C Y C L O T R O N L A B O R A T O R Y

Department of Physics

The University of Michigan

Annual Report

March 1, 1971 - May 1, 1972

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INTRODUCTION

This report contains a brief summary of the research and technical development carried on in the Cyclotron Laboratory of the Department of Physics at The University of Michigan during the period March 1, 1971 to May 1, 1972.

Much of the effort of the laboratory this past year was devoted to the instrumenting of the new beam line and "neutron tunnel" and to an intensive program of orbit studies and cyclotron improvement. While this necessarily infringed on the research activity on problems in nuclear structure, we believe the investment will result in enhanced productivity in the immediate future.

Again it is a pleasure for the research staff to acknowledge their indebtedness to Professor K. T. Hecht and Dr. J. P. Draayer for their theoretical help and guidance which contribute in a very significant way to the research effort.

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A. EXPERIMENTAL PROGRAM

A1. The Reaction $^{16}\text{O}(d,h)^{15}\text{N}$

M.A. Firestone and J. Janecke

The experimental procedure and preliminary results for this reaction were reported last year. The reaction is of interest because recent theoretical investigations of ^{16}O predict a ground state configuration which is approximately 21% two particle - two hole 1^1 and in addition contains a small four particle - four hole component.

By far the strongest transitions observed in the spectrum, at a deuteron bombarding energy of 29 MeV, are those to the ground state ($1/2^-$) and the ($3/2^-$) state at 6.32 MeV. If there were no particle-hole admixtures, these would be the only low-lying states observed since they arise from the pickup of a $p_{1/2}$ and $p_{3/2}$ proton, respectively. The angular distributions for these states are shown in Fig. A1-1 together with the distribution predicted by the distorted wave code DWUCK. The ($1/2^-$) ground state is fit very well using a local zero-range potential and yields a spectroscopic factor of 2.85 for a least-squares fit with $\chi^2 = 5$. A non-local finite-range potential gave a spectroscopic factor of 2.22 with a $\chi^2 = 13$. The 6.32 MeV ($3/2^-$) state yielded a spectroscopic factor of 6.34 and $\chi^2 = 10$ for the local zero-range potential and a spectroscopic factor of 5.81 with $\chi^2 = 40$ for the non-local finite-range predictions. The optical potentials used are given in ref. 2. The simple shell model would predict values of 4 and 2 for the $3/2^-$, 6.32-MeV state and $1/2^-$, ground state respectively if there were no fragmentation of the proton

L/ZR

NL/FR

Fig. A1-1

hole strengths. While our results are larger than these predictions, the ratios of our spectroscopic factors are 2.2 for the local zero-range potential, and 2.6 for the non-local finite-range potential. The former result is in good agreement with the simple shell model picture within the validity of the DWBA approach.

Figure A1-2 shows angular distributions for some of the weak positive-parity levels. These were extracted from the gas cell spectra with the help of a peak fitting program, SAMPO.³⁾ Some of these states result from the pickup of a proton outside of a closed shell and thus give information about the particle-hole structure of the ground state of ^{16}O . From this direct process $5/2^+$, $1/2^+$, and possibly $3/2^+$ levels would be produced from $(1d_{5/2})^2$, $(2s_{1/2})^2$, $(1d_{5/2}, 1d_{3/2})$, etc., configurations in ^{16}O . However, as pointed out last year the $7/2^+$ state at 7.57 MeV cannot be easily understood on the basis of a direct pickup because the $1g_{7/2}$ level is much too high in energy to contribute. It is possible that this state is the result of a two-step reaction in which the 3^- state in ^{16}O at 6.13 MeV is first produced from an inelastic scattering and then a $p_{1/2}$ proton is picked up. This would also produce a $5/2^+$ state. Another possibility is that a segment of the $2p-2h$ ^{16}O ground state has its two holes coupled to an angular momentum of 1^+ and has its two particles in the $d_{5/2}$ level. After the pickup the remaining $5/2^+$ particle could couple to the 1^+ of the holes resulting in states of $7/2^+$, $5/2^+$, and $3/2^+$. This type of process has been proposed for some of the positive-parity levels of ^{15}N .⁴⁾

The distributions shown in Fig. A1-2 have not been satisfactorily fit by DWUCK curves. An attempt to describe some of these states by a two-step reaction mechanism is now under way. Further experimental work will involve the use of a solid Al_2O_3 target and magnetic analysis to resolve the $5/2^+$, $1/2^+$

Fig. A1-2

doublet at 5.3 MeV and some other presently unresolved levels.

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 - 3) J.T. Routti, S.G. Prussin, *Nucl. Inst. & Meth.* 72, 125 (1969).
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-

A2. Deformation Effects and the $^{26}\text{Mg}(d,h)^{25}\text{Na}$ Reaction

J. Janecke

Preliminary results from the experimental study of the (d,h) reaction on ^{26}Mg were reported last year. The experimental work is complete and a paper is being prepared for publication. One conclusion of the analysis of those data is that the angular distributions have a strong dependence on the deformation of the nuclear shape. As a consequence uncertainties are introduced into the evaluation of spectroscopic factors.

Kunz, Rost and Johnson ¹⁾ have pointed out that the effects of strong coupling to inelastic channels in the initial and final nuclei can be important in particle transfer reactions, particularly on deformed nuclei. They introduced an approximate procedure to account for these effects by increasing the radii of the real and imaginary optical potential wells. They gave an explicit expression for this factor in terms of Nilsson coefficients for cases where the target nucleus is even-even and the coupling term is due to the quadrupole deformation.

The nucleus ^{26}Mg has a deformation ²⁾ of $\beta = 0.28 \pm 0.01$. Therefore, one would expect the above effect to be quite strong. This is indeed the

case. Figures A2-1 and A2-2 show experimental and calculated angular distributions for the strongest $\ell=2$ ($E_x = 0$ keV) and $\ell=0$ ($E_x = 1068$ keV) transitions, respectively. The curves were calculated using the computer code DWUCK (non-local/finite-range) and the optical parameters given in refs. 3 and 4. The unmodified curves (heavy lines) agree very poorly with the data for both transitions. This is particularly evident for the maxima near 36° - 40° and the forward angle points below 10° (which demonstrates the importance of forward angle measurements). Increasing the radii as described above leads to considerably better agreement for both transitions at forward angles, the high-angle side of maxima near 16° - 20° , and the position of maxima near 36° - 40° . Best agreement is obtained for $\Delta R/R \approx (8 \pm 4)\%$ ($\ell=2$) and $\Delta R/R \approx (13 \pm 4)\%$ ($\ell=0$). Using the theoretical coefficients obtained by Kunz et al.,¹⁾ and $\beta = 0.28$ gives $\Delta R/R = 3\% - 11\%$ ($\ell=2$), depending on the mixing between the respective Nilsson orbits, and $\Delta R/R = 19\%$ ($\ell=0$) which is in good agreement with the experimentally determined values.

A problem arises with respect to the extraction of spectroscopic factors. The factors C^2S obtained by adjusting the maxima near 16° - 20° increase strongly with increasing radius. A radius increase of $8\% / 13\%$ for the $\ell=2/\ell=0$ transitions results in increases by factors of $1.6/4.5$, respectively. Thus, not only the absolute value of the spectroscopic factors is changed considerably but also the relative strength. For $\Delta R/R = 0$ the added absolute spectroscopic strength from the $1d-2s$ shell is about 3.0 (including several weak $\ell=2$ transitions) while for $\Delta R/R \neq 0$ it is about 5.3. The first value is too small; the second one too large compared to the theoretical sum-rule value of 4. If one normalizes the spectroscopic strengths to the sum-rule value, the strength C^2S of the $\ell=0$ transition still varies between about 0.2 and 0.5. It is interesting to note that the second value ($\Delta R/R \neq 0$) is much closer to the

Fig. A2-1. Experimental angular distribution for the (d,h) transition to the $5/2^+$ ground state in ^{25}Na . The distorted-wave predictions shown with the data were obtained with the computer code DWUCK (non-local/finite range) and standard parameters (heavy line) or with increased radii (thin lines) according to the suggestion of Kunz *et al.*¹⁾ for deformed nuclei.

Fig. A2-2. Experimental angular distribution for the (d,h) transition to the $1/2^+$ state at $E_x = 1068$ keV in ^{25}Na . The distorted-wave predictions shown with the data were obtained with the computer code DWUCK (non-local/finite range) and standard parameters (heavy line) or with increased radii (thin lines) according to the suggestion of Kunz *et al.*¹⁾ for deformed nuclei.

value of 0.55 predicted theoretically by Wildenthal ⁵⁾ on the basis of a shell-model calculation.

