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OHIO UNIVERSITY TANDEM VAN DE GRAAFF ACCELERATOR

Final Report

MASTER

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ABSTRACT

This report summarizes the work carried out at the John Edwards Tandem Accelerator Laboratory of Ohio University during the period 1970 to 1977 under Contract AT(11-1)-1717 between Ohio University and the United States Energy Research and Development Administration.

The main emphasis of the work has been studies of neutron-nucleus interactions, and of nuclear structure using neutrons as probes, work that utilizes the main and unique characteristic of the accelerator: high current, high voltage tandem. Certain applied areas have also been studied, such as the production of short-lived isotopes for use in medical diagnoses, production of very high neutron intensity to observe possible sputtering effects, and proton induced x-ray emission with a microprobe beam.

1. INTRODUCTION AND HISTORY

In 1967 Ohio University was awarded \$1,000,000 by the U.S. Atomic Energy Commission under Contract AT(11-1)-1717 to purchase a high-current, high-voltage tandem accelerator to pursue an experimental program strongly oriented toward neutron physics which requires high beam currents at high energies. Specifications and designs were then developed and a construction contract was awarded to High Voltage Engineering Corporation (HVEC) in 1968. The University provided the building, faculty, staff and operating funds for the Tandem Accelerator Laboratory for a period of at least 4 years. Because this was the first such high-current, high-voltage tandem accelerator, difficulties in achieving full specifications were experienced by HVEC. The accelerator was delivered in 1970 at reduced performance for limited research work while a revised accelerating tube structure was manufactured to reach higher voltage. In 1973 the accelerator was upgraded to its present performance and the research program moved to full scale.

Since this is such a unique facility with its excellent pulsed-beam feature, a cross-sectional diagram of the accelerator is shown in Figure 1. Most all other high-energy tandem Van de Graaff's have charging belts (or pellet belts) which run parallel with the accelerating tubes, but to achieve the high beam currents so vital to successful high-energy neutron work this accelerator uses a belt perpendicular to the accelerating tubes. Figure 2 shows a layout of the main part of the Laboratory and indicates features of the experimental equipment. The following table shows a brief summary of the performance specifications now available with the accelerator:

T-10 Tandem Van de Graaff

TABLE 1

ACCELERATOR PERFORMANCE CHARACTERISTICS

Energy	1 - 10 MeV protons
Maximum D.C. beam on target	
Protons, deuterons	$\geq 80 \mu\text{A}$
Helions, alphas.	4 μA
Average pulsed beams on target	
Protons.	5-10 μA @ 5 MHz
Deuterons.	4-8 μA @ 5 MHz
Pulse width	
Protons, deuterons	~ 0.5 n sec.
Pulse repetition rate	150 kHz to 5 MHz

11. TANDEM VAN DE GRAAFF ACCELERATOR AND PERFORMANCE

While the design objective of 11 MeV (5.5 MV on the high voltage terminal) was not achieved for long-term practical use, the accelerator has operated at 10 MeV for useful periods of time and runs routinely at or above 9 MeV for week-after-week continuously in long neutron experiments. This small deficiency in maximum energy is not important in neutron work compared to the very fine pulsed-beam properties which turned out to exceed specifications and enhanced our program considerably by permitting us to do experiments of very sharp time resolution that other laboratories, including national laboratories, could not do.

This unique feature of exceptionally high beam currents (needed for neutron work) with unusually sharp time resolution at high energies has established a special capability here at Ohio University. This was demonstrated at the recent meeting on "Neutron Cross Sections in the Range 10-40 MeV" at Brookhaven National Laboratory, May 3-5, 1977 where the only reported differential cross section measurements above 15 MeV were those from Ohio University. This special capability is also illustrated by the fact that ours is practically the only group doing extensive high resolution differential cross section work with neutrons in the range 4-8 MeV.

