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WEAPONS GROUP

NUCLEAR RESEARCH DIVISION

PROGRESS REPORT

1st July 1966 — 31st December 1966

AWRE,
Aldermaston, Berks.

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June 1967

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NUCLEAR RESEARCH DIVISION

SIX MONTHLY PROGRESS REPORT

for the period

1st July 1966 - 31st December 1966

UKAEA Weapons Group,
Atomic Weapons Research Establishment,
Aldermaston,
Berkshire.

March 1967

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1. ACCELERATOR AND NEUTRON PHYSICS (R. BATCHELOR)

1.1 Accelerator Operation and Development (F. A. Howe)

1.1.1 General

Considerable effort continued to be applied to the development of the three accelerator facilities. During the period allocated to accelerator physics, the Tandem and the 6 MV accelerator were used on the basis of a 70 hour week and the 3 MV facility on a 40 hour week.

Scientists from the Clarendon Laboratory Oxford, Imperial College London and the Institute of Technology Bradford continued to associate with AWRE staff on the use of the Tandem machine.

1.1.2 Tandem Accelerator (D. R. Akers)

During the period, beams of protons, deuterons and tritons up to 13 MeV, and oxygen 6^+ beams up to 45 MeV were used. Beam transmission at low terminal potentials, eg, 3 MV has been poor, possibly due to damage in the low energy accelerator tube.

At the end of the period, the machine was closed down in order to effect a major servicing schedule. This includes servicing the lower spherical tube coupling, changing the low energy tube, installing dog leg steering plates in the injector, and fitting an improved extract system above the ion source assembly. A new charging belt drive arrangement will also be installed.

The total time available during the period was 1680 hours, 1200 hours of which were used by AWRE scientists, 210 hours by scientists from the universities and 270 hours were required for modifications and maintenance.

The associated test bench was used for trials on pulsing and bunching of O^{16} beams. Bunched beams of 5 ns width at half height were obtained. Efforts are currently being made to dispense with the grids used on the present bunching system. The buncher apertures are currently 4 in. in diameter, being designed to cope with negative beams produced by the charge exchange process. A reduction in this diameter may permit the removal of the grids with their attendant problems, and increase beam transmission efficiency. Tests on the modified system with bunched proton beams from the direct extraction negative ion source will be carried out shortly.

1.1.3 The 6 MV Accelerator (G. James)

The accelerator has now been developed into a very adaptable facility. As well as dc beams, nanosecond and microsecond bunched and pulsed beams are available. The recent installation of a gas stripper now provides for He^{++} beams. 6 μA at 3.7 MV on the terminal and 2.0 μA at 5.4 MV has been obtained. Pulsing and bunching of the beam will be attempted shortly. During September a damaged insulator in the differential pumping tube was replaced, and close inspection of the tube showed no apparent deterioration, eg, no sparking tracks or discoloration of the insulators. An electrical fault in the windings of the terminal alternator occurred and the spare unit fitted.

From October onwards, the machine has been used on dc beams and bunched beams, and with the gas stripper in place no appreciable reduction of beam transmission resulted.

Total experimental hours used - 700.

1.1.4 3 MV Accelerator (G. James)

The accelerator is now used for both positive ion beam experiments and for electron irradiations on behalf of ESRO. Both rf sources and electron guns have been used for the latter purpose.

A magnetically suppressed accelerator tube was used for the positive ion beam work for several weeks, and produced a beam of 160 μA analysed protons on target at 2 MV. Voltage testing up to 3 MV was carried out and radiation levels were well below normal. Some limitation on performance was found to be due to neutral beams from the source seeing insulators in the gap lens region, and a degree of imbalance in the magnet system; both of these faults can be readily eliminated.

Total experimental hours used - 650.

1.1.5 Accelerator Tubes (F.A. Howe, G. James, A.A. Hunter, R. Prosser, G.W. Eatwell)

A new inclined field tube has been completed for installation in the Tandem accelerator. Modifications to the existing design have been made which it is hoped will improve beam transmission at low energies and reduce risk of damage to the planar section insulators.

The 3 MV magnetically suppressed tube was rebuilt and installed in the NPL accelerator. The tube conditioned up to 3 MV but minor tube sparking was observed. A 5% SF_6 addition was made to the tank gas for a further check, but metal dust from the gas system - discovered after the removal of the tube - rendered this test useless. The tube appeared to be in good condition on inspection and was later fitted to the AWRE 3 MV accelerator. Some imbalance in the magnets was observable, but normal analysed beams, 160 μA of protons on target at 2 MV was obtained and used. The test indicated that the main problems of the magnetic system had been mastered, the minor sparking being due to the ion source beam seeing insulators around the gap lens region - a factor which can be readily corrected.

The magnetic tube for Oxford University is in an advanced state of construction, and magnets for this tube will be calibrated by a crossed field apparatus. This enables the integrated field to be measured as a function of electrostatic deflection plate voltage using a 25 kV proton beam. Accelerator tubes also due for construction are: 2 - 80 section apertured tubes for CISE, Milan, Italy for a vertical Tandem, a 2 MV electron tube for NPL, a magnetically suppressed tube for the new 6 MV Harwell accelerator, and a 2 MV tube for Imperial College. The 3 MV magnetic tube will be modified for further testing.

A 50 kV proton accelerator was completed for NPL during the period. Other projects in hand are a proton source kit for ESRO and a redesign of the AEI 2 MV accelerator at Imperial College, to include slow and fast pulsing.

A modified charging belt drive system for the Tandem was completed and tested ready for installation. A multiple stripper unit for the Tandem is also under construction designed to provide a choice from 2 gas strippers and several stripping foils by remote control.

1.1.6 Target and Counter Development and Radioactive Foils (A.H.F. Muggleton)

(a) Nuclear Targets (G.T.J. Arnison)

Beryllium targets have been supplied to several external customers during this period and the fume box evaporation system has remained as a beryllium facility. It is expected that the fume box will be changed over to radioactive work during the next period.

The motorized rolling mill has been used successfully for producing isotopic tin foils of 3 mg/cm^2 thickness. The inner tin foils were difficult to fabricate by this method and it was necessary to investigate electroplating methods for isotopic quantities. Foils of 1 mg/cm^2 could be produced by total loss plating using a method developed at AERE, Harwell.

Electroplating methods were used in an attempt to produce 8 mg/cm^2 Ni^{58} foils for a gas cell window. These proved difficult to produce pinhole-free. The difficulties were increased due to the fact that the Ni^{58} was tritiated and had to be handled under glove box conditions.

A large proportion of the effort has been concentrated on developing a technique for providing 0.00005 in. thick nickel foils of high purity mounted on a nickel ring 2 in. in diameter. These foils had to be produced to an exacting specification and the variable parameters were investigated in order to find a method which was acceptable to the standards required and to be reproducible.

During the year 283 targets have been supplied for use with the Nuclear Research's Division's accelerators and a further 310 to external users.

(b) Semiconductor Counters (A.H.F. Muggleton)

During the six monthly period covered by this report thirty five silicon surface barrier counters have been supplied to internal users and external organisations.

Considerable effort has been expended in developing and producing suitable surface barrier counters for use in cross section measurements using bomb neutrons. Investigations have continued into the reasons for the distorted output obtained from these devices when used in the current mode. Steps have been taken to eliminate this distortion by (a) using various techniques for obtaining non-injecting rear contacts, ie, boron and phosphorus diffusions, ion implantation and plated contacts and, (b) trying different surface preparations. To date measurements carried out by SSNA Solid State Physics Group and the Counter Section indicate that this distortion can be attributed to effect from fast surface states. The most consistent results have been obtained by copper plating the silicon slice prior to etching. Despite a low yield this technique has produced counters superior to any comparable commercially available devices.

A silicon surface barrier counter with two dimensional position sensitively has been constructed and is awaiting evaluation.

Development of large volume lithium drifted germanium counters for high resolution γ ray spectroscopy continues. Lithium diffusion from an electrolytically deposited film, using a molten LiCl:KCl salts bath is being investigated; consistently even diffusions have been obtained but a low yield of good devices, due to cracking of the crystals under thermal shock, has resulted. Development continues into this mode of diffusion.

Two, new watercooled, drifting assembles are now in operation and a 80 cc crystal is being drifted.

A 75 mm diameter x 30 mm thick germanium crystal has been obtained from GEC Ltd., Wembley and is awaiting fabrication.

(c) Radioactive Foils (S. Walker)

Most of the effort during this period has been devoted to preparing foils for the collaborative programme with LASL on cross section measurements using bomb neutrons. See Section 1.5 for further details.

1.1.7 Vacuum Engineering (J.R. Bailey)

During this period the section moved from Building N54 to Building N56 and the scope of its activities was curtailed. Virtually all research and development work has been shelved although some of the special equipment is being used for training apprentices. Design assistance is still being given on the Yale and Pennsylvania spectrograph vacuum problems and some further outgassing studies have been made.

Most effort has been absorbed in leak testing both in situ and in the laboratory. Halogen diode leak detection equipment reconditioned in the section is now available on short term loan. This method of leak detection is demonstrated during lectures delivered at the Technical Training School.

The section has continued to supply gas control devices and a gas bottle filling service.

