THE PROTON LINEAR ACCELERATOR: A SURVEY

P.L.A. Division
Rutherford High Energy Laboratory

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SUMMARY

The Proton Linear Accelerator has been operating since 1960. Originally conceived as the first stage of a major linac project, it has been steadily developed into a well-equipped nuclear structure facility. This survey, in two parts, is primarily concerned with the outline of the achievements in accelerator and nuclear physics during the past seven years. The first section concerns machine development, including the polarized proton source, and concludes with a note on future machine development possibilities. The second section is a condensed account of the variety of studies in nuclear physics conducted during the period, again concluding with a survey of possible future programmes. In appendices are listed experimental teams using the P.L.A., Ph.D. theses awarded, and so on.

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CONTENTS

A. ACCELERATOR PHYSICS AND MACHINE DEVELOPMENT

1. Introduction

The Proton Linear Accelerator was designed as the first part of a 600 MeV linear accelerator, which was intended to be the first meson factory. Since at the time there was little design or operating experience on proton linear accelerators, the three tanks were built in advance of the rest of the machine to gain such experience. To speed up the building programme the first tank was essentially copied from an existing linac at Berkeley and hence was built with grid focussing. There were no radio frequency power amplifiers in the frequency (202.5 Mc/s) and power (1 to 1.5 MW peak) range required by the accelerator so a design for such a valve had to be undertaken. At the time when some of the major components of the machine were being installed and the probable completion date was still over a year away it was decided to postpone all development work on the machine beyond 50 MeV.

Included in the plans for the 600 MeV machine was a small experimental area for 50 MeV beams, which would have been adequate for the occasional low energy experiment, but inadequate for the new use of the P.L.A. This experimental area was enlarged before experiments could start in 1960 and was further enlarged towards the end of 1961.

Because of the lack of experience in proton linac design, the RF system and the modulators for the RF amplifiers were in many ways experimental. When the grounded grid triodes were developed to a stage where they could be installed on the machine it was soon found that their peak power output was inadequate. Extensive modifications of the RF system were needed to reduce the peak power required from each valve and to obtain sufficient reliability to make nuclear physics use of the machine feasible. The modulators, which were designed initially as prototypes for the rest of the machine, had several basic weaknesses, which were easy to recognise but difficult to correct. For example, ignitrons were used at voltages much higher than they were designed for or normally used. Until the ignitrons were replaced by deuterium thyratrons, and protection circuits, using other deuterium valves, were installed, the modulators were very unreliable.

All this development work on the experimental areas (and their equipment), on the RF and modulators and on other parts of the machine was essential to make it a reliable machine. At the same time, new facilities were being added to the machine, principally the polarized source and the time of flight instrumentation, and new apparatus was required to regulate the parameters of the machine within closer tolerances to give improved beam characteristics.

During the first few years of operation the output of nuclear physics suffered from the unreliability of the machine and the time and effort devoted to machine improvement. However, it was, in the long run, more profitable to operate in this way rather than attempt to optimise the machine first since the experience gained was very useful in deciding how to develop the machine. The cost of running the machine then was high and the output of results was low. During the past few years the machine development has continued, but due to good reliability, the time available for experiments has reached a very satisfactory level. Table I shows how the operating time and reliability of the machine has increased during the years 1960 to 1966.

TABLE I

Running Time 1960-1966

	Hours Scheduled	Hours Available for Use	Availability (%)
1960	1,420	980	69
1961	3,660	2,149	59
1962	5,544	3,971	72
1963	5,453	4,405	81
1964	5,573	4,664	84
1965	6,128	5,260	86
1966	6,303	5,605	89
	34,081	27,034	

2. General Description of the P.L.A.

The P.L.A. consists of a 500 kV injector and three Alvarez type radio frequency accelerating sections (tanks 1, 2 and 3) which are placed end to end and produce output energies of 10, 30 and 50 MeV respectively. Since tanks 2 and 3 have quadrupole magnetic lenses in each drift tube, all three energies are available in the experimental areas and the beam can be transported there without any loss of intensity. Intermediate energies are obtained by using absorbers to degrade the energy of the beam at the output of tank 3. The protons are produced by ion sources in the high voltage terminal of the injector; both unpolarized and polarized ion sources are installed.

The high power RF is generated by a set of amplifiers, which are driven from a common crystal controlled source. The peak powers required are 0.5, 1.2 and 1.3 MW for the three tanks, respectively. Each tank has an automatic tuning system which maintains the phase of the accelerating fields correct to better than $\pm 1^{o}$, and an automatic level control system, which maintains the RF levels to better than $\pm$ 0.2%.

The anode voltages for the amplifiers are obtained from delay line modulators, operating at a duty cycle of 2%. Up to the present the pulse length has been 400 μs (at 50 c/s), giving a beam pulse length of 200 μs (1% duty cycle); 800 μs (at 25 c/s) is now also available giving 600 μs beam pulses (1.5% duty cycle).

The tanks are evacuated by oil diffusion pumps (ten 20" pumps) to pressures below 5×10^{-6} mmHg. The grounded grid triodes are pumped by Vacion pumps. There are several closed circuit water systems, one of which is maintained at 100°F to stabilise the temperature of the resonant cavities in the accelerating tanks.

In the 500 keV beam line there are (a) the deflector plates for the time of flight system (see below), (b) a buncher cavity, which gives a beam current gain of 2.8 and (c) focussing quadrupoles.

The machine is remotely controlled from the control room, where the operation of all parts of the machine and the beam handling apparatus of the experimental areas can be adjusted and monitored. Personnel are protected from the high voltages of the machine and from radiation produced by it by concrete walls and a comprehensive interlock system.

The polarized proton source was one of the first such sources to be used on an accelerator. (Design work started on the source in 1957 and it was installed on the P.L.A. early in 1961.) It has run for nearly 12,000 hours; about one-third of the total operating hours of the P.L.A. The source uses the Stern-Gerlach effect to select the negative magnetic moment states of an atomic hydrogen beam, which is produced by a radio frequency discharge and a multiple collimator. The selection takes place in a long sextupole magnetic field which "defocusses" all but a few per cent of the unwanted atomic states, giving a beam of 8×10^{15} atoms per second with a nuclear polarization of nearly 50%.

In the original source, the atoms were ionised in a low field ioniser, giving a proton beam of about 0.01 μA at 30% polarization (the loss of polarization is mainly due to ionisation of the residual gas). After acceleration to 50 MeV the original beam intensity was a few times 10^{7} protons/sec. In 1964 an adiabatic passage unit, which ideally would produce a 100% polarized atomic beam, and a high field ioniser were installed. These gave an immediate improvement in the beam and after several modifications have led to the present beam of 1 μA at the injector and 1.3×10^{9} protons per second, 53% polarization at 50 MeV. Further modifications are being studied in the laboratory.

TABLE II

Figure of Merit, IP^2, of the Polarized Proton Source

	Intensity (I)	Polarization % (P)	IP^2
March 1961	1.5×10^7	31	0.015×10^8
May 1961	6×10^7	32	0.06
January 1964	2×10^8	35	0.25
April 1966	7×10^8	62	2.7
December 1966	1.3×10^9	53	3.6

The time of flight system on the P.L.A. makes use of the fine structure of the proton beam; each fine structure burst is 0.3 nsec long. Since the 4.95 nsec burst separation is too short for time of flight work it is increased by scanning the 500 keV proton beam across an aperture at the entrance to tank 1 by means of deflectors powered at frequencies which are sub-multiples of the machine RF. The burst length entering tank 1 is less than one RF cycle long; thus isolated fine structure bursts are accepted by tank 1 and because of phase oscillation damping in the accelerator become 0.3 nsec bursts at the output of tank 3. By the time the target is reached the burst length has usually increased to 0.6 nsec due to effects from energy spread.

For neutron experiments with a flight path of 10 metres energies down to 10 MeV can be measured. The overall time resolution including that due to the detectors and associated electronics is 1.2 nsec.

3. Operation and Scheduling

During 1960 and 1961 the machine was scheduled for 12 and 16 hours per day, respectively. This accounts, partly, for the low total operating hours during these years; the other reasons are poor reliability and long shut-downs for installation of new and improved equipment. Since 1962 the machine has been scheduled for 24 hours per day with at first 2 days per week for maintenance and recently 1 day per week, on the average. Normally the machine runs for 12 days during which time 1 to 4 experimental teams have a "run", then there are two days for setting up experimental apparatus, for maintenance and for installation of equipment. There is usually a shut-down around September each year for major modifications.

The machine is operated by two technicians on each shift of 8 or 12 hours. The experimenters take no part in the operation of the machine, but there is close co-operation between the operators and the experimenters to ensure that the desired beam conditions are maintained and that the machine is operated without hazarding personnel or equipment. The accumulated experience of the operators leads to quick recognition and repair of faults in the machine and beam handling equipment.

The scheduling of the machine is discussed on alternate Wednesday afternoons at a scheduling meeting, which is attended by experimenters from the visiting teams and by resident physics and engineering staff. The nuclear physics group is responsible for co-ordinating the needs of the experimental teams, while the engineering group provides a very valuable and much sought after service to experimenters for the design, manufacture and installation of experimental equipment.

4. Machine Development: The Future

In addition to the work concerned with improving the existing machine, the P.L.A. staff have studied ideas aimed at adding new facilities to the machine, and at advancing the knowledge of linear accelerator design.

The accelerator physics group has co-operated with C.E.R.N. on the design study of the injector linac for the proposed European 300 GeV machine. A 200 MeV linac was studied, and optimised parameters evaluated. At the same time, new accelerating structures were studied, and one of the staff spent 18 months at C.E.R.N. developing the cross-bar accelerating structure and proton dynamics computing programmes. There has been frequent and mutually fruitful co-operation with several laboratories in the U.S.A. and several physicists have spent periods of up to one year working there: similarly, several U.S. accelerator physicists have been welcome visitors at the P.L.A. Assistance has been given to a laboratory in Warsaw on the design of a 10 MeV linac. Similarly, the design of a new tank 1 (see below) has been used in Saclay as part of a new injector linac for Saturne and may be used on other machines proposed in Europe and the U.S.A.