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 - 3) E. Newman, L.C. Becker, B.M. Freedom and J.C. Hiebert, Nucl. Phys. A100, 225 (1967).
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A3. Nuclear Structure in the N=50 Isotones

G. Neff and W.S. Gray

The study of proton-transfer reactions in the N=50 isotones is continuing, the objective being the determination of the important proton excitations in these nuclei. The measurements of the $^{88}\text{Sr}(d,h)^{87}\text{Rb}$ reaction initiated last year have been completed, ¹⁾ and a start has been made on the investigation of the $^{87}\text{Rb}(d,h)^{86}\text{Kr}$ reaction. The spectroscopic factors measured for six transitions in the $^{88}\text{Sr}(d,h)^{87}\text{Rb}$ reaction (Table A3-1) are in good agreement with those obtained from the ^{88}Sr ground state wave function calculated by T. A. Hughes. ²⁾ According to this calculation the ^{88}Sr ground state is predominantly of two configurations: about 70% consisting of a "doubly-magic" ^{88}Sr core with every orbital filled up through the $p_{3/2}$, and about 20% consisting of the two particle - two hole configuration $(p_{3/2})^{-2}(p_{1/2})^2$. Transitions with $\ell_p = 4$, such as that observed to the level at 1.57 MeV, are not accounted for by the model since a basis of proton levels up to but not

including the $g_{9/2}$ orbital was assumed.

TABLE A3-1
SUMMARY OF RESULTS FOR THE $^{88}\text{Sr}(d,h)^{87}\text{Rb}$ REACTION

Energy	ℓ_p	C^2S (relative) [*]	For the Assumed (j) ^π
0.0	1	3.8	$3/2^-$
0.40	3	6.0	$5/2^-$
0.84	1	0.40	$1/2^-$
1.58	4	0.04	$9/2^+$
2.42	(1)	0.22	$1/2^+$
2.53	1	0.27	$1/2^+$

* Normalized to give 6.0 for the 0.40 MeV level.

In recent work ^{3,4)} on the β -decay of ^{87}Kr (spin $5/2^+$) the transition to the 1579 keV level in ^{87}Rb is found to be very weak, suggesting that the transition is doubly forbidden, i.e. $\Delta J = 2$ and no parity change. This together with the $\ell_p = 4$ assignment from the (d,h) measurements suggests a spin-parity of $9/2^+$.

The $^{87}\text{Rb}(d,h)^{86}\text{Kr}$ reaction is being studied using an $^{87}\text{RbOH}$ target on a carbon backing. The target preparation presented a problem due to the fact that the inventory form of ^{87}Rb is the chloride, and chlorine is an intolerable impurity due to its wealth of states in the region of interest. Also, rubidium is chemically one of the most active of the alkali metals and has a very low melting point. Targets were prepared by adding $\text{AgC}_2\text{H}_3\text{O}_2$ and chromium to a solution of $^{87}\text{RbCl}$, removing the resulting AgCl precipitate, and reducing the rubidium fraction with thorium metal in vacuum. The carbon

substrate was cooled with liquid nitrogen to prevent the rubidium from being reevaporated due to the radiation absorbed during the reduction process. A spectrum obtained in the $^{87}\text{Rb}(d,h)^{86}\text{Kr}$ reaction at a deuteron bombarding energy of 29.0 MeV is shown in Fig. A3-1. Transitions are observed to the ground state of ^{86}Kr and to six excited states at excitations of approximately 1.56, 2.25, 2.35, 2.72, 2.85 and 2.92 MeV.

References

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 - 3) A. Shihab-Eldin, et al., Nucl. Phys. A160, 33 (1971).
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A4. The $^{139}\text{La}(\alpha,\alpha')$ and $^{140}\text{Ce}(\alpha,\alpha')$ Reactions

F. Todd Baker and Robert Tickle

The investigation of the reaction $^{139}\text{La}(\alpha,\alpha')$, undertaken to study the collective nature of levels in ^{139}La as a complement to our knowledge of the shell model nature of the N=82 isotones obtained from single-nucleon transfer reactions, was reported last year. This work, and in addition an investigation of the $^{140}\text{Ce}(\alpha,\alpha')$ reaction, has been completed and published [Phys. Rev. C5, 182 (1972)].

Fig. A3-1

A5. Single-Proton Transfer Reactions in the Rare-Earth Region

A.S. Broad, J.A. Splett, D.A. Lewis, W.S. Gray,

J. Bardwick and W.C. Parkinson

The investigation of single-proton transfer reactions in the rare-earth region continues. The target fabrication problem has been solved (see Section B-3) and some new data have been obtained.

a) The $^{158}\text{Gd}(\alpha, t)^{159}\text{Tb}$ Reaction

A sample spectrum obtained for ^{159}Tb at an α -particle bombarding energy of 45 MeV is shown in Fig. A5-a-1. Angular distributions have been measured at 5° intervals from 0° to 35°. Measurements to obtain additional information on ^{159}Tb via the $^{158}\text{Gd}(h, d)^{159}\text{Tb}$ reaction at a bombarding energy of 44 MeV and the $^{160}\text{Dy}(d, h)^{159}\text{Tb}$ reaction at a bombarding energy of 34 MeV have been initiated. In addition to obtaining information on the structure of ^{159}Tb , the measurements will also serve to determine whether the currently popular method of analyzing the structure of rare-earth nuclei on the basis of incomplete spectra yields accurate results. As a by-product of this analysis, a better understanding of the reaction mechanism in this region will be obtained.

As a first step in the analysis of the data, a first-order Coriolis code, neglecting β - and γ -interactions, has been written. The code allows for coupling up to nine bands with variable inertial parameters and provides an option for the calculation of Nilsson coefficients.

b) The $^{162}\text{Dy}(d, h)^{161}\text{Tb}$ Reaction

A preliminary spectrum at a deuteron bombarding energy of 29 MeV is shown in Fig. A5-b-1. The target was 100 $\mu\text{g}/\text{cm}^2$ of enriched ^{162}Dy metal on a carbon backing. The outgoing helions were analyzed using two magnets of

Fig. A5-a-1

Fig. A5-b-1. The dispersion is about 2.9 keV/mm. Excitation of the residual nucleus increases with the number of millimeters.

the spectrograph with photographic plates on the focal surface. The dispersion is about 2.9 keV/mm.

The primary problems at a bombarding energy of 29 MeV are count rate and resolution. DWBA calculations predict that the cross sections should increase by about a factor of three to five (depending on the ℓ transfer) as the bombarding energy is increased from 29 to 37 MeV and the angular distributions should show considerably more structure. The width of the peaks is mainly due to straggling of the outgoing helion in the target and will be decreased as the bombarding energy is increased. For these reasons, future data will be taken using an incident energy in the region of 37 - 40 MeV.

c) The $^{162}\text{Dy}(\alpha, t)^{163}\text{Ho}$ Reaction

The experimental work on this reaction has been completed and the data are being analyzed. A spectrum of ^{163}Ho is shown in Fig. A5-c-1. Angular distributions have been measured in 2.5° and 5° steps between 0° and 30° .

A study of states of low- ℓ in ^{165}Ho and ^{163}Ho using the (h, d) reaction is being initiated.

A6. Study of Collective Excitations in $^{203,205}\text{Tl}$

W.S. Gray and H.C. Griffin

A study of the inelastic scattering of 45.5-MeV α particles from the two stable Tl isotopes is presently underway. According to the simple shell model, the low-lying levels of these nuclides would be expected to result from the addition of a single proton hole to the semi-magic nuclides ^{204}Pb and ^{206}Pb . However, studies of proton pickup reactions on ^{204}Pb and ^{206}Pb , leading to ^{203}Tl and ^{205}Tl , indicate considerable fragmentation of the

Fig. A5-c-1

single-hole strength.^{1,2)} The results of the pickup experiments have been reproduced rather well by a model in which the pure hole states mix with other states constructed by coupling the proton hole to collective excitations of the Pb core.³⁾

The objective of the present study is to identify those levels which are strongly excited by inelastic scattering. These strong transitions may be expected to proceed by collective excitations of the core, while the pickup reactions are sensitive only to the pure-hole amplitudes in the residual levels. Thus the inelastic scattering information should provide additional insight into the level structure of odd-mass Tl isotopes and allow a more complete test of the validity of the hole-collective model for these nuclides.