The servicing of vacuum equipment continued and influx still exceeds our handling capacity. Over 60 gauge heads were repaired and or reconditioned including 4 miniature mass spectrometers. Some 37 control units were serviced, also a large number of diaphragm valves, 16 diffusion pumps and about 12 rotary pumps. The economy effected has far outweighed the cost of the service and also provides a continued availability of standardised items.

Three craft and three student apprentices received training in basic vacuum techniques during this period.

1.2 Ion Sources and Ion Optics (L.E. Collins)

1.2.1 Helium Negative Ion Formation (P.T. Stroud, H.S. Pickering)

There have been recent reports that low energy charge exchange in caesium vapour of He^+ beams is a more efficient method of producing He^- but due to the hazards associated with Cs requires careful source design. An experimental rig for measuring the fractions of He^+, He^0 and He^- leaving a Cs vapour cell at energies of 1 - 5 keV has been constructed in order to obtain experience in handling Cs and assess the performance to be expected from a practical system. In order to detect the low energy neutrals a secondary electron emission counter has been developed. Even if a high secondary electron emitter is used a significant fraction of the incident particles will not cause the emission of an electron at these low incident neutral energies. The number distribution of multiple electron emission has been investigated and the distribution found to be Poisson as is to be expected theoretically. It will be possible by counting the relative number of incident particles which cause the simultaneous emission of 1, 2, 3 etc electrons and fitting these to a Poisson distribution to estimate the number not giving rise to an electron, and hence the total flux. The secondary electron coefficient and hence shape of the distribution will also be dependent on the amount of excited He^0 present in the beam and this may enable an estimate of the metastable content to be made.

In a practical source it will be necessary to conserve caesium and a Cs vapour jet with recycling of the Cs is also being investigated.

1.2.2 Negative Ion Injector Test Rig (D. Akers, D. Swann)

Klystron Bunching of O^-

Tests on the Tandem with the existing buncher using O^- beams gave pulses of 17 ns width at half height. In order to reduce this, tests have now been made on the test rig using a buncher with the correct drift length between grids for 30 keV O^-. Pulses 5 ns width at half height have been obtained with a mean bunched current of 2 μA at 22 keV. Technical difficulties prevented operation at 30 keV, the design working voltage, but the indications are that the pulse width would be reduced. It was also found that reducing the gap between the grids also reduced the pulse width.

1.2.3 Direct Extraction Von Ardenne Negative Ion Source (R. H. Gobbett)

There is a requirement to make a duoplasmatron source which is easily demountable to be used especially for tritium and oxygen acceleration with the Tandem. A provisional design is being tested but the H^- output is less than from the original source. This is because it has not been possible to obtain the strong magnetic field necessary in the direct extraction source with the air cooled coil in the new design. A permanent magnet system is being considered but it may not be possible to reduce the size of the source without a reduction in H^- output.

Oxidation and flaking of the hot cathode has been a problem and the life when run on oxygen, is short. Tests will be made with rhenium filaments when this material is received.

1.2.4 Ion Implantation (F.R. Pontet, L.E. Collins)

A 100 kV accelerator has been modified to enable ion implantations to be made in semiconductor materials for the Solid State Physics Group of SSNA. Successful implantations of boron have been made and beams of carbon and phosphorus have been obtained. At present a rf ion source is used but other sources are under consideration. In addition mass analysis in the high voltage terminal at low energy will enable heavier ions to be used.

1.2.5 Electron and Ion Irradiation (F.R. Pontet, R.H. Gobbett, L.E. Collins)

A contract has been obtained from ESRO for the irradiation with electrons and ions of space components, such as solar cells, to simulate the radiations they will receive in space. Improved beam flapping systems to give a uniform beam over a large area have been made and methods of monitoring the uniformity of the beam developed.

1.2.6 Pulsed High Current Ion Source for VERA Accelerator (J. Gray)

The test bench development has been completed and the source is now being tested on the VERA accelerator.

1.3 Fast Neutron Physics - 6 MV Accelerator (J.H. Towle)

1.3.1 Time of Flight Measurements

(a) Neutron Scattering by Ni^{58} and Ni^{60} (J.H. Towle, R. Batchelor, W.B. Gilboy)

Analysis and theoretical comparisons of these data obtained in the energy region threshold - 4 MeV with separated isotopes are now complete. A preliminary report on the inelastic data which show marked differences from earlier measurements elsewhere, was given at the IAEA Conference on Nuclear Data (Paris, October 1966). A full report will be prepared for publication.

(b) Inelastic Scattering at 7 MeV from Reactor Elements (Na, Al, K, Cr, Fe, Ni^{58}, Ni^{60}) (J.H. Towle, R.O. Owens*)

The theoretical work for these elements has been completed and a paper entitled "Absolute Level Densities from Neutron Inelastic Scattering" has been prepared for publication. A full statistical model calculation was carried out for Fe^{56} and Ni^{60} which included scattering to the known discrete energy levels below 3.5 MeV together with a continuum of higher levels given by the Lang and Le Conteur level density formula $\rho(U) = KU^{-2} \exp 2\sqrt{aU}$.

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*Now at Glasgow University.

While the shape of the low energy continuum in the scattered neutron spectrum determines the constant _a_, the cross section of scattering to the discrete levels depends on the constant _K_ (roughly αK^{-1}). By fitting the calculated spectrum to experiment, both _a_ and _K_, and thus the absolute level density, were determined. This has not been achieved previously for the statistical region of nuclear excitation below the neutron binding energy.

These comparisons also show that there is a strong direct reaction component in the scattering to the first levels in these nuclei (apart from K^{39}), particularly for the 2^+ first levels of the even nuclei. There is also evidence for direct scattering to the 3^- collective level which occurs in the 4.0 - 4.5 MeV region in the even nuclei.

(c) Inelastic Scattering to Energy Levels of V^{51} and Y^{89} (J.H. Towle, R.O. Owens, W.B. Gilboy)

Final corrections and theoretical calculations are now in progress.

(d) Neutron Scattering by U^{235} and Pu^{239} (R. Batchelor, J.H. Towle)

The data obtained at 2, 3 and 4 MeV, mentioned in CNR/PR/7, showed some inconsistences and further runs are necessary. These have been postponed until the new detection system mentioned in Section 1.3.1(g) is operational.

(e) Neutron Scattering from B^{10} and B^{11} (J.H. Towle, G.J. Wall)

No further measurements have been made.

(f) Neutron Total Cross Sections (W. Gilboy, A.F. Pojur*, J.H. Towle, G.J. Wall)

Total cross sections for O, Al, Fe, Ni, Nb and W have been measured over the neutron energy range 140 - 410 keV using the pulsed "white-spectrum" technique and a Li^6- glass scintillator. Good agreement with previous data (BNL325, 1st and 2nd edition) was obtained, taking into account the lower resolution of the present experiment (∿15 keV).

(g) Time of Flight Spectrometer Development (G.J. Wall, J.H. Towle)

The installation of a new suspension system to give accurate positioning of the 5 m flight path shielding tank is now complete and will be put into use on scattering measurements in the 5 to 9 MeV region in the near future.

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*Sandwich Course student.

A new detector comprising a 5 in. diameter, 2 in. thick liquid scintillator cell viewed by two XP1021 photomultipliers has been built for use in both the 2 and 5 m flight path positions. An improved system of pulse shape discrimination using integrating gates has been installed and preliminary tests indicate an improvement in both stability and performance over the Owen system previously used.

All slow electronics associated with the time of flight facilities have been replaced by modular units of the Harwell 2000 series and CPA (AWRE) units to give a more compact and compatible system.

1.3.2 γ Ray Spectroscopy with a Li-Drifted Ge Detector

(a) Studies of γ Rays from the Bi^{209} $(nn'\gamma)$ Reaction (W.B. Gilboy, R.E. Coles)

A coaxially drifted Ge-Li crystal (GL39) of 40 cc sensitive volume has been used to continue studies of the Bi^{209} $(nn'\gamma)$ reaction for neutron energies between 3.0 and 3.8 MeV in order to supplement neutron scattering measurements on Bi. A time resolution of $\lesssim$ 10 ns and an energy resolution of 7.5 keV for 2.5 MeV γ rays was obtained with this detector. Several new levels in Bi^{209} have been recognised and cascade transitions between these levels have been observed. The data are being analysed and compared with the predictions of the weak coupling model.

(b) Large NaI(Tl) Annulus (W.B. Gilboy, J.H. Towle)

Negotiations were completed and an order placed for a large NaI(Tl) annulus which will be used to surround a Ge-Li γ detector in order to suppress the Compton continua relative to the full energy peaks. This will considerably ease the analysis of γ spectra and should improve the sensitivity for detecting weak γ transitions by at least an order of magnitude. Preparations have begun for mounting this new detector system on its own beam line in the 6 MV lower target room.

(c) Nuclear Lifetime Measurements (W.B. Gilboy, R.E. Coles and Oxford University)

In conjunction with a group under Professor K.W. Allen at Oxford University preparations have begun for measuring the lifetimes of nuclear states excited in He^4 induced reactions by Doppler shift techniques. A new beam line is being assembled in the upper target room on the 6 MV machine.

(d) Technical Developments (W.B. Gilboy, R.E. Coles)

An improved cryostat which employs ion pumps to achieve clean vacuum conditions has been developed for housing the large Ge-Li counter. This system uses Union Carbide "chicken-feed" dewars which greatly reduce the consumption of liquid nitrogen. The Harwell type 1887A valve pre-amplifiers have been replaced by Nuclear Enterprises 5283 FET solid state preamplifiers which reduced the "pulser resolution" from $\sim$ 10 to $\sim$ 5 keV on the large capacity Ge-Li detectors.

