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LOW-ENERGY NUCLEAR REACTIONS AND NUCLEAR SPECTROSCOPY

TECHNICAL PROGRESS REPORT

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SUMMARY

Good progress has been made on the research program proposed last year concerning low-energy reactions and nuclear spectroscopy. The level of effort and the accomplishments have been about as planned in the theoretical calculations on nuclear reactions, and in the instrumentation for nuclear spectroscopy until the cyclotron became operative (February, 1966) for external irradiations with unmonitored beam. Extensive calculations on the excitation functions of alpha induced reactions on Ag^{107} and on isomer ratios produced in the same reactions have been made using the Monte-Carlo method and the statistical theory of nuclear reactions. Cross section measurements for radiative capture of charged particles have begun. Silicon and germanium detectors have been made and systems for mounting and cooling have been developed. Apparatus for measurement of angular correlations of the type γ - γ , e^- - γ and β^- - γ have been constructed and used. Decay scheme studies on a number of nuclides have begun. Instrumentation for measurement of charged particle evaporation spectra has been assembled and measurements will be undertaken in the near future. It has not been possible to begin the program on spectroscopy by direct nuclear reactions but it is hoped that such investigations can be started when a well monitored cyclotron beam in a scattering chamber will become available in the near future.

Three papers have been submitted to a journal for publication and preprints are forwarded to the commission.

1. NUCLEAR REACTIONS

A. Monte-Carlo Calculations

Computer calculations on selected reaction systems such as $\text{Zn}^{64}(\alpha, x)$ and $\text{Ag}^{107}(\alpha, x)$ have been performed in detail and comparisons with existing experimental data have been made. The experimental data ^{1,2} on the $\text{Zn}^{64}(\alpha, x)$ and $\text{Ag}^{107}(\alpha, x)$ include practically a complete set of excitation functions for the (α, n) , (α, p) , (α, pn) , $(\alpha, 2n)$, $(\alpha, 3n)$ reactions as well as some measurements on the (α, γ) cross section. In the Ag^{107} system isomer yield ratios as well as proton spectra at 40 MeV are available. We have chosen to perform extensive calculations

on this reaction system in order to obtain a formalism which provides satisfactory agreement between theory and all the different types of experimental information with the same set of parameters. In these calculations we have used the predictions of the Fermi-gas model of independent nucleons ³⁾ which predicts for the level density parameter

$$a = r_0^2 \frac{A^{2/3}(Z^{1/3} + N^{1/3})}{29.2} \quad (\text{MeV}^{-1})$$

where r_0 is the nuclear radius parameter in fermis, and Z , N and A are the atomic, neutron and mass numbers, respectively. A value of r_0 about 1.22 fm may be used which yields satisfactory agreement in optical model analyses of elastic scattering cross sections ⁴⁾. With this value a is approximately equal to $A/12.5 \text{ MeV}^{-1}$. A more realistic value of r_0 obtained from nuclear scattering of electrons ⁵⁾ for heavy nuclei is slightly lower, certainly no less than 1.17 fm which gives value $\sim A/15$ for a .

In our calculations we have assumed rigid body values for the moment of inertia I as predicted by the Fermi-gas model for all excitations. We have reduced the value for I/I_{rig} and examined how it affects the calculated excitation functions and the isomer ratios.

In this formalism the gamma-ray competition has been included as electric dipole, but the effect of an assumed pure electric quadrupole emission on both the calculated excitation functions and on the isomer ratios has been investigated.

In calculations of excitation functions it was noticed as expected that the dependence of $\Gamma_x(U, J_c)$, the emission function for particle x , on the angular momentum J_c of the compound nucleus was strongly influenced by the assumed particle separation energies ³⁾. This may mean that erroneous dependence on J_c would be introduced when the separation energies used are off by even one MeV.

In this work we have adjusted the gamma-ray emission strength by varying the only free parameter c_k , a quantity including the reduced matrix element for a given multiple, which was taken as constant ³⁾. A good value of c_k for which the (α, γ) cross section is reproduced can be