As a quantitative measure of the pulsing properties of the accelerator recent experiments with protons routinely gave a full width at half-maximum (FWHM) of 0.7 n sec. and a full width at 1/6-maximum of 0.9 n sec. for the time distribution of the pulse with an average beam of 5 μ A on target at 5 MHz repetition rate. During these experiments the beam current often had to be held back from increasing above this value because of the heating effect in the entrance window of the tritium gas cell which is the neutron-producing

target using the $T(p,n)^3\text{He}$ and $T(d,n)^4\text{He}$ reactions. In other experiments with deuteron beams similar pulse widths were achieved for long runs at 3.5-4 μA . The accelerator has delivered on other targets up to twice these currents with only slight increases in time spreads of the pulses. As new target techniques permit we will be able to deliver substantially higher beams as needed.

The Laboratory is equipped with a versatile on-line/off-line IBM 1800 computer system that includes 32K memory, line printer, CRT, 2 disk drives, 2 tape drives and a core-to-core link between the data analyser and the 1800 computer. This facility is vital to the effective use of the accelerator and has expanded our capabilities considerably. The Laboratory also has acquired a substantial array of nuclear equipment such as scattering chambers, Ge(Li) detectors, a magnetic spectrograph, a large volume split-annulus NaI (TI) detector, a heavy water/beryllium neutron source for CTR simulation, and a large number of electronic modules.

There have been several collaborations with other laboratories in the past and there are several scheduled for the future. Some examples of past collaborative experiments performed here on the Ohio University Tandem Accelerator are: neutron flux measurements to study the response of liquid and plastic scintillators to neutrons from 2 to 20 MeV for R. Madey of Kent State University; measurements of "Anomalies in the $^{72}\text{Ge}(\alpha,n)^{75}\text{Se}$ reaction near Isobaric Analog Resonances in ^{76}Se " with Alex Elwyn of Argonne National Laboratory; measurements of low lying properties of states of Tc isotopes via (p,n) and (p,ny) reactions with H. Kim of Oak Ridge National Laboratory; measurements of time resolution properties of a very large time-compensating neutron scintillation detector with Charles D. Goodman of Oak Ridge National Laboratory; measurements of flux pinning in niobium with Roger Rollins of

our Department (Air Force Contract); measurement of (α, n) reactions using activation methods in cases of astrophysical consequence with William Plough of Ohio State University; and calibration of neutron dosimeters for Dosimeter Corporation of Cincinnati.

Future scheduled collaborations here at Ohio include measurements of neutron elastic scattering cross sections on ^{13}C with George Auchampaugh (Nov. 7-21, 1977) and a year sabbatical leave with Steven Grimes of Lawrence Livermore Laboratory measuring neutron-induced charged-particle cross sections on various fusion-reactor-related nuclides.

As an over-all figure of merit for operation of the accelerator, the accelerator was available for operation 85% of the time requested for experiment.

We normally operate on long runs of one to two weeks duration on a basis of 24 hours/day, 7 days/week. Once bugs and modifications were cleared up, long and intense use has been made of the facility as evidenced by the list of publications given in Section IV of this report. In addition to this list, over 50 invited talks, colloquia, and seminars have been given by members of the Laboratory at various institutions throughout the world.

We truly have at Ohio University a fine facility not available with these special properties at national laboratories or other universities.

III. RESEARCH RESULTS

Most of the research with the accelerator has exploited its unusual neutron physics capability described above. The work has included elastic and inelastic scattering of neutrons from light nuclei to study properties of the shell model, and from medium and heavier nuclei to study properties of the optical model; (p, n) and $(p, n\gamma)$ reactions on various nuclei to determine level assignments and to observe the collective nature of nuclei; $(n, 2n)$ and (n, γ) reactions; emission spectroscopy; the production of short-lived isotopes

for use in medical diagnoses; very high intensity neutron irradiation to observe possible sputtering effects for fusion reactor designs; elastic and inelastic neutron scattering from materials used for structural, shielding and tritium breeding purposes in fusion reactors; proton-induced x-ray emission spectroscopy. In the following paragraphs brief outlines will be given of some of the major areas of research where most effort has been devoted.