In conjunction with Mr. Elphick of CPA a 100 Mc/s time calibrator has been developed and is almost ready for initial tests. This unit provides a series of time marker pulses which are spaced precisely at 10 ns intervals and it will enable very rapid and accurate calibration of time of flight spectra.

A circular surface barrier counter has been ordered from Mr. Muggleton's special technique group which has 3 symmetrically placed electrodes on the front edge and one planar electrode on the back. Its feasibility as a two-dimensional position sensitive counter will be investigated.

1.3.3 (n,2n) Cross Section Measurements

(a) (n,2n) Cross Section Measurements with the Large Scintillation Counter (D.S. Mather, L.F. Pain)

Many runs were performed for the tritium cross section with different sample thicknesses and different beam currents, ie, different background levels. After major corrections have been made the values of the (n,2n) and (n,3n) cross sections are 45 ± 5 and 0 ± 1 mb respectively. The cross sections of B^{10}, B^{11} and Au were measured and these complete the programme of 14 MeV measurements using the "no prompt" technique. Additional machine time was utilised in providing data for corrections to the measured cross sections, eg, the effect of neutrons elastically scattered in the sample and producing (n,2n) events in the steel axial tube through the counter.

The "prompt" system was set up but no measurements were made on Pu^{239} samples; however, the self-background of these samples was pleasingly smaller than anticipated.

(b) Monte Carlo Studies for (n,2n) Cross Section Measurements (P. Fieldhouse, L.M. Harrison, D.S. Mather, J.B. Parker*)

A paper has been written and will be submitted to Nuclear Instruments and Methods for publication with the following abstract:-

The use of Monte Carlo methods to calculate the efficiency of a gadolimium loaded scintillator counter is described. A multiple scatter Monte Carlo programme is also given which assists the analysis of data from an experiment to measure (n,2n) cross sections by irradiating a sample at the centre of this counter with monoenergetic neutrons.

1.3.4 Data Processing and Computing (A.D. Purnell, K. Wyld)

(a) PDP-7 Link

Liaison with CPA (Mr. J.W. Birtill) has continued. The light pen and large area display are now available, and the Data Link (N51-PDP-7) and associated peripheral electronics are almost ready.

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*Member of CMP Division.

The basic time of flight and γ ray spectrum analysis program for both on and off line use is complete and work is continuing to update it as new requirements arise and techniques improve.

(b) DYPSO

This PDP-7 program has been written which allows users with no programming experience to write their own programs on-line for simple and/or repetitive computations which would be too time consuming on a desk calculator or too trivial (or results too long delayed) on STRETCH or ATLAS.

(c) Distribution of Tritium in Thick Targets

A program is being developed to enable the tritium distribution (with depth) to be calculated from (α,n) coincidence rates in the T(d,n) reaction taking into account the multiple Coulomb scattering of the incident beam in the target.

(d) Sundry Computing

Other computer programs have also been developed for specialised applications including: the analysis of fission neutron spectra (for Dr. White); secondary peak suppression in time of flight spectra (for Dr. Gilboy); analysis of γ ray spectra and cross sections from deuteron and triton activation reactions in Ge (for Mr. Dandy) and analysis of secondary electron emission spectra (for Mr. Stroud).

1.4 Fast Neutron Physics - 3 MV Accelerator (J.L. Perkin)

1.4.1 Fission Data

(a) Fast Fission Cross Section Ratio Measurements (P.H. White, G.P. Warner)

The fission cross sections of U^{233}, U^{234}, U^{236}, U^{238}, Np^{237}, Pu^{239}, Pu^{240} and Pu^{241} have been measured relative to the fission cross section of U^{235} to an accuracy of approximately ± 2% at neutron energies of 1.0, 2.25, 5.4 and 14.1 MeV. Combining these ratios with the known values of the fission cross section of U^{235} leads to fission cross sections having an estimated uncertainty of ± 3.5% and which are mostly in agreement with other recent measurements.

(b) Thermal Fission Cross Section Ratio Measurements (P.H. White, J.M.A. Reichelt, G.P. Warner)

The measurements have been completed and the following is the abstract of the paper presented to the Paris Conference on Nuclear Data.

Measurements have been made to an accuracy of ± 2% of the ratios of the fission cross sections of Pu^{239} and Pu^{241} to that of U^{235} in the energy range 0.016 to 0.55 eV and also in two thermalised fields of neutrons.

The monoenergetic neutrons were obtained from a crystal spectrometer on the AWRE reactor HERALD. At the three lowest neutron energies a velocity selector was used to remove neutrons diffracted into the second and higher orders. At the other energies resonance filters were used. One thermal neutron field was an extracted beam from the graphite thermal column and its spectrum measured by a time of flight method. The other thermal neutron field was in a cavity inside the thermal column.

Some discrepancies between the present results and previous measurements are discussed. Corrections and errors due to the neutron spectra of both the monoenergetic neutrons and the thermal beam and errors introduced by beam non-uniformity are described.

(c) Measurement of $\bar{\nu}$ for Cf^{252} (P.H. White, E.J. Axton*)

A direct measurement of $\bar{\nu}$ (prompt) for Cf^{252} has now been completed and yields a preliminary result of $\bar{\nu} = 3.789 \pm 0.030$. The difficulties associated with the self transfer of the californium have been overcome at the cost of an increase in the error of the measurement from a hoped for 0.5%, to 0.8%. A paper is being prepared for publication.

(d) Spontaneous Fission Half-Life of Pu^{240} (P. Fieldhouse, D.S. Mather, E.R. Culliford)

The spontaneous fission half-life of Pu^{240} has been determined from the measured neutron outputs of the Harwell neutron standard, the three Aldermaston standards and their known masses and compositions. An average value of $(1.17 \pm 0.03) \times 10^{11}$ year was obtained. Previous determinations have yielded three results of about 1.2×10^{11} year and several results between 1.3 and 1.5×10^{11} year.

A small trace ($\sim$ 2 ppm) of Cm^{244} in the source material may account for the lower values of the half-life quoted. An analysis of the present source material is being made to test this possibility.

1.4.2 (n,α) Cross Sections for Cr, Fe, Ni and Mo for Fission Neutrons (J.F. Barry, N.J. Freeman)

Samples have been prepared and await irradiation in the Dounreay Fast Reactor. The neutron flux will be determined by γ ray counting Mn^{54} produced by the $Fe^{54}(n,p)Mn^{54}$ reaction. A further irradiation of Cr and Mo samples with α particles from a Van de Graaff accelerator is planned to find the helium extraction efficiency of the apparatus used to heat these high melting point metals.

1.4.3 Measurements and Calculations of the Doppler Effect (J.L. Perkin, P. Fieldhouse, A. Brickstock, A.R. Davies)

The variation of the Doppler effect from the $U^{238}(n,\gamma)$ reaction with neutron energy has been measured using the $Li^7(p,n)$ reaction as a neutron source. The uranium samples were irradiated at a distance of 7 cm from the lithium target and at an angle of 120° with the direction of the proton beam. Other details of the experiment were similar to those described in previous reports.

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*NPL

The results obtained are as follows:-

Neutron energy group, keV	0 - 10	3 - 15	6 - 23	10 - 33	27 - 54
Doppler effect 290 to 770°K, %	11.0 ± 5.7	2.8 ± 2.5	3.8 ± 2.4	3.4 ± 2.3	5.3 ± 1.7

Only the statistical counting errors are included in the quoted errors.

A comparison between these results and those from theoretical calculations awaits the modification of a computer program to suit the particular geometrical arrangement and range of neutron energies used in these measurements.

Previous measurements of the Doppler effect for the $U^{238}(n,\gamma)$ reaction were limited by the proximity of the Sb-Be neutron source used to a maximum temperature of 770°K. In the present experiments with neutrons from the $Li^7(p,n)$ reaction it has been possible to heat samples to temperatures in excess of 1800°K. Doppler measurements for uranium in this temperature region are now in progress using sintered discs of UO_2 instead of the metal samples used at lower temperatures.

The results of these experiments will be of interest in calculations of the safety of large fast reactors especially those concerned with the effect of a fuel element melting.

1.5 Cross Section Measurements Using Bomb Neutrons (A. Moat, E. Moss*, J. Pugh, D.G. Piper)

During this period a state of readiness has been maintained for the next LASL physics shot with most equipment already installed in the field. Development has continued, however, on two outstanding items: detectors and target foils. A 50 keV electron test facility has been built for testing detectors. It is able to show whether detectors are good for use in the current mode, but because of backscatter of electrons from the detector surface, it cannot be used for linearity measurements. Very recently the techniques group have made some detectors using a new cleaning procedure for the slices, with 100% success for diodes which operate in the current mode.

Difficulties have been experienced with the target materials which are deposited on thin nickel backings. The backings fracture if they are taut before the plating operation begins. Attempts have been made to produce foils which are slack to a controlled degree. Other problems arise because of incompatibility of most adhesives with the violent cleaning procedure which is necessary before the plating operation.

Some design studies have been made of a new recording system and a prototype CRT suitable for this system has been ordered.