obtained if the calculated cross sections are normalized to the experimental total cross section rather than those calculated via the optical model. In the systems we have analyzed, data on (α, γ) cross sections were available at low energies below the $(\alpha, 2n)$ threshold. For those energies the quantity $\Gamma_n(U, J_c)/\Gamma_\gamma(U, J_c)$ is a decreasing function of J_c and drops off more sharply for lower excitations. For example for $U = 12.15$ MeV in the $\text{Ag}^{107}(\alpha, x)$ system, it drops from a value of ~ 6 for $J_c = 0.5 \hbar$, to ~ 1 for $J_c = 10.5 \hbar$. We have assumed that the gamma-ray emission strength determined in this way may be used for the neighboring nuclides which are involved in the (α, n) and $(\alpha, 2n)$ reactions. We have no way at present of predicting the dependence of the gamma-ray emission strength on nuclear composition. Arbitrary variations of the gamma-ray emission strength, such as in In^{110} , the (α, n) product, may give (α, n) cross sections dropping less with increasing energy thus providing a still better agreement with experiment. The influence of nuclear composition on the gamma-ray strength needs further investigation. The comparison of calculated excitation functions ⁶⁾ with experiment is illustrated in Fig. 1. It is seen that the main features of the rather complete set of excitation functions is satisfactorily reproduced. It was found that the effect of an increase in the gamma-ray strength increases the magnitude of the (α, n) cross section at the expense of the $(\alpha, 2n)$ but the slope is practically the same.

The effect of the value of the level density parameter a on the excitation functions was investigated next. If the constant c_1 for the dipole emission is kept the same and a increased from $A/12.5$ to $A/6.7$ ($r_0 = 1.64$ fm) the ratio $\Gamma_n(U, J_c)/\Gamma_\gamma(U, J_c)$ decreases markedly so that the cross sections for the (α, γ) and (α, n) are now overestimated. The constant c_1 needs to be decreased from $2 \times 10^{-5} \text{erg}^{-4} \text{sec}^{-1}$ to $5 \times 10^{-7} \text{erg}^{-4} \text{sec}^{-1}$ in order to bring the calculated (α, γ) cross section in agreement with experiment. This brings the (α, n) , $(\alpha, 2n)$ cross sections closer to the experimental, but the overall agreement is worse in that the (α, n) tail drops more sharply with energy than it did when a was taken as $A/12.5$. It was thus found that there are pairs of a and c_1 values for which the gross features of the excitation functions could be reproduced, but only for a between $A/12.5$ and $A/15$ was the best agreement with experiment obtained.

The effect of the assumed values for the moment of inertia on the calculated excitation functions was investigated in some detail. The quantity I/I_{rig} was reduced from unity to 0.6 for all nuclides involved. The results (broken lines) are compared with another calculation with $I/I_{rig} = 1$ (solid lines) in Fig. 2. It is seen that the (α, n) cross section has increased at the expense of the $(\alpha, 2n)$ but the slope at the tail of the (α, n) cross sections has not changed. The (α, γ) cross section is now overestimated and one could decrease c_1 in order to get a better overall agreement with experiment. In one calculation we reduced I/I_{rig} to 0.5 for only the $(\alpha, 2n)$ product nuclide with the result that the (α, n) cross section is now increased and the tail falls off less sharply with increasing energy. One could now reduce again the value of c_1 in order to bring the (α, n) cross section in agreement with experiment. However this approach is rather arbitrary and should not be pursued any further.

In another calculation quadrupole emission was assumed for the deexcitation by gamma rays but no significant difference in the overall agreement with experiment could be found.

In conclusion we can say that good agreement with the experimental excitation functions in the $Ag^{107}(\alpha, x)$ system was obtained when the parameters predicted by the Fermi-gas model are used. These values are $a \sim A/15$, $c_1 = 3 \times 10^{-5} \text{ erg}^{-4} \text{ sec}^{-1}$ and $I/I_{rig} = 1$.

The Monte Carlo formalism adopted in the calculations of excitation functions is most suitable for the evaluation of the distributions in angular momentum that result in each reaction product. From these distributions, evaluation of the ratios of yields of populated isomers can be obtained, thus yielding a method free of approximation about the average kinetic energy or the angular momentum carried by an evaporated particle. In addition, the competition due to gamma-ray emission is naturally taken into account. The details of the program leading to the evaluation of the isomer yield ratios are given in the accompanying preprint submitted for publication ⁷). Here we will emphasize some of the aspects of the angular momentum dependent evaporation model as revealed by following the details of a cascade.

In what follows, the results of the calculations refer to the system $\text{Ag}^{107}(\alpha, x)$. The model parameters used are those described above that gave agreement with experimental excitation functions.