In the region of excitation of several light nuclei, e.g. $A \leq 20$, from the neutron separation energy on up to approximately 8 MeV above this, the nuclear energy levels are reasonably well resolved and can be studied by neutron scattering. While it is well known that the nuclear shell model can in many cases give a good description of the main features of the low-lying structure, especially below the neutron separation energy, its validity above this in the continuum had not been investigated extensively. One of the areas of interest at this Laboratory has been the "Study of Structure of Light Nuclei with Neutrons" and U.S. ERDA has funded this research for the past three years because our measurements of elastic and inelastic neutron scattering from ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$ and ${}^{12}\text{C}$ are useful to fusion reactor designers to determine correct values for tritium breeding and shielding for these reactors. Since ${}^6\text{Li}$, ${}^{10}\text{B}$ and now ${}^{12}\text{C}$ are used as standard cross sections, accurate measurements on these nuclei are also needed. We have over the lifetime of this accelerator so far made extensive high-resolution measurements of elastic and inelastic scattering cross sections on these nuclei from 1.5 MeV up to 8.0 MeV. These data have been analyzed via the R-matrix formalism yielding several new discoveries of level structure and contributions to our knowledge of the extensions of the validity of the shell model into the higher energy continuum region. In the process of analyzing nuclear model structure for basic physics of interest to a university situation these cross section data needed by ERDA for fusion reactor design are not only obtained in their raw form, but more importantly

are evaluated and interpreted in terms of a physical model of the nucleus so that the R-matrix parameters for fits to the data become a vital key in the proper use and interpretation of these data for fusion reactor design. The data and analysis have been major contributions to the nuclear data files (CSISRS) and evaluated nuclear data files (ENDF/B). This work is continuing with emphasis on inelastic scattering needed for shielding and tritium breeding design work for fusion reactors.

The neutron elastic and inelastic scattering from medium and heavier nuclei has been studied in the energy range from 7 to 26 MeV. Table 2 gives a list of the scattering samples and the energies at which both elastic and inelastic data were taken.

The main purpose of this program has been in the understanding and the evaluation of the nucleon optical model potential (OMP); this is of extreme interest, since it is assumed that the OMP describes the interaction between an incident nucleon and a target nucleus. Prior empirical studies of the OMP have been based mainly on the analysis of proton data, elastic scattering and polarization measurements. The input of neutron data to these analyses has been very limited because of the relatively low accuracy of the up to then available neutron scattering data. The work done at Ohio University has improved considerably this situation by providing accurate neutron data for a large number of nuclei.

Several papers have been published on these subjects and the relevant information may be summarized as follows:

a) Neutron scattering on T=0 nuclei (Nucl. Phys. A286 (1966) 232).

The comparison of the OMP analysis of neutron and proton elastic scattering in the case of ^{40}Ca has allowed an empirical determination of the Coulomb

Table 2

Ohio University Neutron Scattering Data

Sample	Neutron energy (MeV)					
	7.0	9.0	11.0	20.0	26.0	other
Mg			X			
²⁷ Al			X		X	
Si			X	X In [*]	X In	
S			X	X In	X In	
Ca			X In	X In	X In	
⁵¹ V			X			
⁵⁵ Mn			X			
Fe			X	X	X	
⁵⁹ Co			X			
Ni			X			
^{90,92} Zr			X In			
⁹³ Nb			X			
^{92,96,98,} ¹⁰⁰ Mo	X	X	X In	X	X	
In			X			
^{118,120,} ^{122,124} Sn			X In			¹²⁰ Sn: 9.4; 22.8
¹⁶⁵ Ho			X			
¹⁸¹ Ta			X			
^{206,208} Pb	X	X	X In	X	X In	
Pb			X			
²⁰⁹ Bi			X			

* In = inelastic measurements

correction term which may be parameterized as $0.46 Z/A^{1/3}$.

b) Neutron scattering on T non zero nuclei. (Phys. Lett. 62B(1976)399). The analysis of elastic scattering data of neutrons and protons on the same nuclei at $E_n = E_p$ and $E_p = E_n + \Delta E_c$, in terms of the OMP, has yielded isospin dependent potentials with isospin parameters $V_{1r} = 22.7 \pm 0.6$ MeV and $W_{10} = 12.7 \pm 0.8$ MeV.