1.6 Theoretical Studies (A.C. Douglas)

Studies on the pulse approximation in multiple Coulomb excitation have been continued by comparing with results of exact computer calculations. The variation of the best value of the pulse width as a function of interaction strength has been derived for a number of physically interesting cases.

*Member of CPA Division.

2. TANDEM VAN DE GRAAFF (D. ECCLESHALL*, J.H. TOWLE)

2.1 Stripping and Pick-Up Reactions with the Multi-Angle Magnetic Spectrograph

2.1.1 A Survey of (t,p) and (t,α) Reactions (S. Hinds**, R. Chapman, H. Marchant)†

During the recent tritium acceleration period, exposures were made for (t,p) reactions on the following target nuclei at incident triton energies of about 12 MeV: Ca^{43}, $Sn^{112,124}$, $Os^{190,192}$, $Tl^{203,205}$, Hg^{204}, $Pb^{207,208}$. Exposures were also made for the following (t,α) reactions: $Ca^{42,44,46}$, $Ca(t,\alpha)K^{41,43,45}$, $Sc^{45}(t,\alpha)Ca^{44}$, $Tl^{205}(t,\alpha)Hg^{204}$, $Pb^{207}(t,\alpha)Tl^{206}$ and $Bi^{209}(t,\alpha)\,Pb^{208}$.

Progress in analysing earlier exposures is as follows:-

Cr(t,p) (E_t = 12 MeV).

The analyses of the reactions $Cr^{50,52,54}(t,p)$ have now been completed. No strong 0^+ excited states were observed in any of the final nuclei

Ni(t,p) (E_t = 12 MeV).

The (t,p) exposures on the target nuclei $Ni^{58,60,62,64}$ have been fully scanned and analysed. No strong 0^+ excited states have been observed as in the case of Cr(t,p).

(a) $Ni^{58}(t,p)Ni^{60}$

Altogether 37 excited states of Ni^{60} were observed up to an excitation energy of 6.586 MeV. From the shapes of the proton angular distributions, spin and parity assignments have been made for some of the states observed. There is good agreement with previous measurements.

(b) $Ni^{60}(t,p)Ni^{62}$

Up to an excitation energy of 5.64 MeV, thirty-five levels have been identified. Spin and parity assignments have been made for some of the states.

(c) $Ni^{62}(t,p)Ni^{64}$

This exposure was done in collaboration with W. Darcey, University of Oxford, and the plates have been analysed at Oxford.

(d) $Ni^{64}(t,p)Ni^{66}$

From the spectrograph exposure, the ground state Q-value of this reaction was calculated as Q_o = (6.559 ± 0.025) MeV. Up to an excitation energy of 6.73 MeV in Ni^{66}, 58 levels were observed. Spin and parity assignments have been made for thirteen of these states. There are no previous measurements with which to compare the results.

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* Dr. Eccleshall is on leave of absence at the University of Pennsylvania.
** Dr. Hinds is now at the Nuclear Physics Laboratory, Daresbury, Warrington.
† Some of the work is in collaboration with scientists from the Niels Bohr Institute, Copenhagen.

2.1.2 Finite Range Effects in (t,p) Reactions (P.F. Bampton, A.C. Douglas, R.N. Glover)

The DWBA code was modifed to include finite range effects for two nucleon transfer reactions. The approach used was a modified version of the theory of Bencze and Zimanyi [1] based on the local energy approximation. It is concluded that finite range effects are important, the main observations being: (a) that the calculations are less sensitive to the choice of triton optical potential than are zero range calculations, (b) that the cross sections tend to be enhanced, and (c) that the relative intensities predicted for capture of a neutron pair into different shell model configurations can differ very significantly from the relative intensities predicted by zero range theory.

2.1.3 Shell Effects in the Excitation of 0^+ States by (t,p) Reactions (R.N. Glover, A. Macgregor*)

It can be shown that the sudden change from strong transitions to excited 0^+ states for residual nuclei with $N \leq 28$ to weak transitions for $N > 28$ is basically due to closure of the $f_{7/2}$ shell and the consequent transfer of p strength (D.W. calculations predict the ratio of p to f strength to be $\sim 10:1$) from 0^+ excited states to the ground state. This shell effect explanation was confirmed by the experiment $Sr^{86}(t,p)Sr^{88}$ wherein the neutron pair closes the $g_{9/2}$ shell leaving the final nucleus with N = 50. In the $g_{9/2}$ shell one would again predict, from shell model considerations and D.W. calculations, a weak ground state and strong 0^+ excited state transitions. In fact two strong excited states were observed with a total intensity of 1.6 times the ground state. This compares with a figure of 1.9 for the similar reaction $Ca^{46}(t,p)Ca^{48}$ where the added neutron pair closes the $f_{7/2}$ shell leaving an N = 28 residual nucleus [2].

2.1.4 Study of Even-Odd Nuclei in the f-p Shell (A. Ball*, G. Brown*, A. Denning*, R.N. Glover)

Experiments of the type [A - 1](t,p) and A(d,p) to the same final even-odd nucleus [A + 1] have been undertaken and an attempt made to assign configurations which are consistent with both sets of experimental data. A feature of the (t,p) reaction is that L = 0 transitions can only occur to residual states with spin equal to that of the target nucleus. Hence for f shell nuclei the (t,p) reaction enables us to distinguish between states of spin $5/2^-$ and $7/2^-$ and so to check directly the validity of spin assignments based on J-dependence effects for $l = 3$ transitions in (d,p) reactions.

The final nuclei investigated so far are Ti^{49} and Ti^{51}. In the latter case two low-lying levels at 1.43 and 1.56 MeV were shown to give good $l = 3$ stripping patterns in the $Ti^{50}(d,p)$ reaction whereas earlier work [3] at lower deuteron energy reported these levels as non-stripping. The $Ti^{49}(t,p)$ reaction shows an L = 0 transition to the lower state. The lower state can thus be assigned spin $7/2^-$ and the upper state $5/2^-$. The assignments which would be made on the basis of J-dependence are consistent with these spins. In the $Ti^{49}(t,p)$ reaction a very strong L = 0 transition was also observed to a level at 2.69 MeV. This level is not observed in the $Ti^{50}(d,p)$ reaction. Hence it probably has a configuration $(f_{7/2})^{-1}p^2$ and is excited in the (t,p) reaction by adding two p neutrons to the Ti^{49} ground state. Interaction between these $7/2^-$ states probably accounts for the $7/2^-$ level at 1.43 MeV lying

*University of Bradford.

1. Nuclear Physics, 81, 76 (1966)
2. S. Hinds et al.: Physics Letters, 21, 328 (1966)
3. Barnes et al.: Phys. Rev., 136, B438 (1964)

below the $5/2^-$ level in contrast to the predictions of shell model calculations. Configurations have been assigned to several levels below 3 MeV which are consistent with the observed (d,p) and (t,p) relative intensities.

2.1.5 (t,p) Reactions on the Zn Isotopes (R.N. Glover, R. Hudson*)

Scanning of the plates for the $Zn^{64,66}(t,p)$ reactions is well advanced. It is interesting to note that the strongest transition to a 0^+ excited state in the residual nucleus Zn^{68} has an intensity $\sim 25\%$ of the ground state transition, in marked contrast to the nickel isotopes where the strongest L = 0 transition is $\lesssim 10\%$ of the ground state strength.

2.1.6 (d,p), (t,p) and (t,α) Studies in the Region 85 ≤ A ≤ 100 (R.N. Glover, G. Brown et al.*)

The $Sr^{86}(t,p)Sr^{88}$ data are being processed and results on the L = 0 transitions were presented above. The nucleus Sr^{88} is of special interest, having a magic number of neutrons N = 50. The reaction $Sr^{87}(d,p)Sr^{88}$ has also been studied. The data will be supplemented by information on the proton configurations from the reaction $Y^{89}(t,\alpha)Sr^{88}$. The (t,p) reactions on Zr^{90}, Mo^{92} and Mo^{96} have been done as part of a general study of (t,p) reactions in this region. The (d,p) reactions on Sr^{88} and Mo^{98} have been done to complement future (t,p) work on even-odd nuclei.

2.2 The Six Gap β Ray Spectrometer (R. Chapman, R.R. Harris)

The six gap β spectrometer (orange type) was delivered from the AWRE workshops in November.

The spectrometer should be capable of detecting electrons within the energy range 5 keV to at least 5 MeV and with momentum resolution settings of 0.4, 0.8 and 1.4% at transmission values of 1, 5 and 10% respectively.

Using the K internal conversion electrons (624 keV) from Cs^{137} as the monoenergetic electron group, tests have been started to check the pole plate profiles and the cooperation of the gaps. The transmission switch described by Bisgård [1] is being used for this purpose.

Work is proceeding on the automatic control of the β spectrometer using the PDP7 computer.

2.3 Coulomb Excitation

2.3.1 Coulomb Excitation of Deformed Nuclei (G.D. Symons, A.C. Douglas)

The effect of band mixing on the probability for multiple Coulomb excitation within the ground state rotational band has been studied using the Winther-de Boer computer code. Recent data for Sm^{152} have been re-evaluated and a limit set on the magnitude of the angular momentum dependence of the intrinsic quadrupole moment Q_o.

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* University of Bradford.