To provide a basis for comparison with the collective strength observed in ^{203}Tl and ^{205}Tl , angular distributions have been measured for the stronger (α, α') transitions to levels in ^{204}Pb and ^{206}Pb . The measurements on ^{203}Tl and ^{205}Tl are still in progress, and angular distributions obtained so far are not complete enough as yet to warrant definite ℓ -transfer assignments or determination of transition strengths.

The information obtained to date for ^{203}Tl and ^{205}Tl is summarized in the sample spectra shown in Figs. A6-1 and A6-2. These were taken with targets fabricated from isotopically enriched $^{203}\text{Tl}_2\text{O}_3$ and $^{205}\text{Tl}_2\text{O}_3$. The groups labeled with excitation energies have been determined to correspond to levels in the Tl isotope indicated in each figure. The ^{205}Tl data were taken with a relatively thick target, using only the first element of the three-magnet spectrograph system. The resolution obtained varied from 35 - 45 keV FWHM. Because of the closer level spacing observed in ^{203}Tl , the data for this nuclide were taken using two analyzer magnets. The resulting resolution of 20 - 25 keV FWHM was sufficient to resolve all the strong transitions

Fig. A6-1

Fig. A6-2

of interest.

References

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 - 2) D. Royer, et al., Nucl. Phys. A158, 516 (1970).
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A7. The $^{208}\text{Pb}(h,h')$ Reaction at 43.7 MeV

F. Todd Baker and Robert Tickle

Angular distributions for the (h,h') reaction exciting the first 2^+ , 3^- , 4^+ , and 5^- levels of ^{208}Pb have been measured from 13° to 50° at a bombarding energy of 43.67 MeV. The purpose was to determine the phase of the effective microscopic interaction. The results indicate the phase is near $\pi/3$ for this reaction. The work has been completed and published [Phys. Rev. C5, 544 (1972)].

A8. $J_{15/2}$ Single-Neutron Strength in ^{209}Pb

Robert Tickle and W.C. Parkinson

Several investigators using the (d,p) and (t,d) reactions have reported that the level at 1.42 MeV in ^{209}Pb contains only about half of the $1j_{15/2}$ neutron strength. The $j_{15/2}$ shell-model state is the only odd-parity state in the shell. As a consequence, it is expected to mix with the $15/2^-$ members of particle-vibration multiplets, e.g. the $|3^-; 9_{9/2}\rangle$ and $|3^-; 11_{11/2}\rangle$ multiplets. Calculations by Hamamoto ¹⁾ predict that the missing $j_{15/2}$ strength is carried

in two fragments; one at 3.21 MeV containing 26% of the total strength and the other at 3.5 MeV with 10% of the total strength. As reported last year the (α, h) reaction, which enhances high- ℓ transfers, was used to look for these missing fragments with negative results. As a continuation of this investigation the (α, h) reaction at 58 MeV is being used to measure the spectroscopic factors for exciting the $g_{9/2}$, $i_{11/2}$, and $j_{15/2}$ levels in ^{209}Pb . Angular distributions have been measured in the range $10^\circ - 60^\circ$ and a search has been made without success for levels containing significant $j_{15/2}$ strength up to 6 MeV excitation. The $\ell=4$, $\ell=6$, and $\ell=7$ angular distributions are relatively structureless and quite similar from 10° to 60° . It is planned to measure the angular distributions between 0° and 10° where DWA calculations predict discernible differences between the different ℓ transfers.

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A9. The Two-Proton Multiplet Structure in ^{210}Po

Robert Tickle and J. Bardwick

The $^{209}\text{Bi}(\alpha, t)^{210}\text{Po}$ reaction at 45 MeV has been used to study the two-proton multiplet structure in ^{210}Po . Many new levels were observed and proton configurations are suggested for the lowest three multiplets. The work was completed and the results published [Phys. Letters 36B, 32 (1971)].

A10. Multiplet Structure of ^{210}Bi From the
 $^{209}\text{Bi}(d,p)$ and $^{209}\text{Bi}(\alpha, ^3\text{He})$ Reactions

C.K. Cline^{*}, W.P. Alford^{*}, H.E. Gove^{*}, and R. Tickle

Levels in ^{210}Bi have been studied by the $^{209}\text{Bi}(d,p)^{210}\text{Bi}$ reaction at 19 MeV (using the University of Rochester MP tandem Van de Graaff) and the $^{209}\text{Bi}(\alpha, ^3\text{He})^{210}\text{Bi}$ reaction at 58 MeV (using The University of Michigan 83-inch cyclotron).

Transfer l values have been determined and spectroscopic strengths deduced by comparison with measurements of the $^{208}\text{Pb}(d,p)^{209}\text{Pb}$ reaction. The levels populated by high l transfer have been further identified and studied by a comparison of the $^{209}\text{Bi}(d,p)$ and $^{209}\text{Bi}(\alpha, ^3\text{He})$ results.

The observed levels can be interpreted as members of multiplets arising from the weak coupling of an $h_{9/2}$ proton with a neutron in one of the orbits $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, or $g_{7/2}$. The lowest three multiplets are quite pure, while appreciable mixing is found between members of the $\pi h_{9/2} \nu d_{5/2}$ and $\pi h_{9/2} \nu s_{1/2}$ multiplets and between members of the $\pi h_{9/2} \nu g_{7/2}$ and $\pi h_{9/2} \nu d_{3/2}$ configurations. The results show good agreement with recent theoretical calculations of the structure of ^{210}Bi . A paper describing the work is in press (Nuclear Physics).

^{*} University of Rochester

A11. In-Beam Gamma-Ray Spectroscopy

R.L. Shoup, H.C. Griffin and K.L. Hull

The in-beam gamma-ray spectroscopy program was described at some length

last year. In brief these studies, which involve the investigation of gamma-ray transitions produced by (particle,xn) reactions, have as their major purpose the complementing of information obtained from charged-particle reaction studies performed in this laboratory. The technique is used to determine the energies, spin, parities, and lifetimes of excited product nuclei and is particularly useful in identifying high-spin states which are often relatively difficult to determine by other means.

This past year measurements were extended to include rare-earth nuclei and nuclei in the $Z \approx 82$ region. Approximately one-third of the effort was concentrated on measurements of lifetimes. While experimental difficulties were encountered in the measurement of the low energy gamma-rays from rare-earth nuclei, useful results were obtained for gamma-rays as low as 150 keV.

Early in the year γ - γ coincidence measurements were made [on the reactions $^{139}\text{La}(\alpha,2n\ \gamma\text{-}\gamma)\ ^{141}\text{Pr}$ and $^{141}\text{Pr}(\alpha,2n\ \gamma\text{-}\gamma)\ ^{143}\text{Pm}$] using a NaI counter and a Ge(Li) counter. The NaI counters can be used for those reactions in which high resolution is not required. It is not adequate however for odd A rare-earth nuclei which have high level densities, and measurements in this region were delayed until a second Ge(Li) counter was obtained. The two Ge(Li) detectors, together with the ORTEC ARC timing system, permitted a timing resolution of 50 nanoseconds in the gamma-ray energy range from 100-to-600 keV. Because the timing resolution was less than the cyclotron rf cycle, the true-to-chance coincidence ratio was better than 5 to 1.

A new gamma-ray chamber was built for measuring gamma-ray angular distributions and angular correlations, and while some angular distributions were measured on $N=82$ isotones, these data are of little value because of the poor resolution of a NaI monitor counter being used to normalize the data. Such measurements will require an additional Ge(Li) detector.

The computer program, SAMP0, was adapted to The University of Michigan 360/67 computer to assist in data analysis. The program fits gamma-ray peaks with a skewed gaussian shape and normalizes the data with respect to the energy response of the Ge(Li) counters.

a) N=82 Isotones and Z=82 Nuclides

Timing and NaI-Ge(Li) coincidence data have been accumulated for the reactions $^{139}\text{La}(\alpha, 2n)^{141}\text{Pr}$ and $^{141}\text{Pr}(\alpha, 2n)^{143}\text{Pm}$ at $E_\alpha = 28$ MeV as a supplement to the data obtained by the $^{141}\text{Pr}(\alpha, \alpha')^{141}\text{Pr}$ reaction. Because the preliminary results of the $^{139}\text{La}(\alpha, 2n)^{141}\text{Pr}$ have been reported, ¹⁾ the level scheme is shown but is not discussed here. The measurement of gamma-ray cascades, identified from the coincidence data and intensity and timing measurements in ^{143}Pm permit a level scheme to be constructed. Part of the timing data for ^{143}Pm is shown in Fig. A11-1. The 271-keV state contains two resolved delayed components--one with a half-life of 24 nsec and the other with a half-life of 10 nsec. The level scheme for ^{143}Pm constructed from these data is shown in Fig. A11-2. The cascade starting at the 2928 keV level is believed to be the deexcitation of a high spin state. The spin assignments of the levels above 1 MeV of excitation energy are tentative. These levels lie in the energy region of high spin states of positive parity predicted by Wildenthal. ²⁾ It should be noted that the levels above 1-MeV excitation in both ^{141}Pr and ^{143}Pm do not correspond to states observed in other reactions. Additional angular distributions should help clarify the spin assignments. (The $11/2^-$ states were discussed in the 1971 Annual Report.)