Discussion of machine improvements may perhaps be prefaced by a summary of the unique advantages and limitations of the P.L.A. These are:

(a) The output, bunched in 0.6 nanosecond bursts, has been extensively used in the neutron time of flight experiments.

(b) The development of the polarized proton source has given the P.L.A. a clear lead over all other machines in polarized proton nuclear structure physics.

Against these advantages are the following limitations:

(c) The energy is limited to the three fixed values of 10, 30 and 50 MeV; variation by degradation, or RF distribution variation, is a possible but not an ideal solution.

(d) The duty cycle, now 1.5%, is low compared with the cyclotron's 10 - 20% and the electrostatic generator's 100%.

(e) The energy spread - 250 keV F.W.H.H. at 50 MeV - is larger than some cyclotrons in the same energy range.

(f) Acceleration is effectively limited to protons.

The question of machine improvement is the subject of regular discussion in the P.L.A. Division and notes of one such discussion are given in Appendix I. These may be summarized by saying that of the above limitations (c), (d) and (e) can be removed but (f) must remain, i.e. work with deuterons or He^3 must be done elsewhere (the propinquity of the V.E.C. is to be noted). Proposals related to the other limitations divide into two parts: changes which can be absorbed into the R & D budget, and those requiring capital support. Under the former heading can be noted:

(1) Ion sources. Both polarized and unpolarized beams have increased in intensity by a factor of two or more during recent months: a substantial increase in the latter is possible with the development of a duoplasmatron source.

(2) Division and subdivision of tanks 2 and 3. The provision of one or three dividing partitions will, at a relatively small cost in RF power, decrease the gap between the available energies from 20 to 10 or 5 MeV, i.e. the beam energies would become 10, 20, 30, 40 and 50 MeV or 10, 15, 20, 25, 30, 35, 40, 45 and 50 MeV.

(3) Because of the greatly improved machine stability, studies along several lines have been made of means of reducing the beam energy spread. These include double-buncher injection, to reduce primary phase spread: phasing and RF control in tank 1, again to reduce emergent phase spread: and the transfer of the buncher cavity (originally before tank 1) to a position after tank 3, where it will be employed as a debuncher. It is expected that the debuncher will reduce the energy spread by a factor of 1.85 at 30 MeV and 2.7 at 50 MeV and the overall effect of the combined changes will be greater.

The changes requiring capital expenditure include: a new tank 1 liner, replacing grids with quadrupoles; this would increase the intensity by a factor of at least 5. This proposal, fully supported by engineering designs, was completed in 1964: the most recent cost estimate was £80,000.

Increase of the RF duty cycle to 6% would increase the duty cycle of the output beam to 5%. This proposal, estimated to cost £80,000, would be installed in 18 - 24 months' time. Preliminary tests have confirmed the feasibility of this project.

In addition to these proposals, two others have been considered, but have not yet been fully detailed and costed. One is an on-line computer for experimental nuclear physics for which the cost would be in the region of £40,000: the other is a beam analysing magnet, which would be expected to reduce the energy spread to the order of 20 keV and would cost about £20,000.

In the present situation it may be difficult to foresee how these proposals could be financed. It should be made clear, however, that if they were carried through, the increase in machine potentiality would be considerable.

The mean current of polarized protons would be 10^{-8} amps (i.e. the order of current likely to be available on the Berkeley and Oak Ridge cyclotrons in some 2 - 3 years' time). The mean current of unpolarized beam, increased by between 10 and 100, could be used or modified in a variety of ways. For the neutron experiments, an increase of 100 would allow a whole new range of experiments to be performed in reaction studies. A negative ion source, of intensity one-tenth of the present source intensity, would eliminate the problem of slit-edge scattering in the beam analysing system: for high resolution, slit-edge scattering is a major problem. (In passing, it should be noted that with negative ions a small tandem would give continuous energy variation over a slightly wider energy range.) Increased intensity would be particularly valuable for measurements of triple scattering parameters, and possibly also p-d experiments using a polarized deuterium target. The availability of the computer and a 5% duty cycle would make possible correlation studies of two product particles. Compared to machines in the same energy range, the limitations (c), (d) and (e) above would effectively cease to exist.

B NUCLEAR PHYSICS ON THE P.L.A.

In the next three sections the experiments which have been performed using the P.L.A. will be reviewed. Further details of all experiments can be found in the P.L.A. progress reports which have been published each year from 1961 to 1966 and which cover all the work performed since the P.L.A. became available for nuclear physics experiments. These reports also cover work carried out by theoretical physics groups in association with the P.L.A. The majority of theoretical papers are from the University of Surrey (formerly Battersea College of Technology) but Dr. Hodgson's group at the University of Oxford has also collaborated in the analysis of experiments using the Optical Model.

In order to keep the description of experimental work in a convenient and concise form the names of experimenters or teams carrying out individual experiments have been omitted. A list of the teams using the P.L.A. and their related fields of interest is given in Appendix II.

1. Few nucleon problems

(a) Nucleon-Nucleon Scattering

There has been associated with the P.L.A. a very active programme of work on the proton-proton interaction. Early measurements included the polarization at 45° (c.m.) for 30 and 50 MeV and a measurement of the D parameter at 50 MeV. These measurements considerably improved the accuracy with which some of the phase-shifts were determined. Later experiments included a very comprehensive set of measurements of the A and R parameters at several angles at 48 and 28 MeV. In these measurements the complete flexibility for choice of spin directions for the proton beam from the polarized proton source played a very important part. Other experiments included a development of the polarization experiment apparatus to make precise measurements of the cross-section for proton-proton scattering at 90°(c.m.) between 20 and 50 MeV. These techniques were later used together with the double focussing spectrometer in a high precision (0.5%) measurement of the differential scattering cross-section over the angular range 13° - 90°(c.m.) at 50 MeV.

Throughout this work there has been a very close collaboration between the various experimental teams and Dr. J. K. Perring of A.E.R.E. who has been responsible for several phase-shift analyses of the results. The scattering phase-shifts in the 30 and 50 MeV energy regions are now known very precisely and much of the success of this work has been due to the close collaboration between experimentalists and theoreticians.

The problem of determining the corresponding phase-shifts for neutron-proton scattering is much more difficult. Work on this problem at the P.L.A. has been concerned with the discovery of suitable polarized and unpolarized neutron sources. Measurements on (p,n) reactions using the neutron time of flight technique have shown that the D(p,n)2p reaction may be the most convienient unpolarized neutron source as it has in the forward direction a sharply peaked energy spectrum. However measurements using an incident polarized proton beam have shown that neither this reaction nor the $Li^6(p,n)Be^6$ or $Li^7(p,n)Be^7$ reactions are likely to be useful as sources of polarized neutrons.

(b) Interactions with Deuterium and Helium

The work on the P.L.A. associated with very light nuclei has almost entirely been concerned with deuterium and He^4. Some of the earliest measurements were on the D(p,2p)n reaction in which the energies of the two outoging protons were measured in conincidence. The measurements which were made with scintillation counters could now be considerably improved with the general availability of semiconductor counters and faster electronics.

More recently measurements using the spectrometer magnet have been made of the differential cross-section and polarization for elastic proton-deuteron scattering at 30 and 50 MeV. Whilst the cross-section measurements show a reasonable agreement with theoretical calculations there is no semblance of agreement for the polarization results. In order to assist in the theoretical interpretation of these results a phase-shift analysis is to be made.

Measurements of the differential cross-section and polarization have also been made for p-He^4 scattering at 22 MeV, 29 MeV, 40 MeV and 48 MeV and have been included in a phase-shift analysis made by a member of one of the experimental teams of all p-He scattering data in this energy region. These phase-shifts have been used to calculate the polarization in n-He^4 scattering in this energy region for use in the experiment to measure the polarization of neutrons produced in (p,n) reactions.

As an extension of this work measurements of the polarization have recently been made over a very wide angular range for p-He^4 scattering at 5 closely spaced energies between 25 and 29 MeV. The purpose of this experiment is to investigate the possibility of a resonance at 27.5 MeV due to a level in the mass 5 system. Differential cross-section measurements have still to be made but the polarization results show a slight but noticeable variation in the expected energy region.

Measurements have also been made at ten angles of the spin rotation parameter β in p-He^4 elastic scattering at 48 MeV. Measurement of the parameter β rather than the usual measurement of R or A has the advantage that the result is independent of the value of the incident beam polarization and the analysing power of the polarization analysers used to measure the asymmetries providing these remain constant. The results have been included in the phase-shift analyses discussed above and assisted in eliminating some of the alternative phase-shift solutions.

2. Elastic and Inelastic Proton Scattering

(a) Optical model for spherical nuclei

A very considerable amount of work has been done using the P.L.A. to study elastic and inelastic proton scattering. In view of the early interest of several experimental teams in this topic it was agreed that they should collaborate in a study of certain selected isotopes at both 30 and 50 MeV for use in a subsequent analysis by the optical model. Each team would then be responsible for one set of measurements e.g. polarization on the whole range of isotopes. For these investigations it was decided to choose nuclei such that the optical model assumptions of closely spaced levels and spherical shape would be most nearly met. A further practical consideration was that the first excited state should be sufficiently removed from the ground state so that elastic and inelastic processes could be clearly resolved with scintillation detectors. The nuclei finally chosen were Ca^{40}, Fe^{56}, Ni^{58}, Co^{59}, Ni^{60}, Sn^{120} and Pb^{208}.

Measurements of the polarization differential scattering cross-section and reaction cross-section have been completed at both 30 and 50 MeV. All the data at 30 MeV have been published together with an optical model analysis of the data by Dr. Hodgson's group at Oxford University. The data has also aroused considerable interest at other laboratories and has also been analysed further by Satchler et al at Oak Ridge and Greenless et al at Minnesota. It was in fact these experiments which provided some of the first evidence for a small spin-orbit potential radius and gave much of the stimulus for the work on the relationship between the matter distribution and optical model potentials. All the measurements have been completed at 50 MeV and the final analysis of the raw data is almost complete.

(b) Non-spherical nuclei

The nuclei chosen for the collaboration on the optical model had near-spherical symmetry. Measurements have recently been started on a range of nuclei which have large deformation parameters β and the data will be analysed using the strong coupling approximation. The nuclei chosen were $Zn^{64,66,68,70}$ and Cd^{114}. The data for the zinc isotopes will also be used in an analysis to learn more about the isotopic spin dependence of the optical model potentials.