1. Nucl. Instr. and Meth., 22, 221 (1963)

2.3.2 180° Spectrometer (G.D. Symons, R.A. Brown)

This spectrometer has been thoroughly overhauled and fitted with a 4.8 cm x 0.8 cm position-sensitive solid-state detector for use as a narrow-range ($\Delta E/E \approx 2\%$) spectrograph. It is intended to use the spectrometer for directly recording the scattered particles following Coulomb excitation with heavy ions.

2.4 Neutron Time of Flight Studies

2.4.1 Neutron Scattering (J.A. Cookson, J.L. Wankling, J.G. Locke)

A new programme of fast neutron scattering cross section measurement has begun. The system is basically that used for the scattering of 10 MeV neutrons from Li^6 and Li^7 [1], but a number of improvements have been made to the shielding and the detector system. In preliminary measurements the time resolution for elastically scattered neutrons was 2.3 ns. PDP7 computer programmes for handling the data are under development. The first measurements are likely to be with 10 MeV neutrons on B^{10}, B^{11} and U^{238}.

2.4.2 Analogue States in (p,n) and (d,n) Reactions (J.A. Cookson, D. Dandy)

The experiment using analogue states seen in (p,n) reactions on $f_{7/2}$ shell nuclei to measure Coulomb displacement energies has now been written up, as has work on analogue states from (d,n) reactions (with G.C. Morrison, AERE).

2.4.3 (t,n), (d,n) and (p,n) Reactions (J.A. Cookson)

Time of flight spectra have been obtained for the (t,n) reactions on carbon, silica, calcium, Fe^{56} and Ni^{58} targets but have not been analysed apart from a qualitative check that there was no strong analogue state group in the spectra from the iron and nickel targets.

An angular distribution for the $C^{13}(d,n)N^{14}$ reaction was obtained with 7 MeV deuterons and the excitation function at 20° was measured up to 12 MeV. The intention is to check the reported difference [2] between the ratios of the reduced widths of T = 0 and T = 1 states obtained from (d,n) reactions and the ratios obtained from (He^3,d) reactions.

The analysis of (p,n) measurements of excited states of Co^{54} and Cu^{58} is almost complete.

2.5 Activation Measurements of Ge(d,x) and Ge(t,x) (D. Dandy, G. Garner)

1 mm thick slices of natural Ge have been irradiated with deuterons and tritons at beam energies between 7.0 and 13.0 MeV at approximately 0.5 MeV intervals. Thick target yields of several reactions, eg, (d,n), (d,2n), (d,p), (d,t), (t,n), (t,2n), (t,p) and (t,d), have been measured by observing the γ ray decay of the reaction products using a 17 cc Ge/Li detector. The experimental work is complete and the analysis well under way. Curves of activation cross sections versus energy should be obtained to about 10% in favourable cases.

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1. CNR/PR/7
2. Siemssen et al.: Phys. Rev. Lett., <u>16</u>, 1050

2.6 The Reactions $O^{16}(n,\alpha)$ and $C^{12}(n,\alpha)$ (D. Dandy, G. Garner)

Preliminary work has been carried out on the Tandem in order to assess the feasibility of these measurements (for the Medical Research Council).

2.7 On Line Computer (M.J.L. Yates)

The first stage of putting the PDP7 on line is almost complete. Nuclear pulse ADC's are connected to the computer, and spectra can be accumulated directly from experiments. The data link to N51 is almost complete, and it will shortly be possible to operate the computer via the link. A high speed incremental plotter has also been connected to the computer and is heavily in use for data analyses and output. In addition a 17 in. CRT and light pen have been provided and some modifications to the input/output interface which were found to be necessary when using the priority interrupt feature have been carried out.

The Fortran system has been modified to make extensive use of the magnetic tape, which has considerably improved its convenience in use. Magnetic tape programmes now both read and write tapes for transfer to STRETCH. A multichannel analysis programme has been written which provides all the facilities of a large fast kicksorter, including up to four ADCs, simultaneous operation of all peripherals, and paper tapes compatible with present (IBM) standards.

The second stage of the on-line connection will include the monitoring and control of a β spectrometer, and also some of the accelerator functions such as strong focus control, using a multiplexed ADC for input and stepping motors for the output.

3. RESEARCH REACTOR HERALD; INTEGRAL NEUTRON DATA; PHYSICAL MEASUREMENTS; SOLID STATE PHYSICS (DIVISION HEAD: J.J. McENHILL)

3.1 Research Reactor HERALD

3.1.1 HERALD Operation (M.C.J. Todd, Manager; D. Hindley, Senior Engineer; A.F. Thomas, Senior Physicist)

HERALD has continued to operate at 5 MW during the period, and the overall fraction of time at power was 76%.

At the beginning of September the experimental investigation of the corrosion of N4 aluminium in enriched boric acid solution was completed on behalf of RML, Culcheth. This experiment is to be followed by a rig replacing N4 aluminium by magnox.

For most of the period two in-core experiments were conducted on behalf of the Berkeley Nuclear Laboratories of the CEGB. These are investigating the creep of metals at ambient and liquid nitrogen temperatures.

The difficulties experienced with the hydrogen refrigerator and reported in the previous period have now been explained. Complete filling of the secondary hydrogen system is prevented not by the presence of helium but by the location of the heat exchanger in the circuit. This results in vapour locking of the heat exchanger so that it behaves as a condenser. The system layout will be modified in due course to correct this difficulty, but in the meantime the source can be operated in the boiling regime. The measured gains using hydrogen indicate that deuterium should give very high gains, but measurements have not yet been made. The reliability of the hydrogen refrigerator is giving concern due to the appearance of further faults which result in a considerable loss of time in repairs.

3.1.2 Reactor Physics (A.F. Thomas, N.W. Webster)

The measurements of thermal neutron fluxes incident on the control absorbers in HORACE have been completed. A surprising feature of the results was a large diminution in flux at the surface of the cadmium compared with that at the surface of the steel cladding 0.1 in. thick - the ratio varied from 0.2 over the majority of the absorber to 0.3 at the tip. The estimated peak flux at the top of the HERALD B absorbers at 5 MW was estimated to be 6×10^{12} n/cm^2/s. The effect on safety of the burn out in HERALD is not significant - the major effect will be one of loss of control ($\sim$ 1 dollar after 4 years operation).

An investigation of the fast neutron flux distribution in HORACE with sulphur as the monitor has given a peak value in element D5 of 3×10^7 n/cm^2/s at 2 W. The ratio of fast flux/thermal flux was 1.3 and was sensibly constant throughout the core. The values indicate a peak fast flux of $\sim 8 \times 10^{13}$ n/cm^2/s in HERALD at 5 MW - this agrees well with direct measurements using nickel wires as monitors.

The use of the pulsed source has been improved by modifications to the counters, amplifiers and the RIDL timesorter. The counters are silicon surface barrier detectors with 250 g/cm^2 Li^{6}F; a charge amplifier feeds a 2000 series channel. The RIDL has been modified to allow input pulse rates of up to 10^7/s. A switching circuit which feeds counts from two counters into adjacent time channels has allowed measurements of the resolution time of each channel (0.13 μs) to $\sim$ 1%.

A new survey of thermal neutron fluxes in HERALD beam tubes with cobalt monitors has begun. Detailed measurements of the spatial variation of the thermal fluxes in J1 and J2 with gold-aluminium alloy foils has been completed. Previous measurements were with foil carriers with thick perspex distances pieces; the new measurements, with the minimum of moderator, show that previous estimates of the cadmium ratio could have been too high by a factor of two.

Sixty-four irradiated rigs from HERALD were monitored in the period, requiring 181 flux measurements.

3.2 Theoretical Physics (A. Brickstock, J. Cameron, A.R. Davies, B.A. Knock, I.C. Smith)

3.2.1 Doppler Coefficients

Previous calculations for U^{238} are being extended up to temperatures of 2300°K. Further calculations are in hand on the Doppler changes in the reaction rates in small U^{238}, U^{235} and Pu^{239} cylinders. Neutrons with spectra varying in the range 0 to 10 keV will be incident from an external source. These calculations will be compared with experiments being done by J.L. Perkin and P. Fieldhouse.

Doppler coefficients have been calculated for three pulsed reactor (VIPER) systems; they are all rather more negative than previously estimated.

3.2.2 Computer Codes

SWAN A modified version is being written to calculate a series of adjoint fluxes resulting from given source distributions. Integrals required in the calculation of flux perturbation will also be produced.

3.2.3 Criticality

Further calculations are in progress on the critical sizes for mixed uranium/plutonium metal and oxide systems.

Calculations are also being done on the increases in safe dimensions which can be obtained by the use of various types of solid neutron absorbers.

3.2.4 Compound Identification (See also Section 5.11.4)

Approximately 1000 mass spectra have now been punched and written on tape. Tests on methods of matching spectra are well advanced and results to date are very encouraging. Even compounds regarded as difficult to identify (eg, Farnesol) have been readily distinguished from closely related compounds by the best of the methods tried. These tests are continuing.

3.3 Neutron Physics (A.L. Rogers)

3.3.1 Neutron Crystal Spectrometer (J.M.A. Reichelt, A.E. Stormer)

Birmingham University are using the spectrometer to measure radial distribution functions in glasses and have carried out preliminary investigations of the elimination of inelastic effects (Section 3.4).