Measurements are under way in the Z=82 region, and preliminary data have been accumulated on the following reactions:
 $^{198,200,202,204}\text{Hg}(\alpha, 2n)^{200,202,204,206}\text{Pb}$ and $^{203,205}\text{Tl}(\alpha, 2n)^{205,207}\text{Bi}$ at $E_\alpha = 28$ MeV, and $^{203,205}\text{Tl}(\alpha, 4n)^{203,205}\text{Bi}$ at $E_\alpha = 45$ MeV. Figure A11-3 shows

Fig. A11-1. Typical time spectra for gamma-rays (N=82 and Z=82).

Fig. A11-2. Level scheme for ^{141}Pr and ^{143}Pm from gamma-ray data.

$^{205}\text{Tl}(\alpha, 4n) ^{205}\text{Bi}$

Fig. A11-3. Singles gamma-ray spectrum for the $^{205}\text{Tl}(\alpha, 4n) ^{205}\text{Bi}$ reaction. Energies listed are in keV.

a spectrum of ^{205}Bi from the $^{205}\text{Tl}(\alpha,4n\gamma)^{205}\text{Bi}$ reaction. A number of delayed gamma-rays are observed, some of which are illustrated in Fig. A11-1. The spectra show both prompt and delayed components in the timing peaks.

b) Odd-Proton Deformed Nuclides

Much of the effort on the in-beam gamma-ray measurements is now being devoted to those rare-earth nuclei being studied via the charged-particle reactions. As one example, the level structure of ^{163}Ho is being studied by the proton transfer reaction $^{162}\text{Dy}(\alpha,t)^{163}\text{Ho}$ (see Section A5-c) and also by means of the $^{164}\text{Dy}(p,2n\gamma)^{163}\text{Ho}$ reaction. The acquisition of a second Ge(Li) detector has permitted more fruitful measurements, such as γ - γ coincidences, to be made and makes it possible to identify cascade relationships within individual bands and between bands.

Data have been accumulated on the following reactions:

$^{158,160}\text{Gd}(p,2n\gamma)^{157,159}\text{Tb}$ and $^{162,164}\text{Dy}(p,2n\gamma)^{161,163}\text{Ho}$ at $E_p = 15$ MeV,
 $^{151,153}\text{Eu}(\alpha,2n\gamma)^{153,155}\text{Tb}$ and $^{159}\text{Tb}(\alpha,2n\gamma)^{161}\text{Ho}$ at $E_\alpha = 28$ MeV and
 $^{159}\text{Tb}(\alpha,4n\gamma)^{159}\text{Ho}$ at $E_\alpha = 45$ MeV.

Particular emphasis has been placed on the $^{160}\text{Gd}(p,2n\gamma)^{159}\text{Tb}$ and $^{164}\text{Dy}(p,2n\gamma)^{163}\text{Ho}$ reactions. The singles gamma-ray spectra are shown in Fig. A11-4. The prominent gamma rays have been identified as transitions within the ground state rotational band and as decays from an excited intrinsic band head to members of the ground state rotational band. Part of the timing measurements for these nuclei are illustrated in Fig. A11-5. The separation between the two peaks in each spectrum represents a cyclotron rf cycle (~ 108 nsec). The level schemes constructed for ^{159}Tb and ^{163}Ho are shown in Fig. A11-6. These schemes were based on the partially completed coincidence data, the timing measurements, published reports, and predictions of the level spacing of rotational bands. The energies of the $5/2^+[413]$

Fig. A11-4. Singles gamma-ray spectra for the $^{160}\text{Gd}(p,2n)^{159}\text{Tb}$ and $^{164}\text{Dy}(p,2n)^{163}\text{Ho}$ reactions. Energies listed are in keV.

Fig. A11-5. Typical time spectra for delayed gamma rays of rare-earth nuclei. The 1.1 second half-life of the 298-keV gamma ray in ^{163}Ho was obtained from ref. 3.

Fig. A11-6. Level schemes for ^{159}Tb and ^{163}Ho . Level energies are in keV. The $7/2^+ [404]$ intrinsic band in ^{163}Ho is tentative.

and $5/2^- [532]$ intrinsic band heads for ^{159}Tb and the energy of the $1/2^+ [411]$ band head for ^{163}Ho were known. 3)

The study of the isomeric transitions in these nuclei forms an important part of the gamma-ray program inasmuch as such transitions are related to the reduced matrix elements connecting the two levels.

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A12. Physics with Heavy Ions

J. Janecke and A.M. VanderMolen

a) Acceleration and Detection of Heavy Ions

Beams of 125 MeV $^{12}\text{C}^{+++}$ ions have been accelerated and extracted from The University of Michigan 83-inch cyclotron, and internal currents up to 24 pamps have been obtained with 15-20 namps in the scattering chamber. Heavy ion production necessitates a low, stable gas flow, and to accomplish this a special gas supply system was built. A Hasting flowmeter was installed to permit accurate gas flow monitoring, and although the present control is being operated manually, an automatic control is being considered. By introducing the gas directly into the ion source chimney, beam currents have been increased and filament and chimney lifetime extended. Data on beam current vs arc voltage were reported last year. A curve showing internal beam current as a function of gas flow is shown in Fig. A12-a-1.

Fig. A12-a-1. Internal $^{12}\text{C}^{+++}$ beam current at extraction radius vs. gas flow. Gas flow is uncorrected for CO_2 . Arc voltage and currents are given in parenthesis.

The gas flow is measured in cc/min STP uncorrected for CO_2 . At a flow below 0.5 cc/min, the arc becomes unstable. The instability appears to be associated with the power supply. In general arc conditions are consistent with those reported by others with similar ion sources.¹⁾ The carbon anode buttons initially used caused carbon deposits to form in the chimney which soon shorted the button to ground. Better results are obtained with a tantalum button. The life of the filament and chimney, while improved by these changes, still remain a problem. These difficulties will probably not be eliminated until an ion source specifically designed for heavy-ion production is developed.

Two methods to detect the heavy-ion reaction products have been used. One method makes use of a ΔE - E solid-state detector telescope. The resolution, limited by kinematic broadening, has been improved by installing a new slit, 1 mm wide, which subtends an angle of 0.3° in the reaction plane. Because the stopping power of the detectors varies greatly for the wide range of heavy-ion reaction products, to obtain reasonable resolution it is necessary to select the reaction products and energy range of the ions being detected by carefully choosing detector combinations to maximize charge collection and signal size. An array of detectors has been obtained for this purpose.

The second method of detection makes use of the magnetic spectrograph in conjunction with photographic plates. Illford K-m1 plates are quite satisfactory. Because of the large kinematic shift in the focal surface of the magnet with mass of target and reaction product, the reaction products cannot be brought to a focus on the photographic plates except at forward angles. The present plate holder is being modified to rectify this. One difficulty encountered with magnetic analysis of heavy ions is the large number of combinations of reaction product, charge state and energy which

result in the same magnetic rigidity. The problem can be partially circumvented by careful choice of the absorber thickness in front of the photographic plates. A more promising solution is the kinematically complete experiment. For example, instrumentation is being developed using the ΔE -E telescope and the new PDP-15 computer to detect ^{20}Ne - α particle coincidences.

b) Reactions Induced by 125 MeV ^{12}C Ions

Investigation of direct ^{12}C -induced reactions on ^{12}C above the Coulomb barrier at 125 MeV has begun using both the ΔE -E solid-state detector telescope and magnetic analysis. Preliminary angular distributions have been measured for elastic and inelastic scattering as well as the one- and few-nucleon transfer reactions. A typical spectrum taken at $\theta_{\text{lab}} = 15^\circ$ with a ΔE -E detector telescope and the Victoreen 20,000 multi-channel analyzer is shown in Fig. A12-b-1. Each ridge represents a given element with fluorine being the uppermost ridge. The one-dimensional carbon spectrum extracted from this two-dimensional array is shown in Fig. A12-b-2. The resolution is of the order of 1.6 MeV FWHM and of this 1.2 MeV is attributed to kinematic broadening. The observed peaks include those from elastic scattering, single and double excitation of the 4.43-MeV state and transitions to the broad peaks at 14 and 20 MeV. Preliminary angular distributions for the first three transitions compare well with those reported by Garvey et al. ²⁾ The present limits on resolution of isotopes and energy levels will be improved with the addition of a 0.3° slit for the telescope to reduce kinematic broadening, by careful choice of detector thicknesses, and by kinematically complete measurements.