c) Neutron scattering from ^{208}Pb (Nucl. Phys. to be published). Elastic scattering of 7, 9, 11, 20 and 26 MeV neutrons from ^{208}Pb have been analysed in terms of the OMP. The energy dependence of the real and imaginary parts of the potential have been obtained. A comparison with proton OMP parameters has been done and we have made consistent calculation for the (p,n) quasi-elastic cross section. Deformation parameters for the $3^- (E_x = 2.615 \text{ MeV})$ and $5^- (E_x = 3.198 \text{ MeV})$ states have been obtained at incident energies of 11 and 26 MeV.

d) Inelastic scattering (Phys. Rev. Lett. 39 (1977) 443). Isospin effects in nucleon inelastic scattering have been studied by comparing quadrupole deformation parameters deduced from measured (n,n') cross sections with values for (p,p') and values for electromagnetic excitation found in the literature. Proton-vibrational nuclei with $N=50$ and neutron-vibrational nuclei with $Z=50$ were studied. Predicted effects of core polarization are observed.

The above data and analysis have been the major contribution to the nuclear data files (CSISRS) for neutron scattering data in the energy range above 9 MeV. Many of the elements studied are used and will be used in reactor shielding.

The (p,n) and (pn, γ) reactions have been measured for several cases where the nuclear spectra were not available. $^{104}\text{Pd}(p,n)^{106}\text{Ag}$ and $^{106}\text{Pd}(p,n)^{106}\text{Ag}$ and the (p,n γ) spectra and angular distributions were measured at proton energies between 6.0 MeV and 7.0 MeV in order to exploit the enhancements on the $5/2^+$, $1/2^+$ and $3/2^+$ isobaric analogue resonances in

^{105}Ag and the $5/2^+$ and $1/2^+$ resonances in ^{107}Ag . In ^{104}Ag and ^{106}Ag we were able to assign 43 spins and parities for the 52 observed states by comparison of neutron enhancements, Hauser Feshbach calculations and angular distributions.

The direct measurement of inelastic spectra in neutron induced reactions have now been expanded to include $(n,2n)$. Preliminary measurements on carbon indicate considerable structure in the $(n,2n)$ energy spectra. These effects are not predicted by macroscopic theory such as the Hauser-Feshbach compound nuclear model. A large number of targets from carbon to Pb are under consideration for these studies. The coincidence spectra should yield more reliable cross sections than those measured using radioactivity.

As an application of nuclear techniques to medicine, we demonstrated a method to produce the short-lived isotope ^{11}C (by the $^{11}\text{B}(p,n)^{11}\text{C}$ reaction) in a tandem accelerator with usable quantities for medical purposes in the form of ^{11}CO and $^{11}\text{CO}_2$. While this general technique had been used on cyclotrons at much higher energies, it had not been done before in this way on a tandem Van de Graaff. Since many universities have tandems (and now higher energy single ended Van de Graaffs) but fewer have cyclotrons this opened up a new possibility for more general use of ^{11}C in medicine.

Efforts are presently being made to develop a scanning proton microprobe which utilizes the technique of proton-induced x-ray emission spectroscopy to analyze elemental composition of samples of biological and environmental interest. Since very large proton beam intensities are available from the Ohio University Tandem, simple collimation can be used to produce substantial beam currents in small beam spot sizes. X-ray spectra are then measured as a function of position on the sample.

In summary, U.S. ERDA and Ohio University have cooperated to establish and raise to a high level of productivity a unique facility, faculty, and staff that contributes significantly to our basic understanding of the nucleus, to the nuclear data needs of the energy community, and to the production of young scientists in the neutron physics field. While the University has been able to support the very minimum crew of an Accelerator Engineer and a Nuclear Instrumentation Engineer together with supplies and equipment to so far maintain operation, we must continue to rely on support from outside agencies such as NSF and ERDA to fund the experimental side of the research.

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VI. PRESENT FACULTY, STAFF, AND STUDENTS

Faculty

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Roger M. White, Research Associate

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Robert Wood