Solid State Physics Division, AERE, have carried out total diffraction measurements on heavy water at room temperature and plan to continue the measurements on a high temperature sample.

The spectrometer has been used to investigate mosaic structures of single crystals of aluminium for neutron monochromation purposes. The results from a number of crystals which were grown from the melt and then cooled at different rates showed that fast cooling tended to produce a more symmetrical and smaller mosaic distribution.

3.3.2 Pulsed Neutron Diffraction (R.J.R. Miller, J.M.A. Reichelt)

A system has been set up in which three separate experiments share the chopped "white" neutron beam.

The magnetic structure of metallic oxides and intermetallic compounds have been observed and illustrate a further application of the time of flight method.

Coherent inelastic scattering measurements on a single crystal of aluminium continue.

Incoherent inelastic scattering measurements, using the inverted polycrystalline beryllium filter method, have been carried out by Birmingham University on ammonium chloride and graphite [1] (Section 3.4).

New choppers have been designed, with optimised specifications; which will eventually replace the existing fast neutron chopper as the pulsed source.

3.3.3 Fission Mechanisms (A. Clarke, W.G.F. Core, E. Finch*, E.E. Maslin)

A paper describing neutron emission measurements using the large liquid scintillation counter facility has been prepared for publication. Data which have recently been collected from the fragment pair corroborate the earlier work on emission from individual fission fragments and in particular bear out that under certain conditions a maximum in the total excitation energy in the region of most probable fission can occur.

A preliminary run has been made to measure the energy and mass distribution of fission fragments from ternary fission events arising in thermal neutron induced fission. The objective is to determine the origins of a group of events in binary fission with lower than average kinetic energy. So far some 10^5 fissions have been recorded of which 8×10^3 are ternary events.

The fission fragment time of flight facility [2] is being reassembled for nuclear structure studies, preceded by surface barrier counter calibrations.

3.3.4 β Decay of Pu^{239} Fission Product (R.L.G. Keith)

A new set of β heating irradiations have been carried out for Pu^{239}. The results show that at infinite irradiation time the β power output from Pu^{239} falls more rapidly than was found for U^{235}, being 6% lower at 10^3 s and 20% at 10^4 s.

3.3.5 Thermal Fission Cross Sections (R.L.G. Keith)

Measurements have been made in a well-thermalised reactor spectrum to obtain precision values for 2200 m s^{-1} fission cross section of U^{233}, U^{235} and Pu^{239} relative to $Co^{59}(n,\gamma)$; to be 535.7 ± 5.0, 584.1 ± 6.1, and 742.0 ± 6.5 respectively. A paper on the measurements is being written for publication.

3.3.6 The Half-Life of U^{233} (R.L.G. Keith)

A measurement of the half-life was made by two different specific activity determinations and found to be $1.550 \pm 0.009 \times 10^5$ year compared to the accepted value of 1.620×10^5 year; and the value was used in the fission cross section evaluations in Section 3.3.5.

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*Oxford University.

1. M. Beg: M.Sc. Thesis, Birmingham University (1966)
2. G. Andritsopoulis, T. Cornell and A.L. Rodgers: "Physics and Chemistry of Fission I", IAEA, 481 (1965)

3.3.7 Neutron Diffractometers (J. Birtill*, J.M.A. Reichelt)

At the request of the Neutron Beam Research Committee of the SRC a design study of an automated single crystal neutron diffractometer and a powder diffractometer which work off the same neutron beam in the B5 hole has been made. A feature of the system is the control by on line computer.

3.3.8 On Line Computer (E.E. Maslin, S. Terry)

The PDP-8 computer with 4K of fast memory is operating in a time shared mode, allowing simultaneous data monitoring from one 4-parameter experiment, one time of flight experiment and periodic data transfers from a conventional analyser. In addition either an interruptable version of the multi-analyser programme can be used for more effective display and handling of the data or an interruptable version of the Editor programme can be used, either of which can be loaded without disturbing data collection.

Recently the magnetic DEC tape has been delivered and when installed will greatly facilitate the communications between the experimenter and the experiment via the memory.

3.4 Experiments Sponsored by the Science Research Council

3.4.1 Neutron Scattering Experiments (Physics Dept., Birmingham University. Professor J. Walker, D.K. Ross, Y. Sanalan, E. Lorch, M. Beg. G. Tuckey (AWRE))

(a) Cold Neutron Apparatus

During the period under review the cold source was commissioned and the enhanced flux produced made it possible to collect data at a much more reasonable speed. With the present liquid hydrogen source the total cold neutron flux ($\lambda > 4$ Å) increased by a factor of about 14. This gain is not constant with wavelength but increases from 8 at 4 Å to 16 at 5 Å and the peak neutron flux now occurs at about 4.8 Å. Although teething troubles with the cold source and the data analysis system still persist, runs with satisfactory statistics have been completed for vanadium, room temperature water and water at 234°C, the last two making use of the high pressure tubular steel sample and the automatic sample changer. The various computer programmes for the preliminary reduction of the data are working satisfactorily and the remaining analysis is under way.

In connection with the assessment of the cold source performance, a programme has been written to derive the filtered spectrum from the transmitted data at different rotor speeds and this has been done for both the low and high resolution rotors. The results from the latter indicate that the use of the beryllium Bragg edge is no longer necessary for adequate resolution and that for the liquid hydrogen source the best intensity is actually obtained, as mentioned above, at 4.8 Å. The spectrum measured from the ambient hydrogen source is in general agreement with that obtained on the water source by means of the disc chopper but has much more detail as a result of the better resolution.

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*Member of CPA Division.

The next experiment is a measurement of the scattering from high temperature graphite. The sample and its control electronics are ready and the preparation for its installation are almost complete. Further measurements on benzene and water are planned as an extension of previous work.

(b) Neutron Diffraction Studies on Glass

In the interval before the operation of the cold source some of the Birmingham effort was transferred to other HERALD facilities. The D face crystal spectrometer has been used in the measurement of the radial distribution of silica and germania and the possibility of converting it to a triple axis machine for measuring elastic diffraction are being explored.

(c) Down-Scattering Ray Inverted Filter Method

The usefulness of the fast chopper on E face for down-scattering experiments has been demonstrated. The white pulse of neutrons from the chopper is allowed to pass down the 20 m flight path after which the neutrons are scattered from a sample. Those scattered down to less than 0.05 eV may pass through a beryllium filter to a detector. The ratio of the time of flight spectra in the detector to that in the beam gives the corresponding cross sections. Measurements on ammonium chloride, graphite and zirconium hydride have been performed.

3.4.2 Neutron Scattering by Crystal Defects (J.J. Thomson, Physical Laboratory, The University of Reading; J. Belson, C.D. Clark, B.H. Meardon, E.W.J. Mitchell and R.J. Stewart)

During the period under review work has been in progress on beam tube GIC - containing the cold source - and G2C. Measurements are continuing on germanium, silicon and graphite and will be reported when completed. G2C is currently being used for the range 6 - 13 Å and GIC for wavelengths up to 17 Å.

Towards the end of the period the liquid hydrogen source became operational and measurements of the spectrum and flux have been made with a slotted disc velocity selector. Gains of 14 in the wavelength range 6 - 17 Å have been obtained compared with the best results with any ambient source previously used for this work on the HERALD reactor.

The work on the cryostat for making long wavelength neutron scattering measurements at liquid nitrogen temperature is nearing completion. The cell is to be used in conjunction with the present sample changer, the new cell being moved automatically in and out of the beam when the sample changer moves to and from the specimen position. A new velocity selector has been designed using a slotted magnesium-cadmium cylinder and will have a transmission of up to 50%.

Calculations have been carried out for interstitial defects in graphite to examine the defect scattering anisotropy which arises from the relaxations which have been calculated in various models of isolated interstitial atoms in graphite.

Further attention has been given to the possibility of analysis of data by the Fourier transform of the wavelength dependence of the total defect scattering cross section.

4. INTEGRAL NEUTRON DATA EXPERIMENTS (J.W. WEALE)

4.1 VERA Assemblies (P.W. Benjamin, H. Goodfellow, W.B. McCormick, M.H. McTaggert, W.J. Paterson)

4.1.1 Assemblies 18A and 18B (M.H. McTaggart, AWRE; J.C. Smith, H. Atkinson, DERE)

The measured reaction rates in the nickel reflector region of the cores built to simulate the composition and critical size of the Dounreay Fast Reactor are being compared at Dounreay with cylindrical diffusion theory calculations using various data sets. The data sets comprise FD2 which is derived from the data file, a revision of the nickel data in FD2 by Ravier and the Russian data set. The main conclusions from these preliminary calculations are:-

(1) All three sets agree with the experimentally observed threshold reaction rate $U^{238}(n,f)$.

(2) Of the three sets the FD2 set with Ravier nickel data does best at predicting the low energy reaction rate $B^{10}(n,\alpha)$. All three sets, however, predict a higher reaction rate than is observed.

(3) As with the B^{10} reaction rate, FD2 with Ravier nickel data does best at predicting the $U^{235}(n,f)$ reaction rate variation through the nickel region. The FD2 and the Russian sets overestimate by 50% and 30% respectively.