A spectrum taken at $\theta_{\text{lab}} = 8.5^\circ$ with the magnetic analyzer and photographic plates is shown in Fig. A12-b-3. The magnetic field was set to detect ^{12}C ions in the 6^+ charge state with energies of the order of 115 MeV.

Fig. A12-b-1. ΔE -E solid-state detector spectrum taken at $\theta_{\text{lab}} = 15^\circ$.
 The strong central range is carbon and the remaining ranges
 represent other elements, starting with the uppermost range
 being fluorine.

Fig. A12-b-2. Carbon spectrum at $\theta_{\text{lab}} = 15^\circ$ extracted from the spectrum in Fig. A12-b-1. The ^{12}C g.s. is in channel 350 with higher excitation levels to the left. The peak on the shoulder of the g.s. is due to ^{16}O contamination in the target.

Fig. A12-b-3. Spectrum taken with the magnetic analyzer and photographic plates. The magnet was set to detect 115 MeV ^{12}C ions in the 6^+ charge state.

States in ^{12}C with excitations up to 14 MeV have been observed with an energy resolution on the order of 285 keV FWHM. This will be improved when the plate holder can be set correctly at the focal surface. A measurement has shown that only about 5% of the carbon ions leave the target in the 5^+ charge state.

A preliminary investigation was made to determine the feasibility of using the gas cell (described last year) in conjunction with the $\Delta E-E$ telescope to study the ^{12}C -induced reactions on ^{16}O . It was determined that the resolution was not quite satisfactory. Improvements in the present beam will allow the pressure in the gas cell to be reduced and therefore the resolution improved.

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A13. Study of Coulomb Energies of Deformed Nuclei

J. Janecke and J.P. Draayer

An analytic expression for the Coulomb energies of deformed and vibrational nuclei has been derived based on the assumption that the matter density in the nuclear interior and the diffuseness of the surface are the same for all nuclei and independent of deformation. A least-squares analysis of the experimentally known Coulomb displacement energies (over 100 data for $Z \geq 28$) resulted in very good agreement with a standard deviation of about 30 keV. ¹⁾ It could be shown, however, that the dependence on the deformation

must be about 10 - 30% stronger than given by the first order correction term. More detailed calculations which include higher order correction terms as well as hexadecapole moments and an angular dependence of the diffuseness are presently under investigation. Explicit analytic expressions which include all these contributions for the electric multipole moments of nuclei with diffuse surfaces have already been obtained.

An expression for the dependence on N and Z of the rms radius of spherical and non-spherical nuclei has been derived. It is possible with this expression to predict for any nucleus the isotope, isotone and isobar shift coefficients $\gamma_N = \frac{3A}{R} \frac{\partial R}{\partial N}$ ($Z = \text{const}$) $\gamma_Z = \frac{3A}{R} \frac{\partial R}{\partial Z}$ ($N = \text{const}$) and $\gamma_{T_z} = \frac{3A}{R} \frac{\partial R}{\partial T_z}$ ($A = \text{const}$). Detailed experimental information exists only for γ_N , and Fig. A13-1 shows the comparison. Here we have the well-known Brix-Kopfermann diagram (taken from ref. 2) with the experimental data and a calculated curve for nuclei along the stability line. The agreement is very encouraging.

References

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A14. Nuclidic Mass Relationships and the Residual

Neutron-Proton Interaction

J. Janecke

The quantity $I_{np}(N,Z) = B(N,Z) - B(N,Z-1) + B(N-1,Z-1) - B(N-1,Z)$ represents an approximate measure for the residual neutron-proton interaction

Fig. A13-1. Isotope shift coefficient γ_N as a function of N (Brix-Kopfermann diagram). The experimental points are from ref. 2. The solid line has been calculated for nuclei along the stability line.

in nuclei. Here $B(N,Z)$ denotes the binding energy. Thus, mass data can be used to extract information about this interaction. A comparison of I_{np} for the mirror nuclei based on the 1971 atomic mass evaluation ¹⁾ showed no indications for significant symmetry breaking charge-dependent nuclear effects. ²⁾ This result is contrary to the recent conclusions of Basu and Banerjee. ³⁾

The quantity I_{np} can be used to construct nuclidic mass relationships. It was discovered in the course of this study that the well-known Garvey-Kelson nuclidic mass relationships ⁴⁻⁶⁾ contain systematic errors. These errors, small as they probably are, accumulate and lead to considerable total errors in the predicted masses of very neutron-rich and proton-rich nuclei. It can be shown that the diverging predictions from the transverse (GK-T) and longitudinal (GK-L) relationships represent only estimated upper and lower limits. A new generalized nuclidic mass relationship has been derived. It is less rigid than the earlier relationships. The new relationship, while exact in principle, requires for its application a certain knowledge about the A and T_z dependence of the quantity I_{np} . The numerical verification of the above conclusions is presently under way. ⁷⁾

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A15. Computer Code BOUND

A.S. Broad

One of the most difficult problems in the analysis of direct reactions on deformed nuclei is the correct computation of the bound state wave function. In spherical nuclei this presents no problem as one can easily compute radial form factors for central potentials. Computer code BOUND has been written to compute bound state wave functions for particles in deformed wells via a coupled channels technique.

The Hamiltonian assumed is $H_0 + V'$, where H_0 is the spherical Woods-Saxon potential and V' is the potential due to deformation. The functions ϕ_i are defined by

$$[H_0 + V'] \sum_{i=1}^N \phi_i = E \sum_{i=1}^N \phi_i$$

or

$$[H_0 - E] \phi_i = - \sum_{i'=1}^N \int_0^{\infty} \phi_{i'} V' \phi_i dr$$

The code BOUND solves this equation for each member of the set ϕ_i . The numerical method is similar to that developed by Rost.¹⁾

Calculations in the rare-earth region show that the "deformed" wave function differs significantly from the "spherical" wave function near the nuclear surface. This is of considerable importance inasmuch as the predicted stripping or pickup cross sections depend strongly on the magnitude of the wave function in this region. Further, the wave functions now depend on Ω (the projection of $\vec{J}_2$ onto the symmetry axis) whereas the spherical wave functions have no such Ω dependence. As an example the $1h_{11/2}$ member of the $1/2^- [521]$ orbital of ^{185}W is shown in Fig. A15-1. The dashed curve

W-185

1/2-(510)

2*J= 11

L= 5

Fig. A15-1

is for the usual spherical Woods-Saxon potential and the solid curve is for the deformed potential.

References

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A16. ^{11}C Labeled Dopamine

An area of interest to some members of the Cyclotron Laboratory that has been growing in the last few years is the application of the techniques of nuclear physics to the field of nuclear medicine. As a starting point in developing and applying existing and new techniques and as a result of mutual interest between the Department of Nuclear Medicine and the Laboratory, Professor John Bardwick is undertaking the production of ^{11}C , an isotope that cannot be produced at the nuclear reactor or purchased commercially, for use in the preparation of ^{11}C labeled dopamine to be used for visualizing the adrenals. (The twenty-minute half life of ^{11}C precludes its being obtained elsewhere.) The first trial production is awaiting the completion of the hot-chemistry facilities necessary to label the dopamine with ^{11}C . The necessary laboratory space is available to the Department of Nuclear Medicine, and the funding for the necessary equipment is being negotiated for by them. As a preliminary, Professor Bardwick has been cooperating in the study of the oxidation of graphite in vacuum in the presence of various catalysts.

A17. High Resolution In Vivo Monitoring
of Low Energy β -emitters

John Bardwick

A small grant from the Michigan Memorial Phoenix Project was awarded for the development of a probe suitable for in vivo monitoring of low energy β -emitters in animals.

The use of radioisotope techniques in nuclear medicine, and in animal research on biological phenomena, is increasing in scientific importance.

Nuclear medicine techniques suitable for visualization of organs or tumors in human patients are not applicable to the small animals used in biological research for several reasons. First, the resolution presently obtainable is not adequate to delineate the separate regions of the brain of a mouse, for instance. Second, the isotopes chosen for visualization of human organs are not necessarily involved directly in the functioning of these organs; it is sufficient that they concentrate in or around the organ in sufficient quantity to allow the organ, and any abnormalities, to be seen.