Measurements have been made of elastic and inelastic scattering cross-sections for the nuclei Ti^{50}, V^{51} and Cr^{52}. These nuclei are interesting because they have 22, 23 and 24 protons respectively together with a closed shell of 28 neutrons. Simple theory indicated that the angular distributions for the first five excited levels of V^{51} should have the same shape as the angular distributions from the first excited states of Ti^{50} and Cr^{52}. This prediction agrees with the experimental results, but the intensity ratios do not agree with the theoretical calculations. The nuclei are also distorted and again the results will be analysed using the strong coupling approximation.

The polarization of 30 MeV protons scattered elastically and inelastically from Fe^{54} has also been measured. In this case the motivation is to study the way in which the polarization data are sensitive to the configurations of the initial and final states involved in the transition. In the case of Fe^{54} due to the configurations of the states involved only orbital angular momentum may be transferred the transfer of spin angular momentum being forbidden. DWBA calculations in which the effective interaction is taken to be a real Yukawa potential do not agree with the experimental results and it has been suggested that a complex interaction may be required.

These inelastic scattering polarization studies are also being applied to p-shell nuclei and in particular Be^9. Polarizations and differential cross-sections have been measured for elastic and inelastic (2.43 MeV) scattering. Analysis of the data is at present in progress.

Cross-sections and polarization angular distributions have also been measured for Mg^{24}, Li^6 and Li^7. In these cases the data are primarily required to obtain optical model potentials for elastic scattering. These potentials will then be used in DWBA analyses of reaction studies on these nuclei which are discussed in a later section.

(c) Special Studies

It is an essential feature of many experiments that the polarization of the beam from the P.L.A. should be known accurately. The polarimeters generally used on the P.L.A. degrade the energy of the incident protons to 15 MeV where they are scattered from carbon at 45°. The polarization at this angle and energy from carbon is large. A polarimeter of this type has been calibrated in a series of three scattering experiments using both the polarized beam and also the unpolarized beam in a double scattering experiment. This polarimeter was then used to calibrate the standard polarimeter situated at the end of Tank 3. The calibration of this polarimeter has more recently been checked in a comparison with p-He^4 scattering at backward angles at 10 MeV. The two sets of calibration appear to be in good agreement.

Measurements have also been made at various times by several different teams of the elastic and inelastic scattering of polarized and unpolarized protons by C^{12}. This information which is often required since carbon is a contaminant in many targets is of interest in its own right since the ground state and first excited 2+ state at 4.4 MeV are strongly coupled. Analyses of quite an extensive set of data have been made using both the optical model and strong coupling approximation with some success.

During the course of some of these measurements it was found that the polarization angular distribution near 30 MeV varied strongly as a function of energy. Data obtained at a closely spaced set of energies has now been successfully analysed in terms of a model which included both scattering from an optical model potential and from resonances in the compound nucleus N^{13}. Three resonances are found to be required to fit the data and their positions and widths are consistent with other data. In view of these results and the possibility of similar effects occuring in other nuclei polarization measurements have also been made on a range of targets at 25 MeV. C^{12} was the only nucleus in which resonance scattering appears to be significant in this energy region.

3. Nuclear Reactions

A considerable programme of nuclear reaction studies have been carried out using the P.L.A. For convenience these have been somewhat arbitrarily split into four sections.

(a) Pick-up Reactions

One of the earliest experiments carried out on the P.L.A. was a survey of pick-up reactions in a range of nuclei. A combination of E, dE/dx and time of flight measurements using scintillation counters were used to discriminate between the various particles. Despite the rather poor energy resolution available with these techniques the results were a useful preliminary to later experiments using the double focussing spectrometer.

In a later series of studies by the same experimental team using the spectrometer magnet measurements were made on (p,d) reactions on a wide range of even tin isotopes for excitations above the ground state up to 3 MeV. The results show not only the well-known l dependence but also for the $d_{5/2}$ and $d_{3/2}$ lines a significant dependence on the total angular momentum j. The analysis of this very large amount of experimental data is still in progress.

This dependence of the angular distribution on the j-value of the transferred nucleon has not so far been seen in the $C^{12}(p,d)C^{11}$ reaction. These measurements were later extended to measurements of the deuteron asymetries observed with incident polarized protons on C^{12}, O^{16}, Si^{28} and Ca^{40} targets. Asymmetry measurements have also been made for the $C^{12}(p,t)C^{10}$ reaction and large values obtained indicating the importance of spin-dependent distortions on the incoming proton and outgoing triton waves.

A C^{12} target has also been used in a study of the (p,He^3) reaction. A comparison of the results with DWBA fits has so far been unsatisfactory, but it is hoped that recent measurements of He^3 scattering by B^{10} will give more accurate optical model parameters for use in further DWBA calculations.

The (p,t) and (p,He^3) reactions have been used to locate T = 2 levels in Mg^{24} and Na^{24}, and T = 3/2 analogue levels in a range of (2s,1d) shell nuclei. The location of such levels is of considerable interest in tests of the validity of isobaric mass formulae relating the masses of nuclei within an isotopic spin multiplet and in the information which the coefficients of such formulae may reveal about the charge dependence of nuclear forces.

The (p,t) reaction has also been used to obtain the mass of Ca^{38} which was previously unknown. Information has been obtained for the first time about the level structure of this nucleus and compared with shell model calculations for A = 38 nuclei.

Studies of inelastic proton scattering and pick-up reactions have also been made for Mg^{24}. In this case the motivation is to study the effect of spherical deformation in the optical potentials used in DWBA calculations. The data is now almost complete but the results have yet to be analysed.

(b) Charge exchange reactions

The time of flight facility available with the Rutherford Laboratory P.L.A. makes it particularly well suited to a study of (p,n) reactions.

One of the earliest experiments concerned the D(p,n)2P reaction but as the results have been discussed earlier, no further mention will be made of this work. These early experiments, in which neutron spectra at 0° only were measured, were extended to medium weight and heavy nuclei. The results showed clear evidence for the excitation of isobar analogue states in nuclei as heavy as Uranium. Previous measurements had only shown that such states could be excited in light and medium weight nuclei. The results also showed a striking variation of the excitation cross-section with target atomic weight and incident proton energy. Calculations using the optical model with an isotopic spin dependent potential suggested that the results could be qualitatively explained in terms of a nuclear Ramsauer effect as has been used to explain variations observed in neutron total cross-sections.

More recently angular distribution measurements have been made for the excitation of isobar analogue states in a range of nuclei. Whilst neither the experiment nor theoretical analysis are yet complete, the results already show considerable evidence for a surface peaked form factor for the isospin dependent term in the optical model potential.

Isobar analogue states excited in a (p,n) reaction have $T = T_Z + 1$. Double analogue or $T = T_Z + 2$ states have also been observed in (p,n) experiments at the P.L.A. but the very small excitation cross-sections have precluded any angular distribution measurements.

Studies of the $Li^7(p,n)Be^7$ and $Li^6(p,n)Be^6$ reactions originally made as part of an investigation of possible high energy neutron sources have been extended to study the excited states of Be^7 and Be^6. Original measurements which indicated many excited states for Be^6 have now been shown to be in error and more recent results are in satisfactory agreement with other work. A full analysis of the data has still to be completed.

Measurements have also been made of the polarization of neutrons produced from polarized protons incident on D Li^6 and Li^7. The experiments are technically difficult but the results which are in satisfactory agreement with impulse approximation calculations show that none of these reactions are likely to be useful as a source of polarized neutrons.

(c) Capture and resonance reactions

An early experiment was the study of the radiative capture of protons by C^{12}. The results showed three regions of excitation in N^{13} where the radiative strength to the ground state is concentrated in agreement with theoretical predictions for the $T = \frac{1}{2}$ part of the dipole states in N^{13}. Similar studies were also made for the $N^{15}(p,\gamma)O^{16}$ reaction where a large capture cross-section was observed.

As an extension of these experiments measurements were also made of the γ rays from the $(p,p^1\gamma)$ reaction leading to the 15.1 MeV T = 1 state in C^{12}. The results showed a sharp peak in the excitation function at 20 MeV. Calculations using distorted wave theory showed that this peak could be associated with a resonance in a partial wave of the wave function describing the outgoing proton.

As an extension of these studies measurements have also been made of the angular distributions of inelastic protons in the reaction $C^{12}(p,p^1)C^{12*}$ again exciting the 15.11 MeV T = 1 level. Measurements were made at a series of proton energies between 20 and 30 MeV and especially in the region of the sharp peak observed in the earlier work at 20.5 MeV and in the region of weaker resonances at 22.25 and 25.5 MeV. The angular distributions were found to change dramatically with incident energy. The reaction was envisaged as the collision of the incident proton with a $p_{3/2}$ nucleon raising it to the $p_{1/2}$ state to give the 15.11 MeV level of C^{12}. For a 30 MeV incident proton the outgoing nucleon has an energy of 13 MeV and escapes immediately. At lower incident energies the energy of the outoging nucleon is low and may be strongly influenced by the distorting potential of the excited C^{12} nucleus. At an incident energy of 20.5 MeV it is found that an outgoing 1 = 2 wave resonates and at 26.0 MeV and $\lambda = 1$ wave resonates. This seems to be one of the earliest examples of the so called "doorway" states. The results are also in good agreement with calculations assuming specific configurations for the various compound levels in N^{13}.

Since the 15.1 MeV state in C^{12} is a member of the isobaric spin triplet having as its other two members the ground states of B^{12} and N^{12} it was thought interesting to study the process $C^{12}(p,n)N^{12}$ to see if this behaved in a similar fashion. The $\beta+$ activity of the N^{12} ground state, which has a half-life of 11 milliseconds, was detected using the repetition rate of the P.L.A. reduced by a factor of four so that beam bursts of 200µ.sec. duration were produced every 80 milliseconds. Whilst the shape of the $C^{12}(p,n)N^{12}$ and $C^{12}(p,p^1)C^{12*}$ excitation functions are similar at the higher energies the resonance observed near 20 MeV in the (p,p^1) results is not seen in the (p,n) data. This difference is thought to be due to the importance of coulomb effects on the slow outgoing proton in the (p,p^1) reaction.