From our cascade data we have collected those events that lead to a specific product, say the (α, n) product. Here we will discuss a typical case, say that of 24 MeV He^4 -ion energy or $U = 26.15$ MeV of initial excitation. This energy is well passed the maximum of the (α, n) cross section so that the gamma-ray competition and its dependence on angular momentum will be most pronounced. In Fig. 3 we show the relative probability of emission of neutrons with kinetic energy falling in the intervals 2-4 MeV, 4-6 MeV, 6-8 MeV, and 8-10 MeV as a function of the angular momentum J_f of the final state. For all emissions with kinetic energy below 7.7 MeV there was enough residual excitation for a second neutron evaporation. It is seen that for such neutron groups the most probable J_f is very high, so that indeed subsequent evaporation of another neutron was highly hindered. It is interesting to notice that the lower the neutron energy, below the $(\alpha, 2n)$ threshold, the higher the average final spin, J_f . For evaporations below the $(\alpha, 2n)$ threshold, however, the average J_f is practically independent of the neutron energy. The best way to illustrate the importance of gamma-ray competition is to plot the number of events that lead to the (α, n) product as a function of E^* the excitation energy in the (α, n) product, regardless of J_f . This is shown in Fig. 4 (dashed curve) with the $(\alpha, 2n)$ threshold marked. The cross hatched area represents the fraction of the (α, n) cross section formed in a first chance emission to an excitation above the separation energy of the second neutron. For each energy E^* there is a distribution in J_f , the average of which is plotted as a solid line in Fig. 4. We notice that below the $(\alpha, 2n)$ threshold J_f is practically independent of E^* and above the threshold it rises with increasing E^* . The probability of forming the $(\alpha, 2n)$ product as a function of the residual excitation in the $(\alpha, 2n)$ product immediately after the emission of the second neutron is shown as the dash-dot line. The dotted line gives the average $\bar{J}_f$ for the $(\alpha, 2n)$ product as a function of E^* in the same nuclide. This result clearly indicates that for those projectile energies which are

far above the threshold for the second particle evaporations the gamma-ray competition plays a dominant role in determining the fraction of the cross section for the one particle product. We would then like to estimate the ratio $\sigma(\alpha,n)/\sigma(\alpha,2n)$ as a function of the excitation energy in the (α,n) product immediately following the first neutron emission. This ratio is directly dependent upon the gamma-ray emission strength. Fig. 5 gives the calculated neutron kinetic energy spectrum. The solid line corresponds to the total neutron spectrum, the dashed line gives the kinetic energy spectrum of the neutrons that populated the (α,n) product and the dash-dot curve the spectrum of all the neutrons that populated the $(\alpha,2n)$ product. This ratio is shown in Fig. 6 for two initial excitation energies as a function of the excitation energy E_2 above the neutron separation energy of another neutron from the (α,n) nucleus. Thus, it is seen that for $U = 26.15$ MeV and $E_2 = 1$ MeV, that is when the second neutron can carry a 1 MeV kinetic energy at the most the ratio $N_1(\alpha,n)/N_2(\alpha,2n)$ is equal to ~ 10 , or alternatively, the gamma-ray to neutron emission probability ratio is ~ 10 .

The effect that has been previously termed as "spin fractionation" ⁸⁾, that is the different distribution of angular momenta between the two products (α,n) and $(\alpha,2n)$, can now be estimated. In Fig. 7 $\sigma(U,J_c)$, that is the initial distribution in J_c for $U = 26.15$ MeV, is shown as a solid curve (continuous curves are drawn through the quantized J values for clarity in the illustration). The average $\bar{J}_c$ value is $8.62 \hbar$ units. We have collected the cascades that ended in the (α,n) product and plotted the number of cases as a function of J_f the final spin. These spin values are those populated after the emission of the first neutron for the cases where no second neutron was evaporated. The average $\bar{J}_f$ value for the (α,n) product is $11.4 \hbar$ units, which is considerably higher than $\bar{J}_c$. We also give the distribution in J_f for the $(\alpha,2n)$ product, following the second neutron emission. In this case the average $\bar{J}_f$ value is $8.0 \hbar$ units. The area under the two curves labeled $(\alpha,2n)$ and (α,n) is proportional to the cross section for the corresponding reaction.

Similar effects are observed in the case of $(\alpha, 2n)$ and $(\alpha, 3n)$ competition which are discussed in the paper submitted for publication ⁷⁾.

The calculated isomer ratios for the reactions (α, n) and $(\alpha, 3n)$ are compared with the experimental measurements of Bishop et al. ⁸⁾ in Fig. 8. The solid curves have been drawn through the experimental points. The dashed lines correspond to the calculated ratios $\sigma_m/(\sigma_m + \sigma_g)$ and are given for two sets of assumed spin values for the isomers (7,2) and (7,3) for the spins in $\text{In}^{110m, 110g}$, and (7,0) and (7,2) for $\text{In}^{108m, 108g}$, respectively. The dotted lines are the calculations of Bishop et al. ⁸⁾ using $a = A/7.4$ and $I/I_{rig} = 0.75$. The increased yield for the high spin isomer observed in the experiment is reproduced in our calculations, which as a matter of fact seem to overestimate the yield of the high spin isomer. We have performed another calculation where c_1 was reduced from $3 \times 10^{-5} \text{erg}^{-4} \text{sec}^{-1}$ to $1.5 \times 10^{-5} \text{erg}^{-4} \text{sec}^{-1}$. The results of this calculation are shown in Fig. 9 as dashed curves and are compared with experiment. It is seen that the agreement with the experimental yield ratios for the (α, n) reaction are particularly good if the spins 7 and 3 $\hbar$ units are assumed for the isomers.