On the other hand, biochemical research on the central nervous system (generally performed using small animals) requires information on the location and concentrations of naturally occurring substances. These for the most part have in common only carbon, hydrogen, nitrogen, and oxygen, and thus one is forced to use one of these elements as a tracer.

Present techniques for localization of ^{14}C or ^3H labeled tracers all involve killing the experimental animal with the clear possibility of disrupting the system under investigation. Attempts to minimize this disruption by rapid killing, i.e. immersion in liquid nitrogen or microwave irradiation, are common. ¹⁾ Even if the sacrifice of the animal doesn't disrupt the

system, one is still left with uncertainties caused by variability between animals, which further complicates the study of time-dependent phenomena.

One can avoid the experimental errors intrinsic to the above techniques by using a low energy beta emitter such as ^{14}C as a tracer, allowing the limited range of the electrons (~ 0.1 mm) in tissue to define the area observed, and then detecting the electrons with a small probe placed in direct contact with the physiological system of the living animal. This procedure will allow the mapping of the tracer isotope in living, surgically-prepared animals, with a resolution that could be in ideal cases a fraction of a millimeter.

Detection of the beta particles will be done with a small scintillator coupled to a photomultiplier via a light pipe. The general technique is of course old, and similar instruments for detecting neutron or gamma radiation are commercially available.²⁾ They are not suitable for detection of low energy betas however due to window thickness and noise. There is available a commercial instrument using an avalanche-type semiconductor which eliminates the problem of background noise, and is thus suited for low level β counting.³⁾ However, it suffers the disadvantage of lack of flexibility due to the fact that the expensive semiconductor is not easily tailored to a specific application.

The unique features of the proposed instrument are the following:

1. Resolution is obtained by allowing the short range of the electrons in tissue (~ 0.1 mm for ^{14}C) to define the area observed. This requires placing the sensitive area of the probe in direct contact with the sample.
2. Since the probe is in direct contact with the substance being analyzed, the counting geometry is essentially 2π , ensuring efficient

counting of low levels of activity. Counts from outside of the area of interest can be eliminated by slightly recessing the scintillating material.

3. Background is reduced by minimizing the sensitive volume of the detector. A typical size for the scintillator would be .060" x .060" x .005".

4. The active area of the probe is not subject to surface contamination, nor does it require electrical connections of any kind.

5. The scintillator material is inexpensive and easily fabricated, and thus can be tailored to maximize the efficiency of the probe for any specific application. For example, the head of such a probe can be immersed in liquids, shaped to fit into small cavities, or made hollow to surround various shaped structures.

References

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B. INSTRUMENTATION

B1. Neutron Time-of-Flight

a) Detectors

R. Polichar, P. Julien and W.C. Parkinson

The multi-counter array of neutron detectors described last year has been completed and tested. The array consists of ten disk-shaped counters, each of which has an active volume 9-5/8" in diameter by 1" thick containing NE213m liquid scintillator. The liquid in each counter is viewed by an RCA8575 phototube mounted on the axis of the disk and immersed in the liquid. The array, mounted on a portable cart together with the electronics associated with signal summing and high voltage fan-out, is shown in Fig. B1-1.

Each of the ten phototubes has its own timing discriminator (a modified ORTEC 270 constant-fraction timing unit) built into the base. The fast logic signals from the ten discriminators are added with virtually no degradation in resolution compared to that of a single counter. The linear signals are also added and sent to a delay line amplifier for energy analysis and pulse-shape discrimination. The relative gains of the photomultipliers are adjusted with a variable fan-out. The tubes and bases have been matched so that full advantage can be taken of the wide dynamic range of the constant-fraction discriminators. Timing variations between tubes due to minor differences in high voltage or temperature drift are compensated to within ± 50 picoseconds by means of calibrated delay boxes between each counter

Fig. B1-1

and the fast adder. A block diagram of the counter electronics is shown in Fig. B1-2.

To facilitate the checking of the relative timing of the counters both in the initial setup and during an experiment, a light emitting diode (LED) has been installed on each counter. The light pulses from the diodes can be attenuated by small camera irises. An electrical pulse, formed by discharging a precision capacitor through a mercury relay into a 50Ω line, provides a trigger signal and drives the LEDs. The RC time constant associated with each LED is adjusted to approximately reproduce the shape of the scintillation pulse. These light pulses, stable in shape and time, provide a reliable standard by which the performance of the counter array can be checked and monitored.

The counter array has been tested using gamma rays produced by the internal cyclotron beam striking a carbon target. By narrowing the phase width of the circulating beam, gamma-ray pulses of 600 psec duration were produced. Using these "flashes", the several time constants in the fast discriminator circuit were adjusted to optimize the response of the circuit to the light pulses from the disk counters. Such an adjustment is essential since the shape of the light pulse is determined by the particular geometry of the counter. From these measurements the time resolution of the total array was determined to be 800 ± 50 psec and is no more than 50 psec larger than that of a single counter. In making these measurements the gamma "flashes" produced by the beam were monitored by a small counter of known resolution so that contributions due to the time spread of the beam could be removed.

The array subtends a solid angle of 2.5×10^{-4} str. at 40 meters, and has a theoretical detection efficiency of 7% for 15 MeV neutrons.

Fig. B1-2. Block diagram of neutron time-of-flight electronics.

The array has been used to obtain a neutron spectrum from the $^{12}\text{C}(h,n)^{14}\text{O}$ reaction. Because the new beam line (Section B1-c) is not yet operational, the measurements were made as described last year. The target was placed in the vacuum duct of the second beam preparation magnet and the array in the passageway between the experimental area and the control room. The results have been uniformly disappointing in that the spectra are no better than that shown in last year's report. This is largely because of poor stability in the time spread of the extracted beam of ^3He . This problem has been investigated in detail and corrective measures are being taken (see Section B5). Because a stable 22-MeV deuteron beam was available of width 1.4 nsec on target, an attempt was made to measure the neutron spectrum from $^{208}\text{Pb}(d,n)^{209}\text{Pb}$. The high neutron background from the deuteron beam washed out the spectrum, indicating the need for better shielding between the target area and the counters.

b) Gated Ion Source

R.H. Day and W.C. Parkinson

A gated ion source of an improved design with respect to the geometry of the electric field was built and tested. The new design improved the characteristics of the gated current but suffered a mechanical failure during test. Since the source is an essential element for the neutron time-of-flight facility, work on it will be resumed in the near future. At the moment it is of low priority, in part reflecting confidence that it is a solved problem and in part because the modifications to the cyclotron (Section B5) require a modified geometry for the ion source. A complete description of the design and test results has yet to be prepared for publication.

c. The Time-of-Flight Beam Optics

J. Bardwick, J.F. Petersen, and W.C. Parkinson

The instrumentation for the new time-of-flight beam line is installed, including the permanent wiring, switch gear and plumbing. The switching magnet, one of the two quadrupole pairs, and the "neutron magnet" are visible in Fig. B1-3. The "neutron magnet" and tunnel are shown in Fig. B1-4. The "neutron magnet" was fabricated by modifying an existing analyzing magnet of one-meter radius of curvature to convert it to 1.4-meter radius uniform-field magnet. It will be recalled that positioning the target at various azimuths in the magnet duct allows neutron angular distributions to be measured from 0° - 80° with the neutron detector in a fixed location, namely at the end of the neutron tunnel. The slits, vacuum systems and much of the duct work necessary to run beam through the entire system have been fabricated. The alignment and calibration of this system is partially complete. While beam from the cyclotron has been brought to a focus in the new bay by the first quadrupole magnet, the remainder of the alignment and final positioning of the magnets must await the completion of the modifications to the cyclotron (Section B5) since it is expected that there will be a shift in the apparent source position of the beam from the cyclotron.

B2. The Position-Sensitive Detector Array

W.S. Gray, D. DuPlantis, and D.A. Lewis

The array of position-sensitive detectors, previously used in conjunction with the Victoreen 20,000 channel analyzer, has been successfully interfaced to the PDP-15/30 data acquisition system. The transfer to the PDP-15 has

Fig. B1-3

Fig. B1-4

resulted in a considerable increase in the flexibility and rapidity of data manipulation, which can now be performed in the background-foreground mode while data acquisition continues in the foreground.