Further studies have been made of capture reactions in a range of heavy nuclei using radiochemical techiques and induced activity measurements. The results did not show satisfactory agreement with either the statistical theory or with calculations describing the process in terms of radiative single particle transistions of the incident nucleon during its free motion in the complex nuclear potential field.

(d) <u>Multi-particle reactions</u>

One of the first series of experiments carried out with the P.L.A. was the study of (p,2p) reactions. The work mentioned earlier using a deuterium target was later extended to C^{12} and Ca^{40}. Severe problems were encountered due to the very small observed cross-sections but the somewhat limited results were in general qualitative agreement with distorted wave and impulse approximation type calculations.

The technique of using the pulsed beam from the P.L.A. to study short half life β emitter has also been used in a search for C^9 as a product of the reaction $B^{10}(p,2n)C^9$. The results indicated that if C^9 has a half life in the 20 to 100 ms. range then the cross-section for formation by this reaction must be less than 10 ub.

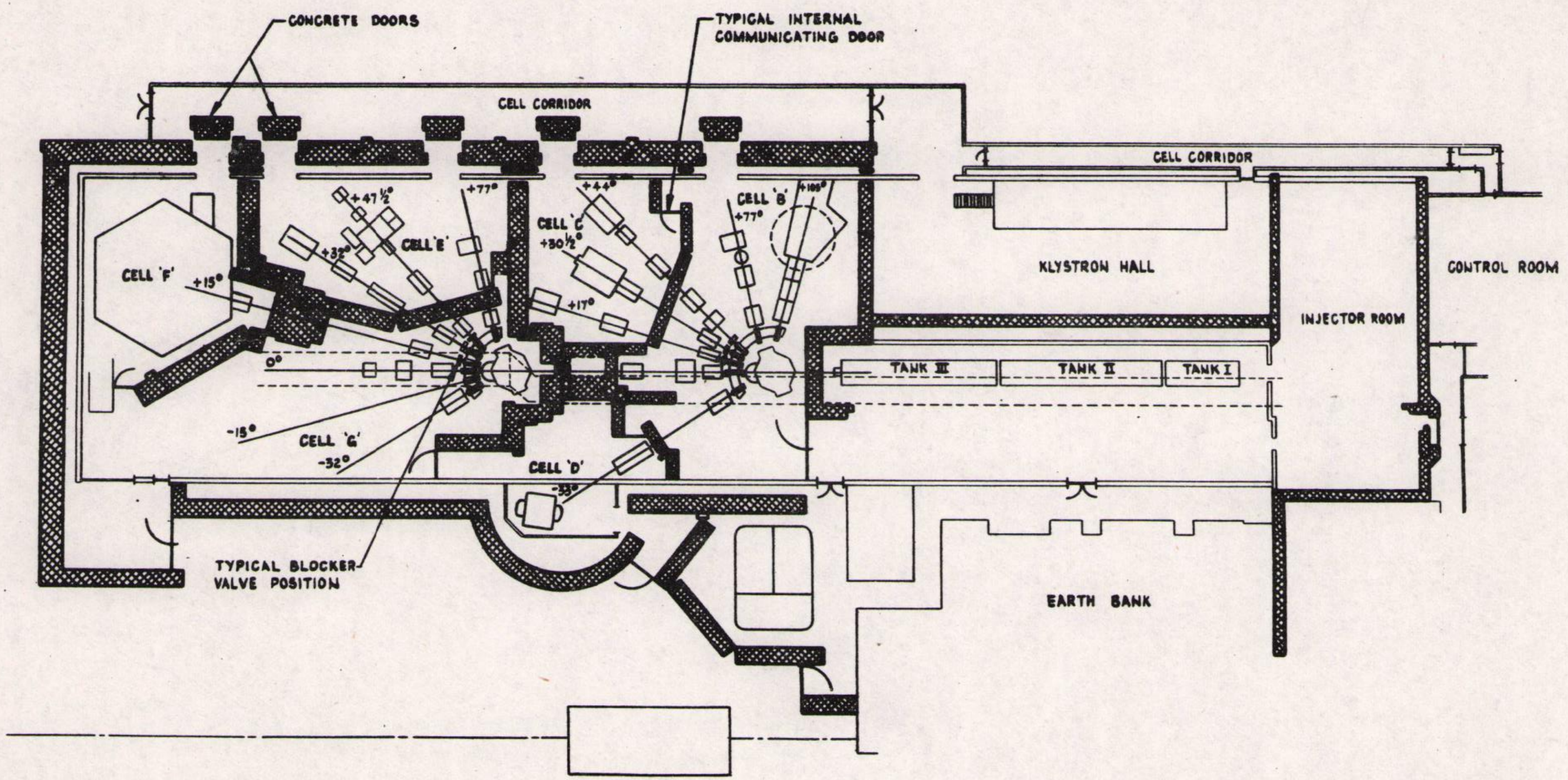
Measurements have been made on $(p,p^1\alpha)$ reactions in C^{12} and O^{16} to investigate both the levels which are excited in the (p,p^1) reaction and then decay by α emission and also as an indication of direct α knock out effects. In the case of O^{16} the results indicated a rather un-selective mechanism of excitation in which many levels are excited.

Some work has been carried out on proton induced fission. It has been shown that in Bi^{209} for an increase in incident proton energy from 30 to 50 MeV that roughly one third of the extra available energy appears as kinetic energy of the fission fragments in contrast with other experiments. It has also been confirmed that the relative ratio of ternary to binary fission does show a dip, so far unexplained, for excitation energies in the region of 20 MeV.

4. <u>Experimental Facilities</u>

The layout of beam lines at present available from the P.L.A. is shown in the figure . A magnet placed close to the end of the accelerator is used to direct the beam along any of the six beam lines in the first experimental area. A second bending magnet is used in a further experimental area giving a total of twelve beam lines each fitted with the necessary quadrupole magnets, available for experiments. One of these beam lines is permanently used by the neutron time of flight facility and a second by the double focussing spectrometer. The remaining beam lines are allocated between the experimental teams as necessary.

To improve accessibility to experimental apparatus whilst the accelerator is in use, the radiation shielding has been placed to form a set of six experimental cells. At present access is possible into cells C, D, E or F whilst the beam is being used in any other cell. Additional shielding is being installed so that access to cell B will also be possible whilst cell G has been left in its present form in view of the possible installation of a new improved beam line to the double focussing spectrometer.



Arrangement of shielding

Between the end of tank 3 and the first bending magnet are a number of items used to monitor the beam from the accelerator. The facilities available include instruments to monitor the beam current for high and low intensity proton beams, to measure the machine energy, to measure the magnitude of any transverse component of beam polarization, to degrade the beam energy by any required amount and to define the profile of the beam by inserting adjustable slits. The polarimeter uses a sampling technique and so can be used to monitor the average polarization of the proton beam during an experiment.

The bending magnet in cell G is used together with two sets of slits to provide a momentum analysed beam for the double focussing spectrometer. With the present arrangement a beam of 50 keV resolution (F.W.h.h.) can be obtained with an overall transmission of approximately 1%. This gives a maximum beam intensity of 0.05uA at the target. Both sets of slits are heavily shielded to cut down the radiation hazard. The first set of slits can also be used together with the bending magnet and further sets of slits to provide momentum resolved beams in cell E. This cell will shortly be provided with overhead shielding to allow the use of high intensity beams.

The spectrometer magnet is of the $n=\frac{1}{2}$ double focussing type. Its specification is given below:-

Mean radius of particle trajectories = 40 inches.

Current supply stability - better than $\sim$1 in 10^5.

Accuracy of angular setting - 2 minutes of arc.

Range of angular movement = $\pm$ 152°.

Acceptance solid angle = 2 millisteradian.

Constancy of solid angle during rotations =$\sim$0.2%

Maximum magnetic field at normal radius 17 Kg.

Maximum usable energy protons $\sim$150 MeV
deuterons $\sim$100 MeV
tritons $\sim$50 MeV

Resolution (50 MeV protons) $\sim$ 0.05%.

The magnet is utilised by several experimental teams and is used for about 40% of all the P.L.A. experimental time available. The detector systems are usually either wedge shaped scintillation counters for experiments at high counting rates with poor energy resolution or sonic spark chambers for good resolution at lower counting rates. Particle identification techniques using dE/dx scintillation counters are used to separate protons, deuterons and tritons.

The neutron time of flight facility can be used to measure the energy spectra of neutrons from (p,n) reactions over the angular range 0° to 80° in 5° steps. Flight paths of 6m and 10m are available and a 3 ft. thick concrete wall to reduce the background surrounds the target region. A magnet after the neutron producing target is used to clear the proton beam passing through the target from the forward direction and the beam is stopped in a well shielded beam catcher. The overall time resolution of the detector and electronics system is 1.2 - 1.5ns.

As an aid to experimental teams using the P.L.A. all the facilities described above have been fully documented in Rutherford Laboratory reports and memoranda.

RHEL/M 101. User guide to the P.L.A. double focussing spectrometer. Edited by F. J. Swales.

RHEL/M 109. User guide to P.L.A. beam line ancillaries.

RHEL/R 121. Ion Optics of the P.L.A. double focussing spectrometer.

5. Nuclear physics on the P.L.A: Future programme

The purpose of this section is to outline the way in which the research programme of the P.L.A. division and its visiting university teams can develop during the next three to five years and to assess the relevance of this work to the extension of basic understanding of nuclear structure and the nuclear many-body problem. Reference is made to certain experiments in progress or recently completed. Further details can be found in sections (a-c) above.

Research programme

(a) Optical model studies.

The analysis of the differential cross-section and polarization for elastic proton scattering at 30 MeV and 50 MeV has been a feature of the programme for several years. The data are fitted using computer programmes developed at Oxford, and in general satisfactory fits have been obtained although the parameters often do not vary in a systematic fashion. The experiments now in progress or planned include measurements on groups of neighbouring nuclei, e.g. the isotopes of zinc, molybdenum, tin, and samarium; such measurements are clearly necessary if a systematic variation of optical model parameters with mass number within a major shell is to be determined. The differential cross-section for inelastic scattering from the same nuclei is also measured, and the results are analysed in terms of the generalized optical model using the distorted wave Born approximation (DWBA) or strong coupling approximation (SCA) as appropriate.