The third type of information available from our cascade data is the total kinetic energy spectrum of various types of evaporated particles. In the reaction system $\text{Ag}^{107}(\alpha, x)$ which we have analyzed in detail, the most prominent particles evaporated are neutrons and less than 10% of the evaporations yield protons. The only evaporation data available for this system are the proton spectrum of Eisberg et al. ⁹⁾ from a 40 MeV He^4 -ion bombardment of Ag^{107} . Curve 1 in Fig. 10 reproduces this spectrum. Curves 2 and 3 are the data of Hurwitz et al. ¹⁰⁾ for 30 and 20 MeV He^4 -ions on Rh^{103} . Unfortunately, the computation time per cascade at 40 MeV is prohibitively long for a 10,000 cascade run which would barely suffice to provide enough statistics at the high energy part of the spectrum. Again this is due to the low proton yield for this particular system. We have, however, calculated the proton spectra for 20 and 30 MeV He^4 -ion bombardment and these are given in Fig. 10 as curves 4 and 5, respectively. The values of the parameters used in these calculations are those described above. It is apparent that the slope of the high energy side of the spectrum

decreases with increasing projectile energy. From these data and from another calculation with 2,000 cascades at 40 MeV we find that the high yield of high energy protons observed experimentally is not exactly reproduced. It appears that a decrease in $\underline{a}$, the level density parameter, would improve the agreement. It is worth noticing that Hurwitz et al.¹⁰⁾ have used $\underline{a} = A/56$ in order to fit the data in this system. We notice, however, that these data are taken at the very high energy end of the spectrum and any direct interaction contribution in the reaction mechanism could account for the discrepancy. It would be interesting to extend the spectrum to lower energies and also measure the proton spectrum at 20 and 30 MeV of He^4 -ions and compare those with the calculations. We have calculated neutron evaporation spectra for various He^4 -ion energies and in Fig. 11 curves 1 and 2 give the two spectra at $U = 40.2$ and 46.2 MeV of initial excitation, respectively. The expected hardening of the evaporation spectrum is seen as the excitation energy is increased. Curves 3 and 4 give the inelastic neutron spectra of Thomson¹¹⁾ and correspond to 6 and 5 MeV of neutron bombarding energy on indium. The compound nuclei in this and in our system are different, but a rough comparison can be made not at the same excitation, but at the same total energy available for neutron emission. These energies are shown as $\epsilon_n(\text{max})$ and it is seen that the $\text{In}^{115}(n_{5.76}, n')$ and $\text{Ag}^{107}(\alpha_{14}, n)$ reactions have the same maximum kinetic energy available for neutron emission. The slopes of the $\{\ln[N(E)/E]\}$ vs. E_n plots are not very different. We next performed a calculation of the neutron evaporation spectrum that arises in the reaction $\text{In}^{110}(n, n')$ for a projectile energy of 7 MeV. We used the same model parameters with those of the $\text{Ag}^{107}(\alpha, n)$ system. This projectile energy would produce the same compound nucleus In^{111} at the excitation energy of 16.96 MeV, but perhaps with different population of angular momentum states than the corresponding 14.8 MeV He^4 -ion bombardment on Ag^{107} which produces the same compound nucleus with the same excitation energy. The spectrum obtained is shown in Fig. 11 as curve 5. It is surprising that the slope of this spectrum is comparable with that of curve 1. The difference in the angular momentum population is unlikely to be responsible for this effect because the assumed

target spin was $2\frac{1}{2}$ which gives an average spin in the compound nucleus not much less than that obtained in the He^4 -ion bombardment. This effect needs further investigation.

In summary, we can say that the evaporation model as discussed earlier gives satisfactory agreement with experiment in a unified treatment of excitation functions, isomer yield ratios and particle evaporation spectra with the same set of model dependent parameters.

There is still, however, a small discrepancy in fitting the high energy side of the excitation function for the (α, n) reaction and in the high energy side of the evaporation spectra. Recoil measurements of the (α, n) reaction product in the case of Rh^{103} by Hurwitz ¹²⁾ indicate that there is in that system an incomplete momentum transfer indicating the presence of an admixture perhaps of a direct mechanism estimated not to exceed 30%. Similar recoil measurements in the Ag^{107} system are needed in order to see whether or not direct reaction contribution can account for the small differences between evaporation theory and experiment.