4.1.2 Assembly 19A

In the period June to September 1966 an assembly was built with a core of $PuO_2/UO_2/CH_2$ compacts and a reflector of natural uranium. The purpose of the measurements is to provide experimental data against which calculations and nuclear data can be checked and adjusted to give better estimates of critical sizes of mixtures occurring in fast reactor fuel production plants. The measurements included critical mass, the central core spectrum from 0.5 eV to 10 MeV and the prompt neutron decay constants at several positions in the core and reflector at reactivities between critical and 3% subcritical.

The corrected experimental sphere critical mass of 18.7 kg Pu^{239} indicates a surprisingly large error in the prediction (26.8 kg Pu^{239}) of a SWAN diffusion code calculation using FD2(R) nuclear data: Reasons for this discrepancy are being investigated and a comparison with a GEM Monte Carlo code prediction is planned.

Preliminary analysis of the spectrum measurements below 1 MeV indicates quite good agreement with the spectrum given by the SWAN calculation and the relative values of the reaction rates $U^{238}(n,f)$, $U^{235}(n,f)$ and U^{235} in Cd(n,f) agree with the calculated values to within 10%. Direct measurements of the fluxes above 1 MeV by the nuclear emulsion technique are not yet analysed.

The prompt neutron decay measurements show no significant deviations from a single exponential at any of the positions in the core and reflector. The decay constants extrapolate to a value at delayed critical 2.6 x 10^3 s^{-1}. Comparison with a time dependent calculation is still to be done.

4.2 Fast Neutron Spectrometry (P.W. Benjamin, J. Redfearn)

4.2.1 Development of Techniques

The PANDA system has been built with a copy of VERA assembly 5A. This system is being used to compare and check the accuracy of the various spectrometry techniques. So far the part of the gas counter work without γ discrimination has been subjected to a number of tests to examine the effects of count rate, space charge saturation and counter environment. As a result of these tests some changes have been made to the head amplifier operating conditions and a maximum useable count rate established. Also the absolute accuracy of the gas counter technique over the range 30 keV to 1 MeV has been shown to be better than 10%.

Measurements with the gas counter in VERA assembly 19A using γ discrimination showed that the high count rate inherent in a plutonium core was causing spectrum distortion by head amplifier saturation. Therefore a new amplifier has been built with the first stage inside the reactor next to the counter. This is now being tested.

4.2.2 ARGUS Computer

Delivery of the ARGUS 400 was scheduled for 1st October 1966. However it is now anticipated that the computer will not be installed until January 1967. Because of this delay programmes are having to be tested on the Ferranti factory computer at Manchester. The ARGUS 500 has been ordered and is due to replace the 400 in October 1967.

4.3 Criticality Physics (L.J. Dalby, H. Goodfellow, R.C. Lane)

4.3.1 SCAMP

Mechanical assembly of the rig in Building A7A experimental cell, apart from the installation of glove ports, will be completed by mid-December 1966. Water testing and calibration work will occupy a further four to six weeks and during this time glove positions will be defined so that installation can proceed. Handover for acid testing and nuclear commissioning is scheduled for the end of January 1967.

The first experiments on SCAMP will be measurements of the critical parameters of a mixture of plutonium and natural uranium nitrates, having Pu:U = 1:3 and a range of H:Pu atomic ratios, to extend the work recently done on ARIES with mixed oxide compacts at H:Pu:U = 18.6:1:3. Further experiments are planned to evaluate the effect of heterogeneous poisons, held in pyrex glass, on the critical size of a plutonium nitrate solution.

4.4 Development of High-Current Accelerators as Neutron Sources (H. Goodfellow)

4.4.1 VERA Accelerator

Results of the ion source test bed work are being confirmed on the accelerator proper. A cylindrical or "gap" lens gives good beam injection conditions for matching the ion source to the accelerator tube and has the advantage of control simplicity. Pulsed ion currents of 40 mA (four times greater than previously obtainable with this accelerator) have been accelerated successfully and brought to an acceptably small spot focus. Beam focussing on the target which in the VIPER position is about 20 ft beyond the accelerator tube, has still to be tested with existing electrostatic quadrupole lenses.

4.4.2 HVEC ICT Accelerator - PANDA

The U^{235} sub-critical PANDA rig was complete in August and neutron spectrometry development work was transferred to the new rig when the VERA reactor was shut down on 26th September. The PANDA time of flight detector hut shielding is being improved to reduce neutron background effects. In the meantime measurements are being confined to in-core flux ratio comparison with threshold fission detectors and spectrum comparisons in the core and in the extracted neutron beam using proportional gas counters.

Minor changes in the ion source electrode design have increased the maximum available pulsed current from 12 to 20 mA.

4.5 VIPER Pulsed Reactor (L.J. Dalby, H. Goodfellow, R.L. Long, W.B. McCormick, M.H. McTaggart, G.V. Stupart, E.G. Warnke)

The reactor has been assembled in AWRE workshops and functional testing of the mechanisms has begun. Detailed safety assessment of the instrumentation, the safety circuit, the control mechanisms and the accident potential is proceeding. Thermocouple core temperature sensors have been developed and are being tested. A prototype fast acting γ sensitive shut down channel incorporating a scintillator and a photodiode is being built. Provision is being made to record reactor power versus time during a pulse by converting the detector signal to digital form and storing a sequence of such outputs in the ARGUS computer ready for subsequent analysis.

Progress in the safety documentation has involved three drafts of the basic Safety Document which has been modified to take account of (a) comments made by the Safety Panel, and (b) progress in detailing the design. Drafts of the Standing Orders and Operating Instructions have been submitted to the Safety Panel.

5. PHYSICAL MEASUREMENTS GROUP (N.R. DALY)

5.1 Isotopic Analysis by Mass Spectrometry

5.1.1 Tandem Mass Spectrometer - MSX (M. Morgan)

The design for the Ferris wheel type of ion source is being detailed. Six samples will be loaded into the source at the same time and analysed in turn without opening the source region up to air.

5.1.2 Tandem Mass Spectrometer - MSY (A.C. Tyrrell)

The instrument continues to analyse samples as small as 10^{-16} g.

A test series of using the "internal standard" technique for uranium with the MSY has proved that the precision for the 235/238 ratio available is equal to or better than the MSX performance. In fact the precision obtained approaches within 25% of the theoretical precision at ± 0.1%.

5.1.3 MS/5 (J.W. Roberts)

A number of measurements have been made for Harwell, Culcheth and Winfrith using thermal ionization and crucible source techniques.

Elements examined were Li, B, Sn, Fe, Te, Zn, Ag, Sb, Cd, U and Pu.

Particular study of the measurement of boron using the borax method showed that the reproducibility of ratio measurement was ∿ ± 0.1% or better. This will be used to compare boron with cobalt for flux monitoring. The precisions obtained using the digital voltmeter output were significantly better than that obtained using the normal chart measurements.

It has been possible to measure less than 1 μg samples of iodine using negative ions. The normal potentials and magnetic fields on the standard MS/5 are reversed. Memory effects can be overcome.

5.2 High Sensitivity Gas Analysis Mass Spectrometer, (n,α) Cross Sections (N.J. Freeman, Miss N.L. Campbell)

High purity samples of Fe, Ni, Mo and Cr have been prepared for irradiation in DFR. The irradiated samples, each containing 10^{-6} to 10^{-5} st cc of helium will be ready for analysis in the high sensitivity gas mass spectrometer by March 1967. The technique for extracting helium from Mo and Cr requires further development.

5.3 Surface Physics (N.J. Freeman, I.D. Latimer)

The burial of 60 keV D^+ ions in stainless steel (EN58B) and titanium has been investigated over a range of target temperatures. The targets were 0.005 in. foils clamped to a liquid N_2 cooled tube. The temperature, which was measured by a thermocouple spot welded to the back of the target, was controlled by the beam current. The variation of the reflection coefficient with dose of D^+ ions was obtained by comparing the partial pressure of D_2, as measured by the MS/10 during the loading, with the D_2 pressure when the target was a 100% reflector or emitter (0.002 in. Ag-Pd foil). For stainless steel the fraction of the incident beam which is trapped in the target (η) decreases with target dose and tends asymptotically to zero. The total number of particles trapped in the metal N is calculated from these curves and it is found that N increases sharply with temperature. For example, at 400°K N is ∿ 10^{17} atoms/cm^2, while at 170°K N is ∿ 2×10^{18} atoms/cm^2.

Saturation curves (ie, curves tending to 100% "reflection") were not found for titanium. Titanium has a narrow temperature range of 325 - 425°K over which η remained constant at ∿ 97% even up to doses of 3×10^{19} atoms/cm^2. Outside this temperature range η decreases with D^+ dose.

Apparatus for stage II of the programme is almost manufactured, and will be assembled early in 1967. It consists of a 12 in. radius mass spectrometer which will be used to study directly the neutral and ionized particles which leave the surface. At the moment optical experiments are being undertaken to study the emission spectra of metal targets under fast ion bombardment.

5.4 NPL Separator (N.J. Freeman, W.A.P. Young, I.D. Agnew (WD4), D. Kaine (SPA))

Trial assemblies of major items of the mechanical and vacuum equipment are taking place in Building Cl.5. The delivery of the magnet, 90° beam tube, eht insulator and the major electronic items is behind schedule, so the assembly and testing of the machine in Building A10.1 have been delayed until February 1967.