Since the array has not been fully described in past progress reports, a brief description is given here. The array consists of five detectors manufactured by Nuclear Diodes, each with an active area of 14 mm x 50 mm and a depletion depth of 350 μ . These are mounted on ceramic rings in a case fabricated at the laboratory. The ceramic ring mounts allow the option of cooling to liquid nitrogen temperatures if necessary to improve the position resolution. The two preamplifiers handling the position and energy-deposited signals from each detector are mounted as part of an integral unit containing the detector case. This arrangement is illustrated in Fig. B2-1, which shows a photograph of the five detector units mounted on the positioning frame. The array as a whole is placed in an evacuated box enclosing the image surface of the analyzing magnet. Electrical connections are made through two multi-cable vacuum feed-throughs.

Because of the relatively large dispersion of the magnetic analysis system, the inherent position resolution of these devices (approximately 1 - 1.5 mm) is small compared to the contributions from other sources to the line width normally observed at the image surface of the spectrometer. This fact makes it feasible for most experiments to increase the effective length of the detectors by rotating them with respect to the image surface, without affecting significantly the overall energy resolution. The configuration shown in Fig. B2-1 is normally employed. The array is mounted along the image surface of the spectrometer, at an angle of 37° with respect to the optic axis. Each detector is rotated by 23° about a vertical axis passing through the image surface, which results in an effective length of approximately

Fig. B2-1. The position-sensitive detector array.

72 mm along the image surface. The detectors are spaced in such a way that the dead region between adjacent detectors is approximately one-half the effective length of each detector. Complete coverage of the image surface (approximately 560 mm) is accomplished by taking two exposures, the second with the magnetic field of the spectrometer adjusted so as to shift the spectrum by one-half the distance between the centers of the adjacent detectors.

A schematic diagram of the electronics used with the array is shown in Fig. B2-2. Each detector provides a signal proportional to the energy deposited (E) and the product of position and energy deposited (XE). Since the depletion depths of available detectors are in many cases not sufficient to stop the particles of interest, energy broadening due to straggling can result in serious deterioration of the resolution of the XE signal. This effect is eliminated by using an analog divider, fabricated in this laboratory, which produces a signal proportional to XE/E .

Particle identification is obtained from the E signal, which varies depending upon the magnetic rigidity and range of each type of particle. A single-channel analyzer operating on the prompt E signal from each detector opens a dual linear gate, which passes the delayed E and XE signals only for events corresponding to the particles of interest. The logic pulse from each single-channel analyzer is also used to identify the detector in which the event occurred.

The E and XE signals from the five detectors are fed in common to the inputs of the analog divider, which provides a true position signal (X) in a conversion time of 4 μ sec. The routing pulses from the single-channel analyzers are presented to a router, which generates five different signal levels depending upon which of the single-channel analyzers has fired. The divider and router outputs are analyzed in separate ADCs operated in an X-Y

Fig. B2-2. Block diagram of the electronics used with the position-sensitive detector array.

coincidence mode, using the two-parameter pulse-height analysis routine PHA2 available with the PDP-15/30. In foreground the data are stored as a two-dimensional array, with the position spectrum from each detector occupying a different Y address. In background this array is converted into a 320-channel record consisting of five sequential 64-channel spectra and stored on Dectape.

A sample spectrum taken with this system is shown in Fig. B2-3. The reaction is $^{45}\text{Sc}(d,d')$ at $E_d = 23$ MeV. The elevated portion of the spectrum represents a second exposure in which the field of the spectrometer was adjusted to fill in the gaps between detectors according to the scheme discussed previously. The figure was generated by a routine which reads the Dectape records corresponding to the two exposures, automatically sets the horizontal and vertical scales, calculates the effective shift of the second exposure given the change in optic axis energy, and operates the Calcomp plotter.

The overall resolution observed in this spectrum is about 4-1/2 mm, or 22 keV FWHM, approximately the value estimated from considerations of energy straggling in the target and beam spot size. Since the detectors are not capable of stopping the 23-MeV deuterons detected here, the resolution would have been considerably poorer without the divider. The position resolution which can be achieved in detecting energetic particles has been investigated by placing a thin wire in front of the detector, positioning a particle group so that it falls upon the wire, and analyzing the sharpness of the "shadow" cast by the wire. Measurements of this kind in which 37.6-MeV deuterons were detected have indicated a position resolution of about 1-1/2 mm, or very nearly the value observed with alpha particles which are stopped within the depletion zone.

Fig. B2-3. A sample spectrum taken with the position-sensitive detector array. The elevated portion represents a second exposure taken with a different analyzer field setting, as explained in the text.

B3. Target Preparation

A major problem in the study of the rare-earth nuclei has been the fabrication of suitable targets. Because they have high melting points and large heats of vaporization, most rare-earth elements are difficult to evaporate. In the past the usual procedure was to reduce the oxide (the inventory form) while it was being evaporated in a suitable boat of tungsten, molybdenum or tantalum. Each target material presented its own special problem and it was difficult to control the thickness, uniformity and size of the target. The problem has been solved by the construction of a 200-watt electron gun evaporator similar to that used at the University of Pittsburgh. Electrons, boiled off a tungsten filament biased to -2KV, are magnetically focused onto a small rare-earth oxide pellet. The high power density of the focused beam allows direct evaporation of the rare-earth oxide with good control and without the large heat input (several kilowatts) required by the former technique. Local temperatures in the oxide pellet of up to 2900°C can be obtained easily, and good targets of Dy_2O_3 and Gd_2O_3 have been produced by this method.

The oxide target materials tend to boil off the target under beam bombardment (a 7% decrease in thickness was observed during a 24-hour run with 600 namps of 45 MeV α -particles on a Gd_2O_3 target), and corrections must be made to the measured cross section. This is done by continuously monitoring the α -elastic scattering during an exposure.

B4. Energy Calibration and Mass Determinations

The higher energies available with the new generation of cyclotrons permits the study of nuclear reactions having large negative Q-values and large Coulomb barriers, and the acceleration of heavy ions with a high energy per nucleon opens up the possibility of mass determinations far from the region of stability. New techniques of instrument calibration are required since the old standard $^{210}\text{Po}(\alpha)$ and threshold measurements are no longer suitable. This problem has been investigated in some detail (and formed the subject of an invited paper at the Fourth International Conference on Atomic Masses and Fundamental Constants). One useful technique is that of momentum cross-over,¹⁾ and the kinematics of a number of potential reactions have been calculated. The problem of energy straggling in very thin targets, as well as the limitations on accuracy imposed by the ion-optical system, have been investigated. A detailed paper on part of this work is in press.

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B5. Orbit Studies and Beam Dynamics

W.C. Parkinson, W.S. Gray, J.F. Petersen and R.H. Day

This past year a considerable effort has been devoted to improving the stability and quality of the accelerated beams and developing beams of higher energy. Previously most beams were obtained by "empirical twiddling" by the

research staff for their particular experiments. Over the years this has resulted in inefficient operation and not infrequently damage to components of the cyclotron. A systematic study of the problem has been made, and as a result the cyclotron was shut down in mid-April to make significant modifications. The modifications should be completed by mid-June, and there is confidence that the operation of the cyclotron itself will no longer be the limiting factor in research productivity. As an example of what is to be expected, just before the shut down a 45-MeV α -beam was accelerated essentially continuously over a three-week period with a beam current in the scattering chamber of 100 na per $E/\Delta E = 10^{-4}$. For most experiments, using dispersion cancellation, typical currents on the target were from 300 to 600 na. This number should be improved by at least a factor of two after the modification.

In the course of the studies a number of improvements were made to the diagnostic instrumentation, and a number of minor mechanical and electrical changes were made in the cyclotron. Many of these are listed in Section C2.