(D. G. Sarantites)

B. Experimental Part

As soon as the cyclotron resumed operation and external unmonitored beam became available preliminary experiments for the measurement of the recoil ranges in the reactions (α, γ) , (α, n) and $(\alpha, 2n)$ on Ag^{107} as well as for the measurement of the isomer yield ratios in the (α, γ) reaction were begun. When a Faraday cup is installed in the scattering chamber, we will proceed with these experiments.

Measurements on particle evaporation spectra will be taken in the near future. The instrumentation necessary for at least preliminary experiments is practically ready. The details on instrumentation are discussed in section (4) of this report.

(C. Cazianis, D. G. Sarantites)

2. DECAY SCHEME STUDIES

A. The decay scheme of In^{110} isomers

The experimental measurements as well as our calculations on the isomer yield ratios in the reactions $\text{Ag}^{107}(\alpha, xn)$ critically depend on the detailed knowledge of the decay scheme of these two isomers and on the knowledge of the In^{110} ground state spin. We thus began the investigation of these schemes.

The isomers are produced by the $\text{Ag}^{107}(\alpha, n)\text{In}^{110m, 110}$ reaction on natural Ag, using the W.U. cyclotron at a controlled energy not exceeding the $(\alpha, 2n)$ threshold. The In activity is purified chemically from Cd and Ag by several AgCl and subsequent $\text{In}(\text{OH})_3$ precipitations. A preliminary run was made and the single gamma-ray spectra were followed in time, using a $\text{Ge}(\text{Li})$ detector and the then available 1024-channel analyses with an overall resolution of ~ 10 keV at FWHM. The large number of gamma rays observed was divided into three groups decaying with half periods of ~ 24 min (In^{111}), ~ 66 min (In^{110g}) and ~ 4.9 hr (In^{110m}). A significant number of gamma rays with energies up to 2,500 keV associated with the short-lived isomers have been observed. The energies and intensities from these are being determined using the now available $\text{Ge}(\text{Li})$ detector system with an overall 4.5 keV FWHM resolution. In another experiment the energies and intensities of the gamma radiations from the 4.9 hr In^{110m} isomer were determined after the decay of the shorter-lived activities. The spectrum obtained 10 hours after bombardment is shown in Fig. 12.

The following gamma rays with some relative intensities given in parentheses have been identified with the 4.9 hr period: 120, 247, 283 (0.2), 542 (0.8), 583 (14), 626 (1.8), 642 (32), 658 (100), 707 (32), 758 (1.6), 782 (0.5), 843 (2.9), 883 (98), 937 (73), 997 (2.2), 1018 (0.5), 1045 (1.2), 1084 (1.0), 1108 (0.4), 1117 (4.1) keV. A number of other low intensity gamma rays are seen in the single spectrum. These have a half-life longer than 2 hrs. and shorter than 10 hrs. The energies and intensities are: 205 (17), 409 (0.4), 504 (0.4), 555 (0.8), 562 (2.1)

567 (0.5), 576 (0.7), 590 (0.6), 730 (0.6), 817 (1.9), 900 (2.1), 1064 (0.1), 1088 (0.7), 1140 (0.4), 1175 (0.3), 1192 (0.5), 1336 (0.9), 1418 (0.5), 1474 (1.6), 1558 (0.7), 1573 (0.2), 1592 (0.3), 1622 (0.4), 1653 (0.2), 1699 (0.5), 1727 (0.4), 1797 (0.4), 1902 (0.3), 1982 (0.3), 2104 (0.2), 2128 (0.2), 2279 (0.1), 2300 (0.1), 2422 (0.1), 2482 (0.1), 2497 (0.1). Further analysis of our data is in progress to determine the half period of the last group of gamma rays. A two dimensional 256 x 1024 channel coincidence spectrum has been taken with NaI(Tl) x Ge(Li) detectors and is being processed. We found that a coincidence spectrum with optimum resolution was obtained if the linear signal was obtained from the third stage of the Tennelec TC-200 amplifier with the coincidence timing done by shaping the first stage output in the Ortec multimode amplifier. (D. G. Sarantites)

B. The decay of the 66-min In^{110} isomer

Investigations of the decay scheme of the 66-min In^{110} isomer have been initiated. The Ge(Li) spectra from the experiments designed for the study of the 4.9-hr $\text{In}^{110\text{m}}$ isomer were analyzed and gamma rays decaying with the 66-min period have been identified. The following energies and intensities have been obtained: 173 (2.), 192 (6.2), 212 (2.7), 511 (42), 658 (100), 795 (0.7), 819 (0.8), 937 (2), 1120, 1242 (0.9), 1367 (1.0), 1423 (1.3), 1476 (1.5), 1505 (1.0), 1925 (0.5), 1967 (0.6), 2062 (0.6), 2162 (0.6), 2202 (1.8), 2258 (1.8), 2508 (0.7), 2898, 2960, 3269, 3440. A cleaner source of the 66-min In^{110} can be obtained by milking indium from the 4.0-hr Sn^{110} produced by the $\text{Cd}^{108}(\alpha, 2n)$ reaction. Such clean sources will simplify the investigation of the decay scheme of this nuclide. Further experiments are in progress. (D. G. Sarantites)