5.5 MSG Gas Mass Spectrometer (N.J. Freeman, R.E. Powell, M.C. Jackson, I.D. Agnew (WD4))

This machine is being designed as a replacement for the MS/2 gas machine but will have the advantages of greater sensitivity than that of the nuclide spectrometer and a resolving power up to ∿ 3000. The instrument is based on the Capenhurst spectrometers and will be bakeable to 300°C so that ultimate pressures ∿ 10^{-9} torr will be reached. The recently developed bakeable scintillation detector and retardation device will be incorporated in the design. Mass marking, fast scanning between peaks and scanning of selected regions of a mass spectrum will be achieved with a refined magnetic field scanning system (based on field measurement by a rotating coil) which is being developed. The instrument is expected to be in operation by September 1967.

5.6 Capenhurst Mass Spectrometer for the Analysis of UF_6 (W.A.P. Young, R.E. Powell)

The order for these machines has now been increased from four to six. The first has been delivered to Capenhurst, and the second is under test here. Construction of numbers 3 and 4 has started and orders for the components of 5 and 6 are in hand.

5.7 Laser Source 180° Mass Spectrograph (R.W.D. Hardy)

Development of the new source assembly has led to a significant improvement in the performance of this apparatus and also in its reliability. The total ionization efficiency has been measured and has been found to be in the region of 8%. The cone angle of the beam has been measured and found to be about 150°; an approximate theoretical treatment of this appears to be in fair agreement with the observed value. The apparatus is at present being used to study the spectra of titanium samples in which hydrogen is occluded.

5.8 Laser Time of Flight Spectrometer (N.C. Fenner)

The electrostatic analyser referred to in the previous report is now in use but has not produced the expected improvement in sensitivity. A scintillation detector which will collect more of the emergent beam is at present under construction. Much of the period has been taken up by attempts to penetrate the energetic plasma by the laser so that the ions could be accelerated. This proved a difficult problem and it was resolved by accepting the ions without further accelerations. The energy provided by the laser gives the ions their drift velocity and the electrostatic analyser is used with the plates at about ± 1.0 V. This method of operation required calibration as only a fraction of the ions are used in the analysis and the relative number depends on the energy distribution of ions of that mass. Some samples of material have been analysed and useful information has come from the uncalibrated results.

5.9 Ionization Studies (R.E. Powell)

Collisions between electrons and oxygen molecules and ions have been studied using a mass spectrometer. The formation and subsequent ionization of $O^+(4S)$, $O^+(2D)$ and $O^+(2P)$ to form O^{++} has been shown to take place. Appearance potentials for O^{++} and O^{+++} formed by electron collision with oxygen molecules have been measured, as well as the ionization potential of doubly charged oxygen. The $A\Sigma_u^{+a}$ state of O_2^{++} has been detected. The Wigner spin rule has been used to explain the different charge exchange rates between the $A\Sigma_u^{+a}$ and $X^1\Sigma_g^{+a}$ states of O_2^{++} and oxygen, nitrogen and argon gas.

5.10 Retardation Device for Improving Abundance Sensitivity (N.J. Freeman, R.E. Powell)

The abundance sensitivity of a mass spectrometer is defined as the ratio of the intensity of a beam at mass M to the intensity of the scattered components of the same beam at mass (M + 1) or (M - 1). A typical single stage instrument such as the MS/5 has an abundance sensitivity in the mass 200 region of $\sim 10^4$ on the low mass side and $\sim 2 \times 10^4$ on the high mass side of the peak. A retardation device which transmits to a scintillation detector only those ions which have lost less than 2 - 3 eV in a collision process has been developed. The abundance sensitivity of an MS/5 type instrument has been improved to about 10^6 on either side of a mass 200 peak. This technique will be tested on the MSX two stage instrument where it is hoped to achieve an abundance sensitivity $\sim 10^8 - 10^9$.

5.11 Mass Spectrometry Data Centre (R.G. Ridley)

The Data Centre is supported by the Office for Scientific and Technical Information, Department of Education and Science.

Significant progress has been made in establishing the organization of the Centre and on the specific projects selected for initial study. SSNA staff have obtained invaluable assistance and cooperation from many divisions throughout the site, particularly staff in HTS, SSCD, DA, Computer staff, typing staff, HTS Reproduction staff and illustrating staff.

5.11.1 Mass Spectrometry Bulletin (with HTS Staff)

The first edition (November 1966, Vol. 1, No. 1) of a monthly publication giving a guide to the current literature of mass spectrometry and allied topics has been prepared and printed at Aldermaston and is being distributed by HMSO. It has received a number of favourable comments. Number 2 is being printed and number 3 has commenced its scanning period.

Each copy contains approximately 250 references to papers involving mass spectrometry. Detailed classification and indexes aid retrieval of a particular topic. The information in the Bulletin is placed in a computer file for the Bulletin production to aid the compilation of these indexes and it is hoped to use this file as the base for alternative methods of information retrieval.

"Peephole" cards systems will also be studied.

5.11.2 Survey of the Literature of Mass Spectra

Approximately 450 articles have been indexed for the spectra reference file.

The individual compounds referred to are coded into a compound reference computer file.

The chemical classification system has been devised. Initial tests of its usefulness will be made on the first three Bulletins before extending the classification to the main Compound Reference File.

5.11.3 New Spectral Data

200 new low resolution mass spectra have been received by the Centre for distribution.

The system for measuring spectra on charts has been tested.

5.11.4 Compound Identification (Dr. Kelly, Unilever, Colworth, Bedford, by arrangement with OSTI; A. Brickstock, I.C. Smith)

Computer programmes have been written to study the use of low resolving power mass spectra for compound identification. The program is complete and initial tests are very encouraging.

5.11.5 NBS Data on Ion Processes

The data file has been received from NBS, Washington, and arrangements for answering questions on ionization potentials and appearance potentials have been made.

5.12 Electronic Development (W.A.P. Young, R. Hayes, M.C. Jackson, T.L. Pearce, B. Gooding)

Completion of the first Capenhurst machine has proved some of the new electronic units, including the following:-

(i) A transistorised 6000 V 3 mA power supply stable to better than 100 ppm per half hour for an ambient temperature change of 10°C, unharmed by short circuiting with a recovery to the specified stability within one second. Output variable by 60 V energy less than 1 J, ripple less than 50 ppm. Cost is expected to be about £250, on a standard 19 in. panel.

(2) A sweep generator, output 0 - 9 V with ranges from 7½ min to 2 h, reversible linear sweep, with reset facility at any point. Constructed on a Harwell 2000 type single width unit. Cost is expected to be about £150.

Feasibility studies for an on line computer facility in Building A8.1 are well advanced and some help is being given with a similar scheme for Building R61.1.

6. SOLID STATE PHYSICS (E.M. GUNNERSEN)

6.1 Semiconductor Counter Development (R. Ellis, E.M. Gunnersen)

A joint AWRE-AERE contract for GEC, Wembley to supply large 3 in. diameter germanium crystals suitable for lithium-drifted counters has commenced. An attempt is currently being made to lithium-drift the first such crystal into one counter of 100 cc volume (possibly for application in forensic neutron activation analysis). To assess the suitability of this and other germanium material, low temperature infra-red spectroscopy methods of measuring oxygen impurity content are being used.

The ion implantation technique of making electrical contacts to semiconductor counters has now been successfully developed to the stage where such counters are being supplied for various experiments. On germanium lithium-drifted counters, satisfactory stable and thin ion implanted contacts 0.3 μ thick have been achieved. The potentialities of this technique are being investigated for obtaining larger sensitive volumes by the stacking of several planar germanium counters.

Conventional fabrication of germanium lithium-drifted counters (eg, coaxial) has been improved (a) by means of thermal and l-point probe measurements connected with exhaustion of the lithium sink, and (b) through the achievement of a higher breakdown voltage.

6.2 The Ion Implantation Technique of Fabricating Semiconductor Electronic Components (A. Hitchcock, G. George, E.M. Gunnersen)

AWRE participation in the wider AERE programme is confined to assessing degradations in electrical material parameters which arise from lattice damage introduced by the ion implantation. Work is proceeding along 3 lines:-

(a) Estimation of carrier depletion as a function of depth of implantation by measuring capacitance-bias dependence (before and after annealing) in silicon diodes implanted with various electrically active or inactive ions.

(b) Similar carrier depletion-implantation depth measurements using 4-point sheet resistivity. This method has involved us in the development (for germanium) of anodic oxidation stripping techniques of controlling depth, and has led to some interesting results on unexpectedly large non-uniformities in the surface finish on germanium and silicon oxide films.

(c) Development (Dr. L. Collins, SNP) of a mass separator and ion sources suitable for ion implantation.

6.3 Orientation Dependence of Defect Introduction Rates in Electron Irradiated Silicon at Near-Threshold Energies (P. Stevens, P. Hemment)

Computer calculations, based on an assumed displacement energy-orientation dependence and on previous measurements of electron dispersion in silicon, are being made to determine the dependence of the recoil atom energy spectrum on incident electron energy, angle, and penetration depth. Experimental measurements on variations of defect introduction rate with incident electron energy, angle (near major crystal directions) and temperature are being correlated with these calculations to determine the actual displacement energy profile. These experimental data are being provided by 2 types of measurement: (a) on shallow (2μ) field-effect devices (either surface barrier or ion implanted) capable of giving carrier depletion as a function of depth, and (b) on bulk resistivity in thin (15μ) polished films.

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