In order to remove some ambiguities it is proposed to extend the experimental work to include measurements at small angles and at backward angles, and to measure the reaction cross-sections for the same nuclei. The latter measurement is particularly important since theoretical work at higher proton energies indicates that inclusion of σ_R among the data to be fitted has a significant effect on the optical potential obtained. An attempt will also be made to measure the spin rotation parameter in the elastic scattering of 50 MeV protons from Ca^{40}. Further experiments of this type are feasible on the PLA and may also serve to remove ambiguities in the optical potential. (see part 7(xviii)).

Despite the amount of work already carried out in this field the optical potential in the 30-50 MeV region is not well determined, even though the number of parameters has proliferated. Recently, however, there have been attempts, particularly by the Minnesota group, to find relationships between the parameters and to find a connection between the variation of the radial parameters of the optical potential and the variation of the matter distribution for neighbouring nuclei. The theoretical basis of these preliminary calculations is open to some criticism but the attempt to seek a more fundamental understanding of the parameters of the optical potential is undoubtedly valuable and is leading to further work on this problem.

The time-of-flight facility, which is the only one available in this energy region, makes possible the study of the charge-exchange reaction. The isobaric-spin dependent term in the optical potential may be investigated by analysing the angular distributions for the excitation of isobaric analogue states in medium and heavy nuclei. This work is in progress and indicates that in the 30-50 MeV region this term is peaked in the nuclear surface but further data and analyses are necessary to confirm this conclusion. A study is also being made of scattering from highly excited states observed as resonances in the compound nucleus system. Results for C^{12} have been successfully analysed and this work will be extended to other nuclei.

(b) Microscopic description of inelastic scattering and charge-exchange reactions

The measurements on inelastic scattering provide information about the structure of the target nucleus. In the description of the excitation by means of a collective model, the form factor of the interaction has a standard shape and a fit to the data yields a value for the deformation parameter. The differential cross-section is generally not sensitive to the form factor but there is good evidence that the polarization is extremely sensitive to the nature of the transition and that measurements of polarization will therefore yield much more information about nuclear structure. These measurements therefore lend themselves to a more detailed microscopic analysis in which the form factor is derived from a knowledge of the nuclear wavefunctions of the initial and final states and the effective nucleon-nucleon interaction. Thus, very careful measurements of elastic and inelastic cross-sections and polarization, again on neighbouring nuclei, can be the source of an increased understanding of the effective interaction inside nuclei and can provide a sensitive test of the nuclear models on which the nuclear wavefunctions are based. A large amount of theoretical work has been carried out, notably by Satchler at Oak Ridge, but more systematic analysis and experiment is required.

The charge-exchange reactions can provide further information on the isobaric-spin dependent part of the effective two-nucleon interaction. It is necessary to study the reactions in light nuclei since for these the quasi-elastic transition to the analogue state does not necessarily dominate. The time-of-flight facility will be used to study the charge exchange reaction in a range of 1p shell nuclei and the results will be analysed using a microscopic model and DWBA.

(c) Pick-up reactions

The programme to study the pick-up reactions (p,d), (p, He^3), (p,t), (p,α) is progressing rapidly. The detailed study of the (p,d) reaction on the tin isotopes has clearly indicated the power of this reaction to yield spectroscopic information and to test nuclear models. The j-dependence of the differential cross-sections has been established and is being used to make spin assignments. Neither this j-dependence nor the deuteron asymmetries measured in experiments on lighter nuclei are reproduced by the standard DWBA analysis. These difficulties appear to be particularly associated with the presence of a deuteron, and the theoretical studies of reactions involving deuterons indicate that a more detailed description of the structure of the deuteron is necessary than that given in the standard DWBA programmes. Further measurements on suitably selected nuclei and particularly of deuteron asymmetries are required.

Studies of multi-nucleon pick-up are being carried out in order to study levels of high isobaric-spin. Further studies of multi-nucleon pick-up are planned on groups of nuclei in the 1p shell and the 2p-1f shell, and these experiments are also likely to indicate weaknesses in the present theory. Very recently, experiments on the P.L.A. have indicated that large asymmetries are observed in the (p,t) reaction. This result again demonstrates the value of polarization measurements in studies of the mechanism of nuclear reactions.

In pick-up reactions, the shape of the angular distribution may often be used to identify the quantum numbers of the transferred nucleon or group of nucleons. It can be expected that polarization measurements will yield further possibilities for such identification. In addition, the recent proposal by Pearson and Coz, and by Levin, of relationships between the cross-section for pick-up and the elastic polarization is likely to stimulate further investigation.

(d) Few-nucleon problem

There has been continued interest relating to the few-nucleon problem. Work on proton-proton scattering is now complete and the phase shifts are known to a greater accuracy at 50 MeV than at any other energy above 10 MeV. Work on proton-deuteron scattering is continuing and is likely to be of increasing importance in view of current theoretical efforts to give a complete description of the three-body problem in terms of the two-nucleon interaction. Measurement of polarization in proton-deuteron scattering at 10 MeV is being planned at the suggestion of Professor Noyes of Stanford, and also measurement of triple scattering parameters. The scattering of the polarized proton beam from a polarized deuterium target is a possible experiment on the PLA and would provide information of great value.

There is currently considerable theoretical interest in the excited states of the 4 and 5 body systems. Following a phase shift analysis of p-α scattering in the energy range 14-48 MeV, the polarization is being measured over a wide angular range at 1 MeV energy intervals around the resonance energy of 27 MeV. Measurements on the He^4(p,n) and T(p,n) reactions are also planned.

The multi-nucleon pick-up reactions on the lightest 1p shell nuclei will form a bridge between the study of the few-nucleon problem and the nuclear many-body problem, and the analysis of such reactions should be approached from both points of view. It will be of particular interest to see where standard analyses in terms of DWBA without exchange break down.

(e) Coincidence experiments

With the increased duty cycle coincidence experiments on reactions such as (p,2p), (p,pα) would become feasible but it may be preferable that such experiments should be carried out on suitable cyclotrons in this energy range. However, the facility to carry out coincidence measurements such as (p,$p^1\gamma$) would greatly enhance the value of the programme relating to inelastic scattering.

Value of the programme

The above account has stressed the main lines of research in progress on the PLA. It is clear that all the topics mentioned are points of considerable theoretical interest and controversy, and can therefore be expected to be points of growth during the next few years. Certain experiments, notably those concerning p-d scattering, asymmetry in (p,d) and other pick-up reactions, and charge exchange in light nuclei, have been frequently called for by theoretical physicists to test or clarify the present theories. In addition, the programme entails the development of experimental techniques, the most important of which is the use of the polarized proton beam. It is only by continuing a wide range of experimental studies that unexpected features, such as j-dependence, are likely to be observed.

P.L.A. MACHINE DEVELOPMENT: Notes of a Meeting 27/30 January, 1967

For clarity, these notes are divided according as six separate beam requirements, together with corresponding plans for development: naturally, there is considerable interaction between the sections.

(1) Duty Cycle

The nuclear physics requirement on duty cycle depends on the experimental technique in use. For counter systems, with dead times of the order of 100 ns, a full 100% duty cycle would be usable (the 202.5 Mc/s fine structure of the beam due to the r.f. is ignored). For acoustic spark chambers as used on the $n = \frac{1}{2}$ magnet, where the dead time is of the order of 2 ms (and would at best be of the order 200 μs) a repetition rate of the order 500 c/s could be usable. Because time (about 200 μs) is taken to build up tank fields to operating level, the r.f. duty cycle is greater than the beam duty cycle; at present they are 2% and 1% respectively. Full or very large duty cycles are not feasible, both in terms of the cost of modification or running costs (the alternative of a storage ring with slow extraction would be technically very difficult). However, increases in duty cycle of the order 5 or 6 over the present 1% (beam) are entirely practicable.

Present Development

Modification to the P.L.A. to allow 400 μs, 50 pps or 800 μs, 25 pps operation is scheduled for the end of February, 1967. This will increase the beam duty cycle from 1 to $1\frac{1}{2}$%, with the same mean r.f. power. Modification to the r.f. system to allow 1,200 μs, 50 pps operation of Tank 1 is scheduled for April/May, 1967, and is part of a feasibility study for 6% (r.f.) duty cycle operation of the whole machine, (5% beam duty cycle). The beam current at 10 MeV will be increased by a factor of 5 and will be used in a polarized proton experiment in the near future.

The present trigger system has several limitations in terms of available facilities and maintenance. A new system is being designed based on a megacycle clock pulse with digital logic circuitry to time all trigger pulses on the machine, and will allow, inter alia, variable pulse lengths.

Future Development

The total electricity running cost for an installation is the sum of a fixed charge (based on peak demand) and actual consumption. For the P.L.A., with a high fixed installation charge, it is clearly better economics to run at high duty cycle. The ratio of total running cost to that of the present 2% r.f. duty cycle is 0.49 + 0.255 k, where k is the percentage duty cycle. For example, for 10% r.f. duty cycle the ratio is 3.04, and for 20% the ratio is 5.59. As indicated in the first part of this section, because the r.f. pulse length must necessarily be greater than that of the beam, the beam duty cycle is not a linear function repetition rate. Practically the limits lie between the pulse lengths allowable in pulse transformers and the mean r.f. power rating of components (there are also restrictions in terms of tank tuning and the risk of beating effects at varying repetition rates). Operation of the whole machine at 1,200 μs pulse length, 50 c/s repetition rate would be a good compromise between long pulse length and mean power rating, though it is thought that some variations on this combination are perfectly feasible.

A further improvement may lie in the more efficient utilisation of the beam. Use could be made of a beam splitter to feed the beam to two experiments. Beam splitting could be achieved by use of an r.f. separator, perhaps in combination with a thin magnetic or electrostatic septum. A second possibility lies in slow switching of the beam by a pulsing magnet at the position of the present first bending magnet. Such systems could be very useful in main and parasite experiments (for example, counter calibration) or 'single shot' experiments in radiochemistry.