C. The decay of the 89-sec Zn^{61} isomer

Preliminary experiments have been performed indicating that it is possible to investigate the decay scheme of Zn^{61} using short bombardments with 16 MeV He^4 -ions on natural Ni. Many short bombardments are employed and the single and coincidence spectra are being accumulated

with the use of the buffer-tape system as a function of time. Use of the pneumatic tube system is made in these experiments. With the controls of this system in the hot laboratory of the Radiochemistry Building the bombardments are easily controlled. The activated samples arrive in our laboratory in ~3 seconds from the end of the bombardment. It was found that no chemical separation from the contaminating activity 3.3-hr Cu^{61} is required since for the first few minutes after bombardment the long-lived activities contribute only a few percent of the total, and counting is started at about 10 seconds after bombardment. At present the cumulative spectrum of single gamma rays observed with a Ge(Li) detector indicates the presence of a significant number of low intensity gamma rays with energies above 511 keV. For the 2.1-min Zn^{60} the reaction $\text{Ni}^{58}(\text{He}^3, n)$ will give sources of the Zn^{60} practically free from Zn^{61} which is a serious contaminant if the reaction $\text{Ni}^{58}(\text{He}^4, 2n)$ is employed. However, a rapid chemical separation from the Cu activities will be required.

(A. Xenoulis, D. G. Sarantites)

D. The decay of Pd^{99}

The investigation of the decay scheme of the 22-min Pd^{99} isomer has been initiated as planned. This isotope is produced by the reaction $\text{Ru}^{96}(\alpha, n)\text{Pd}^{99}$ with He^4 -ion energies below 18 MeV, using natural ruthenium chloride as target. The Pd activity is purified chemically by a dimethyl glyoxime precipitation and subsequent $\text{Fe}(\text{OH})_3$ scavenging. Finally Pd is precipitated with dimethyl glyoxime and mounted for counting. In a preliminary run the gamma radiations were followed with time using a 3" x 3" NaI(Tl) scintillation detector. The sources prepared in this method contain activities other than Pd^{99} in amounts not exceeding a few percent.

The following prominent gamma rays have been identified decaying with the characteristic period of ~22 min, 95, 270, 390, 511, 660, 800, 1,280 keV. The following photon energies are associated with the period of ~4.7 hours of the daughter Rh^{99m} and are easily identified as 140, 350, 511, 610, 1230 keV. A complex peak at ~2,200 keV exhibits a short and a long period. Experiments using the Ge(Li) detector are in progress.

(M. Phelps)

E. The decay of the Te^{119} isomers

We have begun the investigation of the decay schemes of the 16-hr Te^{119g} and the 4.7-da Te^{119m} in an attempt to identify the plausible quintet of levels in Sb^{119} arising in a weak coupling of the odd 51st proton with the 2+ one phonon first excited state in Sn^{118} . The expected levels should have spins and parities 9/2+, 7/2+, 5/2+, 3/2+ and 1/2+ with splittings predicted by theory ¹³). The source is prepared by the reaction $\text{Sn}^{118}(\alpha, n)\text{Te}^{119}$ using He^4 -ions of energy not exceeding the $(\alpha, 2n)$ threshold. The target is enriched to 95.6% in Sn^{118} and was obtained from ORNL. The Te^{119} activities are purified from Sb and Sn activities chemically by reduction of the $\text{Te(IV)} + \text{Te(VI)}$ mixed carrier to elemental Te from a 6 M HCl solution, twice. The gamma rays emitted from these isomers were recorded with a Ge(Li) detector and their half periods determined. A spectrum showing the gamma rays observed from both isomers is shown in Fig. 13. Some gamma rays identified from other spectra with better statistics are shown also. The following gamma rays with relative intensities in parentheses have been associated with the 16-hr Te^{119g} : 511*(6), 642*(100), 698*(11), 726 (0.74), 1175 (1.1), 1415 (1.4), 1695 (0.15), 1738*(1.4), 1830 (0.2) keV. The photons with energies marked with an asterisk have been reported previously by Kantele and Fink ¹⁴), with intensities similar to ours. The following gamma rays and intensities have been associated with the 4.7-da Te^{119m} : 153*(110), 271*(40), 915*(11.3) 945*(4.8), 992*(8.8), 1050*(6.3), 1066 (11), 1090 (2.4), 1100 (3.1), 1140 (12), 1220 (100), 1445 (0.49), 1965 (0.65), 2030 (1.2), 2078 (9.4) keV. The photon energies marked with an asterisk have been reported previously by Kantele and Fink ¹⁴) and by Svedberg and Andersson ¹⁵). Coincidence spectra have been taken using $\text{NaI(Tl)} - \text{Ge(Li)}$ detectors in 128 x 1024 channel resolution. Spectra taken in coincidence with the energy range 1000-1100 keV in NaI(Tl) failed to give the 164 keV gamma ray. Further analysis of the coincidence spectra is in progress.