The principal problems studied are described very briefly below.

a) Central Orbit Program

Median-plane electric fields were measured using the electrolytic paper technique for a number of central geometries. Magnetic field data from earlier measurements were used together with the new electric field data to numerically solve the equations of motion for a variety of ions in the central region of the cyclotron. The radial motion as well as the phase history was studied. The results indicated that phase selection could be achieved most efficiently by a slit inside the west dee. This was installed in early 1972.

b) Puller Design

To simplify the central geometry and to aid in phase selection, various puller designs were tried. Generally, the pullers represented attempts to create an electric field-free region just beyond the puller face.

c) Magnetic Field Programs

Computer programs were written to predict magnetic fields resulting from any gradient coil current combinations. Isochronous fields were created by the program and then tested with the actual beam in the cyclotron using the phase probe to measure the phase and phase width of the circulating beam as a function of radius.

d) Radial Motion

The radial motion of the accelerated ions was measured using the "turn pattern" technique. The observed sensitivity of these patterns to dee balance lead to an investigation of the effect of the shape of the dees. Calculations indicated an enhanced effective first harmonic ("gap-crossing resonance") due to the non-radial flare in the dee gap. After the dees were altered to provide a radial flare, the sensitivity to dee balance was considerably reduced (to less than the equivalent of a 5-gauss first harmonic).

e) Vertical Motion

Pullers were designed to limit the vertical aperture and thus the vertical motion near the machine center. Alterations were made to increase the vertical symmetry in the central geometry. Experiments with "suppressor" plates, to suppress the vertical motion, were successful and considerable control of the vertical motion, as observed with mylar burn patterns, was obtained.

f) Equilibrium Orbit and Extraction Programs

Stability limits for radial oscillations and allowable first harmonic

amplitudes were recalculated with an equilibrium orbit program. The extraction of ions of various energies was reexamined with a modified version of the orbit program, and in particular the effects of the phase of the rf voltage and the radial momentum (amplitude and phase of the radial oscillation) on the extracted particles was studied. (See Section 85-h.)

g) The Deflector Problem

In the interest of using larger electric fields in the deflector channel, an investigation was made into the mechanism of electric breakdown. As a result of a search and review of the very extensive literature on the subject, it was concluded that the breakdown was caused primarily by the production of charged "clumps" (in our case a "clump" of carbon atoms knocked out of the septum). A new stainless steel deflector bar, designed to trap the "clumps", and stainless steel liners for the ground sheets in the region of the deflector were installed. The dc breakdown characteristics were improved, but with rf voltage on the deflector channel the situation was, if anything, worse. The reasons for this are believed to be understood and the rf is to be removed from the channel. An equally important reason for removing the rf voltage is that ions accelerated at 0° rf phase (measured with respect to the centerline of the dees) experience, at the instant of extraction, an rf voltage in the deflector channel which is lagging by 60° and is in opposition to the applied dc voltage. Thus a much higher dc voltage is required to extract the ions.

h) Cyclotron Modifications

The conclusions drawn from these studies were that an equivalent small first harmonic in the magnetic field existed near the extraction radius, that gradient coil #8 was introducing a shift in the median surface causing the beam to blow up vertically near 34 inches more or less rapidly depending

on the current in coil #8, that the contributions to the magnetic field by the gradient, bimp and bump coils were not sufficiently well-known to predict isochronous fields with the accuracy required, and that it was necessary to remove the rf voltage from the deflector channel. It was decided to remove the rf from the deflector by converting the cyclotron from a two-dee to a one-dee machine. This in itself is a relatively minor undertaking since it is only necessary to remove the west dee and dee stem, couple the rf power to the east stem and add a "dummy"-dee to the ground sheets. The loss in energy gain per turn is not as serious as might be expected since the dee voltage can be raised considerably. No other significant changes are required in the rf system. But complications do arise in that the conversion requires a new ion-source tube and gated ion-source structure, new phase defining slits, new vertical suppressor plates, and modifications to the beam probes and to the extractor system. During the shutdown for the conversion, extensive magnetic field measurements are being made to locate the cause of the first harmonic, to find and correct the difficulty with #8 gradient coil, to calibrate the gradient, bimp and bump coils, to check the isochronous field prediction program, and to measure "Rose" shims to be used in the future in extending the deuteron energy range from 40 to 52 MeV. The modifications and field measurements are under way and as indicated above are expected to be completed by mid-June.

There is considerable confidence that these changes will result in higher quality and better control of the internal beam and, with removal of the rf from the deflector channel, in higher quality and intensity of beam delivered to the scattering chamber. It might be noted that the rf on the deflector adds to the beam a component of momentum in quadrature, the magnitude of which depends on both the phase and phase width of the beam

appearing at the septum. While this in itself does not affect the apparent source position of the extracted beam, it does cause some increase in the radial phase space density. But more important, a point previously overlooked, it increases the energy spread in the extracted beam. By removing this contribution to the energy spread, the intensity of beam in the scattering chamber for a given quality should be increased by a factor of two to five.

C. FACILITIES IMPROVEMENTS

C1. The PDP-15 Computer

A significant addition to the instrumentation of the laboratory is the new on-line DEC PDP-15/30 computer which arrived at the end of February. Purchased to perform real-time data acquisition in a foreground environment and simultaneously do background calculations, the 15/30 has an 18-bit word length with 24K of memory, four Dectape units, extended arithmetic hardware, storage scope display, Calcomp plotter, and card reader. Two Northern Scientific analog-to-digital converters, Model NS-623, were connected by DEC with a Model NP02-LA interface. While the computer itself was operational within a few days, it was some weeks before the various bugs in the software and interfacing were cleared out and the data acquisition routines were operational. The position-sensitive detector array is now interfaced with the computer (see Section B2) and plans are currently being made to interface other systems such as the spark chamber, counter telescopes, and neutron detectors.

C2. Electronics and Miscellaneous

D. DuPlantis and W.E. Downer

To improve the reliability of the high voltage power supply for the radio frequency system, two major changes are being made. The set of three-

phase saturable reactors was replaced by an autotransformer constructed by Westinghouse Electric Corporation. This was done because of a history of frequent burnouts of the reactors and because a variable voltage output was no longer needed. A solid-state rectifier system constructed by Westinghouse is also being installed. This replaces the set of vacuum tube diodes that have always been subject to frequent breakdowns which resulted in downtime and high operating costs.

The power supplies for the magnets in the new beam line have been installed, together with the required additional electrical switchgear and main power lines from the substation. Each supply has also been converted for remote operation. The construction and installation of the regulator for the "neutron" magnet (Section B1-c) has been completed.

To make space for the new computer, the former electronics shop was converted into the data acquisition room, and the shop moved to the old counting room.

A large number of small improvements were made to the cyclotron systems. These included a new ion-source regulator and new reference sources for the harmonic coils. A device for regulating the field of the main magnet, based on the Hall effect, is being designed to replace the Varian NMR used for the last several years and which suffers from many difficulties. A partial list of other improvements includes:

1. A telescope was installed to measure accurately the position of the ion source and puller.
2. New beam probes were made and installed.
3. A stainless steel extractor was fabricated and stainless steel ground sheet covers were installed above and below the extractor.

4. New "lips" were installed on the dees and damage to the dees repaired.
5. A new slit for phase selection was installed.
6. A flowmeter and gas supply system was installed for the ion source for use with heavy ions (Section A12-a).
7. Vacuum station tanks, vacuum ducts, cooling water, power, air lines, and drains were installed in the new equipment bay.
8. The Pyr-A-Larm smoke detection system was installed and connected to ring in the University Security Office.

Approximately 450 visitors were shown through the Laboratory last year.

D. PERSONNEL

Faculty

J. Bardwick III	R. Polichar
W.S. Gray	R.S. Tickle
J.W. Janecke (on leave 1/1/72 - 8/1/72)	H.C. Griffin (Nuclear Chemistry) (on leave 7/1/71 - 9/1/72)
W.C. Parkinson	

Research Associates

F.T. Baker (Appt. 7/1/71, Term. 8/15/71)
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Student Assistants

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A.S. Broad	J.F. Petersen
M.A. Firestone	J.A. Splett
P.F. Julien	A.M. VanderMolen
G.P. Neff	

Graduate

R.H. Day	D.A. Lewis
D.P. Duston (Appt. 3/9/72)	

Undergraduate and Hourly Assistants

J.M. Atwater (Term. 8/13/71)	A.H. Ringwald (Appt. 9/16/71 Term. 1/17/72)
J.A. Ionson (Appt. 5/2/71 Term. 7/30/71)	J.R. Rumierz (Term. 4/20/71)
J.J. Kotz (Appt. 6/28/71 Term. 9/1/71)	D.G. Smedley (Term. 4/15/71)
R.A. Preston (Appt. 5/3/71 Term. 4/20/72)	A.G. Zajonc (Appt. 3/30/71 Term. 9/8/71)

Engineers

D. DuPlantis - Cyclotron
A.V. Smith - Design
M.K. Willemssen - Electrical (Term. 2/29/72)

Electronic Technicians

R.M. Brenner (Term. 8/13/71)
D.E. Karl (Appt. 4/28/71, Term. 1/31/72)
R.E. Pontius (Appt. 3/3/72)
J.R. Thompson (Term. 9/24/71)

Cyclotron Operations

W.E. Downer - Supervisor
N.C. Galbraith - Operator (Term. 7/9/71)
S. Gillies - Operator
J.A. Koenig - Chief Cyclotron Operator

Instrument Makers

M.W. Prince
D.M. Schleede

Scanners

A. Halstead
F. Hilberer
F. Schreiber (Term. 12/23/71)
W.C. Stout
Mor-Lin Su (Term. 8/31/71)

Secretary

M. Lammers

E. PUBLICATIONS

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* Reported last year as being in press.