(2) Intensity

The intensity of the unpolarized 50 MeV beam has recently been increased from 3 μA mean to 5 μA mean. These values are adequate for most uses, the main exceptions being experiments using the time-of-flight facility, and experiments at backward angles at the $n = \frac{1}{2}$ magnet (but here there is a radiation problem also). Present levels are also acceptable for nuclear chemistry, though in the near future much higher levels could be used. There is thus a need for increased intensity, especially together with better resolution.

Present Development

The present ion source is an r.f. plasma discharge type, delivering about 8 mA. Development is aimed at increasing reliability (by reducing sputtering), and improving emittance (the recent increase in intensity at 50 MeV is due mainly to a reduction in input beam emittance). Work to uprate the intensity is being done on the present source and on one based on the type in use on Nimrod.

Future Development

When satisfactory reliability is achieved on the present source, future effort will be on the duoplasmatron source, where the discharge is supported by a large arc current, rather than r.f. fields. Whilst there is no evidence that the emittance is better than for an r.f. source, the output intensity can be several hundred milliamps (at low duty cycle). A more modest intensity of 50 mA at the P.L.A. duty cycle is within the capability of the duoplasmatron source. Such a beam, with trimming in the P.L.A. itself and in the beam lines, will still give a higher intensity at the target, together with better resolution.

A further method of increasing intensity lies in the use of a new Tank 1, for which a design was presented in the P.L.A. Progress Reports 1963, 1964. Due to the use of quadrupole, rather than grid, focussing, the acceptance would be up to 5 times greater than in the present Tank 1.

(3) Energy Spread

At present the energy spread is about 400 keV (full width) at 30 MeV, and about 500 keV at 50 MeV. An energy spread of 10 - 20 keV is desirable, since at this level the energy resolution of the beam is compatible with the maximum energy resolution of target and detector systems.

Present Development

There are several projects aimed at reducing the energy spread.

(a) A redesign of the low energy (500 keV) drift space; this will include monitoring apparatus (e.g. beam emittance unit, four-jaw boxes, analysing maget, lithium fluoride target, attenuator) to lead to greater beam control; two beam transport triplets; a new double-gap buncher (due to be installed in February, 1967); and a phase limiting device (i.e. a beam deflector in combination with the buncher, or a new system using a double-drift buncher). This project is due for completion in September, 1967, and is more fully described in P.L.A. Progress Report 1966.

(b) A study to determine the optimum E-field shape in Tank 1 (and later Tanks 2 and 3) to limit the overall energy acceptance. Beam from the phase limiting device will be trimmed during its passage through Tank 1 to give a beam of small energy spread at output. (It is clear that a new Tank 1, with its greater acceptance, would allow easier beam control). An advantage of this system is that beam is lost at low energy rather than at 30 or 50 MeV in the beam lines.

(c) A higher intensity ion source to compensate for beam lost in Tank 1 (see section (2) above).

(d) A new beam line to the $n = \frac{1}{2}$ magnet. The beam line resolution ($\Delta E/E = 0.1\%$) for the present momentum selection system is insufficient to take full advantage of the resolving power of the $n = \frac{1}{2}$ magnet. A new beam line is being designed which will allow better resolution (by a factor 2.5), and yet maintain the present transmission factor. Additionally, the effects of slit-scattering will be reduced.

Future Development

A debuncher to reduce energy spread was suggested for use on the P.L.A. in 1962. At that time the technical difficulties were regarded as very serious, particularly those of phase and amplitude stability. (A 1% change in amplitude, or a 0.6° change in phase, leads to a 5 kV energy change). It would now be an entirely feasible project: the vacuum envelope could be that of the old buncher, (though the cavity itself will be considerably modified); the r.f. power could be derived from the present drive for Tank 1 when the new 1,200 μ.sec. drive is installed, and this will allow both phase and amplitude control at the required 100 kW (max.) level.

Based on present figures for the beam, a debuncher positioned 15 m. from the end of Tank 3 will reduce the energy spread at 50 MeV by a factor 2.7, to about 90 keV (F.W.H.H.). It will also reduce the energy spread of the 30 MeV beam by a factor 1.85, i.e. to about 105 keV (F.W.H.H.). These figures could be improved somewhat by actually increasing the energy spread (reducing phase spread) from the P.L.A., this can easily be achieved by setting the levels of Tanks 2 and 3, in conjunction with a "shaped E-field" Tank 1.

(4) Variable Energy

A completely variable energy is clearly very desirable. The P.L.A. has output energies of 10, 30 and 50 MeV, variable by ± 1 MeV at 30 MeV, ± 1½ MeV at 50 MeV by adjusting the appropriate tank tilt tuners. Complete variation can be achieved over 50 - 30 MeV and 30 - 10 MeV by the use of degraders, with the disadvantages of increased energy spread, and divergence, leading to beam loss.

Present Development

None.

Future Development

Tanks 2 and 3 have four frequency tuners each, placed symmetrically along their lengths. It would be possible to divide each tank into four by using partitioning plates from liner to the centres of the appropriate drift tubes, and to drive each quarter separately. With the appropriate sections switched in, output energies of 10, 15.3, 20.0, 25.6, 30.0, 34.9, 39.8, 45.0, 50.0 MeV could be obtained. Finer division by the use of degraders would produce less energy straggling than that now produced.

Additional r.f. power would be required to compensate for the loss due to the dividing plates, 117 kW for Tank 2, and 103.5 kW for Tank 3, and which is readily available. Four separate feeds to each tank would be required, but, with the present r.f. system, is not too difficult. With the tanks divided into (approximately) equal length sections, a frequency tuner would control a section in the same way that the four together control a tank. Separate tuner systems may not be necessary, since the present tank tuning system could be switched to each section in sequence.

A second possibility would be to divide the tanks in two, to give output energies 10, 20, 30, 39.8, 50.0 MeV. Less additional r.f. power would be require (39 kW for Tk. 2, 34.4 kW for Tk. 3); the r.f. feed problem would be considerabl simpler, (since each tank is at present fed from two valves combined into one fee where there would be one valve driving one section; and the frequency tuners would be used in pairs to give both frequency control, and tilt tuning.

In either of these possibilities there will be some gain in pulse length due to the lowering of the tank Q valves. Further, with shortened sections, the transient response of the tanks will be smaller so that the beam loading effects of the projected increased beam intensity will be smaller, with consequent improvement in beam pulse length and quality. The choice between them lies between the cost of modification, and the acceptable reduction of beam quality produced by degraders.

A further possibility lies in the use of the first scheme above, together wi a negative ion source at the input to the machine, and a 2.5 MeV tandem accelerat at the output. Such a combination would allow complete energy variation up to 55 MeV, so that there is an additional bonus of a modest increase in output energ Such a tandem accelerator would be expected to be about 4 feet diameter by 9 feet length so that installation would not be a serious problem.

(5) Other Particles

The ability to accelerate particles other than protons has been considered. Some experiments were made to accelerate deuterons through Tank 1 in 1965, but ve low currents (of the order 10^{-12}A) were achieved, certainly much less than in similar experiments with the C.E.R.N. Injector (which has a quadrupole focussed Tank 1) where 7 mA peak were accelerated. In principle the P.L.A. is capable of accelerating other ions, in particular Helium 3 ions, α- particles. Whereas protons are accelerated in the 2π-mode (i.e. 1 cell transit/r.f. cycle), D, He^3, and He^4 must use the 4π-mode. (It is in fact possible to accelerate He^3 in the 2π-mode, when the normal field gradient must be increased by a factor 1.5: it is doubtful whether this power is available, that Tank 1 in particular could withstand voltage breakdown, or that the 1.5 MeV necessary for injection could be readily provided). In the higher modes of acceleration, the acceptance is very much reduced, both in the longitudinal and radial planes. Again it is clear that a quadrupole focussed Tank 1 could do better than the present gridded one.

Present Development

In conjunction with computations on field shaping for Tank 1, work is being done to investigate the motion of the ions mentioned above.

Future Development

None.

(6) Polarized Protons

A high intensity beam with as high polarization as possible, is required. At present the P.L.A. produces a polarized beam of intensity 1.3×10^9 proton/sec., with polarization just over 50%. With the increase of beam duty cycle to $1\frac{1}{2}$% with 800 μs, 25 c/s operation, the intensity will be 2×10^9 proton/sec.

Present Development

Work is being done to increase the intensity of the atomic hydrogen beam, by use of collimators other than the present capillary type. This should lead to increases in intensity and polarization of the accelerated beam. It would benefit any type of collimator, including that now used, to rearrange the vacuum system in the P.P.S. terminal. This will be done when the final choice of collimator is made. A microwave (2,450 Mc/s) power source for the dissociator is being built for use should the collimator development work necessitate the use of higher pressure discharges than the existing 20 Mc/s supply is capable of sustaining. With these developments, an overall improvement of a factor 2 in the figure of merit IP^2 (at 1% duty cycle) is thought likely. Small improvements continue to be made to the ioniser, though no changes to its basic principle are contemplated. A precession device to provide non-vertical spin directions is being developed.

Future Development

With the operation of Tank 1 in the near future at 1,200 μ.sec., 50 c/s will give 6.5×10^9 protons/sec. at 10 MeV. Though there might be some risk of beam depolarization by using a new quadrupole focussed, Tank 1, the overall acceptance might be 5 times greater than with the present Tank 1, as indicated in Section (2). As far as sources are concerned, a Donally type P.P.S. is worth consideration. The Donally source operates by selective quenching of hydrogen atoms in the metastable $2S_{\frac{1}{2}}$ state, and produces a beam of negative ions. Though obviously well suited to a tandem Van de Graff accelerator, it could be used on the P.L.A.

EXPERIMENTAL TEAMS

1. A.E.R.E., Harwell (1960-1967)

Pick-up reactions using both E, dE/dx counter techniques and spectrometer magnet. Measurement of elastic scattering cross-sections and reaction cross-sections for optical model analysis.

2. Birmingham University (1960-present)

Polarization measurements for elastic and inelastic scattering on a wide range of nuclei at various energies.

3. Exeter University (1960-1962)

Miscellaneous irradiations for beta- and gamma-decay studies.

4. King's College, London (1960-present)

Elastic and inelastic polarization and differential cross-section measurements using spectrometer magnet. Slit scattering studies and measurement of reaction cross-sections.