We have measured the directional correlation of the coincident gamma rays 153 - 1220 keV. Measurements were taken every 15° from 75° to 180° and the single rate in the stationary NaI(Tl) detector and the

coincidence rate were simultaneously recorded using energy selection corresponding to the photopeaks of both gamma rays. Figure 14 shows the correlation obtained. A least squares fit of the data with the equation

$$W(\theta) = 1 + A_{22}^{\text{exp}} P_2(\cos\theta) + A_{44}^{\text{exp}} P_4(\cos\theta)$$

gave the values -0.0446, -0.0002 for A_{22}^{exp} and A_{44}^{exp} for this cascade. The corrected for finite solid angle values of A_{22} and A_{44} are -0.065, -0.006, respectively. Assuming the transition in the cascade 153-1220 keV to be pure E1 and E2 we find from theory -0.0714 and 0 for A_{22} and A_{44} , respectively, for the spin sequence 11/2 (1) 9/2 (2) 5/2, in good agreement with experiment. The directional correlation of the 2078-271 keV cascade has been measured and analysis of the data is in progress.

(E. Hoffman, D. G. Sarantites)

3. SPECTROMETRY VIA NUCLEAR REACTIONS

Progress on reaction spectroscopy has been made along the line of development of the necessary instrumentation. In section (4) of this report we discuss the details of the instrumentation assembled and under construction. We plan in the near future to begin preliminary experiments in order to gain experience on the identification of the ejected charged particles using the $(E + \Delta E) \times \Delta E/\Delta X$ detection system with the associated pulse multiplying circuitry now available.

(S. Greene, D. G. Sarantites)

4. INSTRUMENTATION AND DATA PROCESSING

The major equipment that was added to our laboratory is the "Nuclear Data" 4096-channel two parameter pulse height analyzer, together with the buffer-tape system. The system was installed in January and some minor defects and malfunctions have been eliminated. With this basic system and the buffer tape a two parameter configuration of total 18-bits of binary information can be accumulated. Thus, configuration choices such as 4096 x 64, 2048 x 128, 1024 x 256 and

512 x 512 channels are available. The capabilities of the system have been increased by possible use of the time scale as one parameter. This is feasible with two added units, one time-base generator allowing a range of 0.1 msec up to minutes per time channel and a programming unit for stopping and starting the cyclotron beam and the analyzer. In order to have immediate access to at least part of the data an "Optikon" readout unit was added to the system. Several modifications of the basic design have been added at our request. These include special signals for starting and resetting the M ADC-scaler, the clock pulses for measuring the live time when the buffer is operating, and a switch choice of the option of storing the clock pulses when multi-analyzing (spectra as a function of time) either in channel 0-0 or the first channel of each energy spectrum.

The instrumentation for scattering type measurements of light particles from nuclear reactions is being developed. A large 45" scattering chamber which is being installed by the cyclotron group as a common facility to all cyclotron users is near completion. A smaller 18" scattering chamber with a Faraday cup at a remote position has been installed recently and this will be used, primarily by the nuclear chemistry group for experiments not requiring very accurate angle settings.

A commercial 3-mm Si(Li) detector coupled with a 100-micron transmission counter has been purchased and will be used for charged particle identification and measurements of evaporation spectra as well as in direct reaction studies. A pulse multiplier has been built. This instrument will accept the amplified pulse output (E) of the thick Si(Li) detector and that of the (ΔE) transmission counter and will produce a signal of the form $(\Delta E) \times (E + E_0 + KDE)$ where E_0 and K are adjustable constants. Different charge particles correspond to discrete values of the latter function so that identification and selection of the particle of interest can be made. We plan to begin the calibration of this particle identification system in the immediate future. A specially designed cryostat for mounting and operating a Ge(Li) detector

inside the larger 45" scattering chamber is presently under construction. The rather favorable geometry of this system will permit measurements of gamma rays from on beam and from pulsed beam activation, with good efficiency.

