables the details of acceleration to be studied through virtually the whole process of acceleration. The complete history for a particular proton can be obtained in two minutes, involving some 7000 orbits.

A systematic study of the orbits of protons and other particles is being made for a range of dee shapes, and the use of a magnetic field bump to correct orbit centre movements is also being investigated.

So far the following results are known:-

(a) For any dee shape which is allowed by the R.F. system, radial oscillations up to 3" amplitude will be generated.

(b) There is a large degree of coupling between phase oscillations and radial oscillations. Particles starting with small phase oscillations generate small radial oscillations, whereas large phase oscillations generate large radial oscillations. This appears to happen because in the former case the instantaneous machine centre moves slowly and the orbit centre can follow it in a more or less adiabatic manner. In the latter case the machine centre moves so rapidly that the orbit centre cannot follow it.

(c) The position is complicated by various cancellation effects which can occur when the machine centre jumps rapidly from one position to another.

(d) A magnetic field bump, suitably tailored as a function of radius, should give some improvement to small radial oscillations, but cannot be expected to help when large radial oscillations are generated.

(e) Any such bump must be adjustable, since the required corrections are different both for different particles and for different R.F. conditions.

(f) For deuterons the maximum machine repetition frequency will have to be limited to about 750 cps. Higher rates lead to unstable phase conditions.

Beam extraction (D. West)

Preparatory work on the design of a regenerative extraction system is in progress. In July a visit was made to Orsay, where such a system is in operation, and in September to Philips at Eindhoven, where the people responsible for the design of the Orsay extraction gave us much useful information. Three computer programmes have been obtained from CERN. These enable the motion in the horizontal and vertical planes of particles in a cyclotron to be studied in the presence of any configuration of regenerator field. The third programme deals with orbits in the presence of a magnetic channel. Two of these programmes (written in CERN Fortran IV) have been modified, with help from Miss B. Stokoe, SRC, to run on Atlas 1. The third programme is in the final stages of modification.

We have considered methods of surveying the cyclotron field in order to check the design fields within the regenerator and magnetic channel and to measure the disturbances which these elements produce at smaller radii, so that they can be shimmed out. Some measurements of the field reduction in the channel are to be carried out in the main magnet when drilling of the ion source hole is completed. This should provide adequate information for the preliminary design of the channel. It is hoped to do the initial design of the regenerator purely by calculation.

Modifications to the pulsed beam deflector (A. Langsford, P. H. Bowen and G. B. Huxtable)

We have constructed the pulse shaping section of the new high voltage deflection system described in the previous progress report[94], and tested its operation at a repetition frequency of 1600 Hz with voltages up to 50 kV. The system behaves satisfactorily, producing a 60 nS pulse with a 1 nS jitter. Measurements of the rise time, which is below 15 nS, and of the precise pulse shape are somewhat hampered by a high frequency ripple on the pulse. This could arise from mismatching, from oscillation in the thyratron, or from inadequate earthing, and further investigations are being made. The design of a new deflector plate assembly is well in hand.

(94) Nuclear Physics Division Progress Report, AERE - PR/NP 10, p. 57 (1966).

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