5. Manchester University (1964-present)

Study of elastic and inelastic proton scattering from lithium isotopes

6. Oxford University (1960-present)

Measurement of radiative capture and inelastic scattering for light nuclei. Investigation of (p,d) and (p,t) reactions using polarized and unpolarized protons. Study of isobaric mass formulae using (p,t) and (p,He^3) reactions.

7. Oxford University - Radiochemistry (1960-1963)

Study of radiative capture using radiochemical techniques.

8. Oxford University (1964-1965)

Measurement of reaction cross-sections.

9. Queen's University, Belfast and Westfield College, London (1960-present)

Study of (p,2p) reactions. Cross-section and polarization measurements for p-d scattering. Work on (p,t) and (p,He^3) reactions.

10. Queen Mary College, London (1961-1965)

Measurement of A and R parameters for p-p scattering at 30 and 50 MeV.

11. Rutherford Laboratory and Queen Mary College - Team I (1961-present)

Cross-section and polarization angular distributions for p-He scattering. Measurement of polarization transfer in (p,n) reactions with incident polarized protons.

EXPERIMENTAL TEAMS (cont'd)

12. Rutherford Laboratory and Queen Mary College - Team II (1960-present)

Cross-section and polarization measurements for p-p scattering. Neutron time-of-flight measurements on excitation of analogue states and on the excited states of F^{16}, Be^{6} and Be^{7}.

13. Rutherford Laboratory (Radiochemistry) (1964)

Proton induced fission.

14. University College, London (1960-1966)

Measurement of D parameter for p-p scattering, beta parameter for p-He scattering. Precision measurement of differential cross-section for p-p scattering.

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M. Devine	Measurement of the "A" and "R" Parameters at 30 MeV. Ph.D. London University, 1965.
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* A. J. Cole, Plessey Ltd., Roke Manor, Romsey, Hants.
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APPENDIX VI

PAPERS PRESENTED AT CONFERENCES

Papers read at the Rutherford Jubilee International Conference, Manchester, September, 1961.

E. J. Burge	Theoretical Investigation of Slit Scattering.
P. E. Cavanagh C. F. Coleman G. A. Gard J. F. Turner	Complex Reactions Induced by 30 MeV Protons.

International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 3rd - 8th September, 1962.

C. J. Batty R. S. Gilmore	Preliminary Measurements of the Neutron Spectra at 0° from the Bombardment of Nuclei by 30 and 50 MeV Protons.
P. E. Cavanagh C. F. Coleman J. F. Turner B. W. Ridley G. A. Gard	Cross Structure in (p,t) and (p,d) Reactions at 30 MeV.
G. A. Gard A. G. Hardacre B. W. Ridley J. F. Turner	Total Proton Reaction Cross-Sections at 28.5 MeV.
R. J. Griffiths K. M. Knight W. R. Gibson A. R. Johnston	Shell Structure in Direct Interactions at the Nuclear Surface.
L. R. B. Elton	Direct Interactions in the 100-200 MeV Region.
Miss D. F. Jackson	Exact Distorted Wave Calculations in Direct Interactions.

Conference on Linear Accelerators, Brookhaven, U.S.A., August, 1962.

K. Batchelor	50 MeV P.L.A. at the Rutherford Laboratory. Design of Long iris-loaded Linacs. Superconducting Linacs. Beam Observations in the P.L.A.

The Institute of Physics and the Physical Society Conference on Low Energy Nuclear Physics, Harwell, September, 1962.

L. R. B. Elton	Core Deformation and Quadrupole Moments of Light Nuclei.
R. S. Gilmore C. J. Batty G. H. Stafford	Measurement of the Polarization in Proton-Proton Scattering at 30 and 50 MeV.
R. J. Griffiths K. M. Knight W. R. Gibson A. R. Johnston	Shell Structure in Direct Interactions at the Nuclear Surface.

C. F. Coleman P. E. Cavanagh B. W. Ridley J. F. Turner	Pick-up Reactions at 30 MeV.
C. J. Batty R. S. Gilmore G. H. Stafford	Preliminary Measurements of the Neutron Spectra at 0^{o} from the Bombardment of Nuclei by 50 MeV Protons.
P. E. Cavanagh C. F. Coleman G. A. Gard	Two Nucleon Pick-up at 50 MeV.
R. A. Giles E. J. Burge	The Measurement of Total Reaction Cross-Sections of Carbon and Argon in the Energy Region 10-50 MeV.
G. A. Gard A. G. Hardacre B. W. Ridley J. F. Turner	Total Proton Reaction Cross-Sections at 28.5 MeV.
D. F. Measday P. S. Fisher A. Kalmaykov F. A. Nikolaev A. B. Clegg	The $^{12}C(p,\gamma)^{13}N$ Reaction from 10 to 50 MeV.
E. M. Rimmer P. S. Fisher	The $^{15}N(p,\gamma)^{16}O$ Reaction with Protons from 15 to 35 MeV.
R. A. Giles E. J. Burge P. E. Hodgson	The Measurement of Total Proton Reaction Cross-Sections in relation to the Optical Model.
J. C. Dore R. M. Craig J. S. Lilley P. C. Rowe	Polarization Studies with 30 MeV Protons.
B. W. Davies M. K. Craddock R. C. Hanna	Measurement of Polarization in p-α scattering.

International Conference on High Energy Accelerators, New York, September, 1961.

J. M. Dickson	Supercooled Proton Linear Accelerators. The Polarized Proton Source of the Rutherford Laboratory Linear Accelerator.

Institute of Physics and Physical Society Conference on Low and Medium Energy Nuclear Physics, Manchester, September, 1963.

R. M. Craig J. Dore J. S. Lilley J. Lowe P. C. Rowe	Polarization in the Elastic Scattering of 30 MeV Protons from Ca^{40}, Co^{59}, Ni^{58}, Ni^{60}, Sn^{120} and Pb^{208}.
C. J. Batty R. S. Gilmore G. H. Stafford	Excitation of Isobaric States in (p,n) Reactions at 30 and 50 MeV.
J. A. R. Griffith C. J. Batty R. S. Gilmore G. H. Stafford	Excited States in Fluorine-16.
L. R. B. Elton Miss D. F. Jackson	The (p,pd) Reaction for Li^6 and Li^7.
Miss D. F. Jackson Mrs. J. Mahalanabis	The Density Distribution of p-nucleons in T = 0 and T = 1 States of Li^6.

International Conference on High Energy Accelerators, Dubna, U.S.S.R., 1963.

A. Carne	Structures for High Energy Proton Linear Accelerators.
K. Batchelor A. Carne J. M. Dickson D. J. Warner	Accurate Energy Measurements on a 50 MeV Proton Linear Accelerator.
A. P. Banford	Radio-frequency Measurements on Superconductors for Proton Linac Resonant Cavities.

International Conference on Sector Focussed Cyclotron and Meson Factories, C.E.R.N., April, 1963.

G. H. Stafford	The Proton Linear Accelerator as a Pion Factory.

International Conference on High Energy Physics and Nuclear Structure C.E.R.N. Report, 63-28.

L. R. B. Elton	Configuration Mixing and Cluster Model in Li^6.

Cryogenic Engineering Conference, Philadelphia, August, 1964.

A. P. Banford	The Application of Superconductivity to Linear Accelerators.

PAPERS PRESENTED AT CONFERENCES (cont'd)

The Institute of Physics and the Physical Society Conference on Low and Medium Energy Nuclear Physics, University of Sussex, September, 1964.

A. Ashmore M. Devine S. J. Hoey J. Litt M. E. Shepherd B. W. Davies R. C. Hanna L. P. Robertson	Measurements of the A and R Parameters in Proton-Proton Scattering at 47.8 and 27.6 MeV.
B. W. Davies M. K. Craddock R. C. Hanna L. P. Robertson R. E. Shamu	Measurement of the Differential Cross Section for Elastic Proton-Helium 4 Scattering at 48 MeV, and Phase Shift Analysis.
R. M. Craig J. C. Dore G. W. Greenlees J. Lowe D. L. Watson	Polarization in the Scattering of Protons by C in the Range 20-28 MeV.
R. R. Shaw A. Swift I. S. Towner L. R. B. Elton	Shell Model Parameters and Energy Levels from Elastic Electron Scattering.
Y. Nogami	Charge Independent Pairing Correlations.

The American Physical Society Spring Meeting at Washington D.C. April, 196[4]

A. Ashmore M. Devine J. Litt W. H. Range M. E. Shepherd R. L. Clarke	Measurement of the A Parameter in P-P Scattering.

Symposium on Nuclear Spectroscopy with Direct Reactions, Chicago, March, 1964.

Miss D. F. Jackson	The Validity of the WKB Approximation for High Energy Distorted Wave Calculations.

Gordon Conference on Nuclear Structure Physics, New Hampshire, U.S.A., September, 1964.

Miss D. F. Jackson	High Energy Distorted Wave Calculations and the Use of WKB Wavefunctions.

PAPERS PRESENTED AT CONFERENCES (cont'd)

Congres International de Physique Nucleaire, Paris, July, 1964.

A. Ashmore M. Devine B. Hird J. Litt W. H. Range M. E. Shepherd R. L. Clarke	Measurement of the A Parameter in P-P Scattering at 47.5 MeV.
L. R. B. Elton A. Swift	Shell Model Parameters and Energy Levels from Elastic Electron Scattering.
T. C. Griffith D. C. Imrie G. T. Lush L. A. Robbins	A Measurement of Spin Rotation in Proton-Helium at 48.0 MeV.
R. M. Craig J. C. Dore G. W. Greenlees J. S. Lilley J. Lowe D. L. Watson P. C. Rowe	Polarization in the Elastic and Inelastic Scattering of 30 and 50 MeV Protons by C and Si.
R. J. Griffiths E. A. McClatchie W. R. Gibson S. J. Hall A. R. Johnston K. M. Knight	Angular Correlation Measurements for (p,2p) Reactions in Carbon and Calcium at 50 MeV.
R. J. Griffiths E. A. McClatchie W. R. Gibson S. J. Hall A. R. Johnston K. M. Knight	Polarization Effects in Proton-Deuteron Elastic at 30 MeV and 50 MeV.
P. S. Fisher E. M. Rimmer	$T = \frac{1}{2}$ States in C^{13} and N^{13} with Two Particles Excited to Single Particle States.

1964 Linear Accelerator Conference, MURA, U.S.A., July, 1964.

J. M. Dickson	Performance of the Rutherford Laboratory P.L.A.
J. M. Dickson	The Polarized Proton Source of the Rutherford Laboratory P.L.A.
J. M. Dickson	R.F. Superconductivity Measurements.
A. Carne	R.F. Accelerating Structure.

A. Carne	Beam Energy Measurement on the Rutherford Laboratory P.L.A.

Particle Accelerator Conference, Washington D.C., March, 1965.

K. Batchelor G. E. Gallagher-Daggitt	Accurate Field Level and Phase Control and Monitoring for a Proton Linear Accelerator.

International Conference on Polarization Phenomena of Nucleons, Karlsruhe, September, 1965.

R. C. Hanna	Some Experimental Aspects of the Use of Polarized Beams.
D. A. G. Broad A. P. Banford J. M. Dickson	The Rutherford Laboratory Polarized Proton Source.
R. M. Craig J. C. Dore G. W. Greenlees J. Lowe D. L. Watson	Polarization in the Scattering of 20-30 MeV Protons by Carbon.
R. M. Craig J. C. Dore J. Lowe D. L. Watson	Strong Coupling Analysis of Inelastic Proton Scattering and Polarization at 30 and 50 MeV.
R. M. Craig J. C. Dore J. Lowe D. L. Watson	Polarization in the Elastic Scattering of 25 and 30 MeV Protons from Complex Nuclei.
R. C. Johnson	Contributions from the D-State of the Deuteron to Deuteron Polarization in (p,d) Reactions.
N. S. Chant P. S. Fisher	Deuteron Asymmetries for Four States Excited in the $C^{12}(p,d)C^{11}$ Reaction with Polarized Protons.

I.P.P.S. Conference on Nuclear and Particle Physics, Liverpool, September, 1965.

C. J. Batty E. Friedman P. C. Rowe J. B. Hunt	Evidence for the Excitation of "Double Analogue" States in (p,n) Reactions.
C. J. Batty E. Friedman P. C. Rowe J. B. Hunt	Energy Levels of Be^6 and Be^7 Observed in (p,n) Reactions.

R. M. Craig J. C. Dore J. Lowe D. L. Watson	The Polarization of 50 MeV Protons Scattered from Ca, Ni^{58}, Ni^{60} and Pb^{208}.
L. R. B. Elton A. Swift	Towards a Realistic Shell Model Potential.
L. R. B. Elton	Optical Model for Elastic Proton Scattering at 180 MeV.
Miss D. F. Jackson	Quasi-Free Scattering from α-Clusters.
Miss D. F. Jackson	Form Factors for Inelastic Scattering of α-Particles and Electrons.
R. C. Johnson	Contributions from the D-State of the Deuteron to Deuteron Polarization in (p,d) Reactions.
E. A. McClatchie F. G. Kingston R. J. Griffiths A. R. Johnston W. R. Gibson J.H.P.C. Megaw	(p,d) (p,He^{3}) Reactions at 50 MeV.
J. A. Fannon E. J. Burge V. R. W. Edwards	Proton Scattering by C^{12} and O^{16} at 50 MeV.
V. R. W. Edwards E. J. Burge J. A. Fannon D. A. Smith F. J. Swales	Elastic and Inelastic Scattering of 50 MeV Protons by Zn^{64} and Cd^{114}.

Vth International Conference on High Energy Accelerators, Frascati, Italy, September, 1965.

A. Carne P. M. Lapostolle (1) M. Promé (2)	Accurate Beam Dynamics Equations in Proton Linear Accelerators.
A. Carne G. Dome (1) N. M. Fewell W. Jungst (3)	Development of the Cross-Bar Structure for a Proton Linear Accelerator.
R. Perry (4) P. V. Livdahl (4) G. E. Gallagher-Daggitt E. A. Crosbie (4) W. N. Myers (4)	Characteristics of Beam from the Argonne ZGS Injector Linac.

PAPERS PRESENTED AT CONFERENCES (cont'd)

International Linac Conference, Los Alamos, U.S.A., October, 1966.

A. Carne P. M. Lapostolle (1)	Design Equations in an Alvarez-Type Proton Linear Accelerator.

I.P.P.S. Conference on Nuclear and Particle Physics, Oxford, April, 1966.

J. C. Hardy D. J. Skyrme	T = 3/2 Analogue Levels in Mass 25 and 29.
Miss D. F. Jackson	A Di-Proton Model for the (p,2p) and Similar Reactions.
J. A. Fannon E. J. Burge M. Calderbank N. K. Ganguly V. E. Lewis D. A. Smith	Proton Elastic Scattering from Ti^{50}, V^{51} and Cr^{52} at 50 MeV.
W. G. Davies W. K. Dawson G. C. Neilson K. Ramavataram	A Study of $Si^{30}(d,n)P^{31}$ Reaction.

I.P.P.S. Conference on Nuclear and Particle Physics, Glasgow, September, 1966.

J. C. Hardy D. J. Skyrme	The Mass and Energy Levels of Ca^{38}.
L. R. B. Elton	The Relationship of Overlap Integrals to Single Particle Wavefunctions.
G. S. Mani A. D. B. Dix D. T. Jones F. J. Swales	Elastic and Inelastic, Polarized and Unpolarized Proton Scattering at 50 MeV from Lithium Isotopes.

(1) at C.E.R.N., Geneva.
(2) at C.E.N., Saclay.
(3) at Technischen Hochschule, Karlsruhe.
(4) at Argonne National Laboratory, U.S.A.

C. J. Batty E. Friedman L. E. Williams J. B. Hunt	Angular Distributions for (p,n) Reactions to Analogue States in Residual Nuclei at 30 and 50 MeV.
J. A. Fannon E. J. Burge M. Calderbank N. K. Ganguly V. E. Lewis D. A. Smith	Proton Elastic and Inelastic Scattering from Ti^{50}, Vi^{51} and Cr^{52}.
A. A. Rush E. J. Burge M. Calderbank J. A. Fannon N. K. Ganguly V. E. Lewis D. A. Smith	Proton Elastic and Inelastic Scattering from Mg^{24}.
D. W. Devins R. C. Hanna K. Ramavataram L. P. Robertson S. J. Hoey D. J. Plummer	Polarization Transfer in (p,n) Reactions on Li^6 and Li^7 Using Incident Polarized Protons.
N. K. Ganguly L. Grunbaum	Inelastic Electron Scattering from O^{18}.
P. E. Cavanagh C. F. Coleman A. G. Hardacre J. F. Turner	Nuclear Structure of Tin Isotopes Observed in (p,d) Reactions at 30 MeV.

International Conference on Nuclear Physics, Gatlinburg, Tennessee, September, 1966.

D. J. Baugh M. J. Kenny J. Lowe D. L. Watson H. J. Wojciechowski	The Elastic and Inelastic Scattering of 30.4 MeV Polarized Protons by Fe^{54}.
R. C. Johnson	The Deuteron Optical Potential.
Miss D. F. Jackson L. R. B. Elton	Nuclear Structure Information from the Non-Coplanar (p,2p) Reaction.
C. J. Batty E. Friedman L. E. Williams J. B. Hunt	Angular Distributions for (p,n) Reactions to Analogue States in Residual Nuclei at 30 and 50 MeV.

C. J. Batty T. C. Griffith D. C. Imrie G. T. Lush L. A. Robbins	A Measurement of the Differential Cross-Section in Proton-Proton Scattering at 49.41 MeV.
J. A. Fannon E. J. Burge N. K. Ganguly D. A. Smith	Elastic and Inelastic Scattering of 50 MeV Protons by Carbon and Oxygen.
V. E. Lewis E. J. Burge A. A. Rush D. A. Smith N. K. Ganguly	Polarization in the Scattering of 50 MeV Protons by Mg^{24} and Zn^{64}.
N. K. Ganguly L. Grunbaum	Inelastic Electron Scattering from O^{18}.
P. E. Cavanagh C. F. Coleman A. G. Hardacre J. F. Turner	Single Particle and Collective States in the Odd Isotopes of Tin.

"How and Why Should We Investigate Nuclides Far Off the Stability Line", Lysekil, Sweden, August, 1966.

K. F. Chackett	A Design Study for A Circulating Liquid Target.

Italian Physical Society Conference, Trieste, October, 1966.

G. S. Mani A. D. B. Dix D. T. Jones	Elastic and Inelastic, Polarized and Unpolarized Proton Scattering at 50 MeV from Lithium Isotopes.

Intermediate Energy Physics Conference, Williamsburg, Virginia, February, 1966.

A. Swift L. R. B. Elton	Changes in Radii Between Neighbouring Nuclei.

Conference on Isobaric Spin, Talahassee, Florida, March, 1966.

J. C. Hardy D. J. Skyrme	T = 3/2 Analogue Levels in Mass 25 and 29.

VISITORS TO THE P.L.A.

The following is a list of physicists from abroad who have stayed for an appreciable period of time and made use of the facilities within the P.L.A. division.

R. L. Clarke, A.E.C.L., Chalk River, Canada.

P. Zupranski, Institute for Nuclear Research, Swierk, Poland.

Professor A. W. Fairhall, University of Washington, U.S.A.

W. Kusch, Institute for Nuclear Research, Swierk, Poland.

Z. J. Moroz, Institute for Nuclear Research, Swierk, Poland.

L. P. Robertson, N.R.C. Postdoctoral Fellow, Canada.

J. L. Rouse, University of Melbourne, Australia.

W. Schweimer, Zyklotron - Laboratorium, Karlsruhe, Germany.

A. Zucker, Oak Ridge National Laboratory, U.S.A.

Professor R. M. Eisberg, University of California, Santa Barbara, U.S.A.

J. Bittner, Brookhaven National Laboratory, U.S.A.

S. Giordano, Brookhaven National Laboratory, U.S.A.

B. Pin, University of Grenoble, France.

W. Sax , C.E.R.N., Geneva.

R. E. Worsham, Oak Ridge National Laboratory, U.S.A.