A second commercial 3-mm deep with 2 cm² active area Si(Li) detector with a "guaranteed" resolution for electrons of 0.6% was purchased. A special vacuum chamber with a mounting assembly has been built and modified to allow the operation of the detector at pressures of ~1 micron of Hg at about -40°C obtained by means of thermoelectric cooler. A commercial detector cooler assembly (Ortec Model 806) with cooling to dry ice temperatures by means of liquid CO₂ expansion was purchased and tested. Resolutions of ~15 keV of the 974 keV K-conversion electron from Bi²⁰⁷ have been obtained. Both systems are presently in operating condition.

Considerable progress has been made in the fabrication of Ge(Li) detectors. We have been applying the Li on the Ge surface from an oil suspension, evaporating the oil at ~250°C in an Ar atmosphere and then raising the temperature to 420°C for ~5 minutes. We have employed both the planar and the coaxial method for drifting with satisfactory results. In the first method Li is diffused to the center of one face leaving ~4 mm of undiffused ring, then the Li is drifted parallel to this face so that the intrinsic layer that develops is exposed only on the top face and not on the edges. In the second method Li is diffused in all but one face and then drifted toward the center. This method also minimized the area of the exposed intrinsic layer, and in addition provides optimum sensitive volume. The drifting is done in a chloroform bath at temperatures 25-35°C. As the drifting approaches its end the temperature is lowered to ~15°C and drifting is continued for several days. Finally a cold-drift at the temperature of dry-ice isopropyl alcohol mixture is applied for at least 24 hours. The detectors were originally mounted on a cold-finger dewar assembly which did not give satisfactory performance at liquid N₂ temperature and high vacuum. Satisfactory results, however, were obtained when

commercial cryostats assemblies were purchased (Nuclear Diodes) and used. In one, the detector is held on a cold finger at the end of a 90° bend so that the detector source line is horizontal, while in the second this line is vertical and the detector is maintained cold with a vertical cold finger.

Detectors have been fabricated with sensitive volumes 1-5 cm³ and maintained in operation for several months. With our present systems using the Tennelec TC-200 amplifier with the 100-C preamplifier or a home-made field-effect transistor (FET) preamplifier we were able to obtain ~5 keV resolution on the 1064 keV gamma ray from Bi²⁰⁷. This (FET) transistor amplifier has an estimated noise increase of 0.1 keV per picofarad. Hence the limited resolution is presumably due to the large capacitance values ranging from 20-100 picofarads. We believe that further improvement in the resolution will be obtained with the use of a FET amplifier with slower increase in the FWHF with increasing capacitance especially for the large detectors.

A low noise Ortec multimode amplifier, two time pick-off units, two time pick-off control units and a time to amplitude converter of the Ortec 400 series were purchased and checked. The amplifier will be used in the E + dE/dx counter system which requires two preamplifier-amplifier systems. The time to amplitude converter will be used for pile-up rejection, life time determinations using delayed γ - γ , β^- - γ and particle-gamma coincidences.

For the purpose of measuring angular correlations among coincident gamma rays or electrons and gamma rays a special apparatus was designed and built. The source mounting system is at the center of an Al 26" square plate with provision for placing the source at two levels. There are three detector supporting arms and a stationary "zero" angle position. Special plastic adapters allow the alignment of the detectors on the same plane since the arms are located at different heights so that each one can be placed at any angle. The angles have been marked on the plate to one degree. The vacuum chamber

for the Si(Li) detector that was mentioned earlier was designed to fit at this turn table in such a way that the source which is inside in vacuum is at the same plane with the outside detectors. The Si(Li) detector is the stationary one. This apparatus is being used for γ - γ angular correlation measurements and it will also be used for determination of the angular correlations in coincidences between beta and gamma rays and conversion electron and gamma rays. An additional attachment to the same device allows one to mount and rotate up to 4 detectors around a stationary NaI(Tl) detector so that one can measure the linear polarization of a gamma ray emitted in a coincidence cascade and thus determine the relative parity of the states involved in the cascade.

With the increase in the capabilities in our instrumentation and in particular with the two parameter pulse height analyzer we have proceeded toward the more efficient handling of the large amount of numerical information by means of computers. We have written and debugged a computer program for the processing of the magnetic tape output data from the two parameter analyzer. The data on the magnetic tape appear in two forms. The first one consists of the so-called "dump" which is 4096 channel numerical information in any of the possible two parameter configurations. The second consists of address type information in which 18 binary bits identify one event as double address. The program when processing "dump" data can at choice simply list the information on tape in a tabular form or it can add up the information from any initial configuration to any binary divisor of this. Thus for example eight 512 channel spectra can be totalized to give eight 256 channel spectra; a 64 x 64 two parameter spectrum can be totalized in one 32 x 64 spectrum, etc. In addition, a predetermined interval in one parameter can be chosen and the spectrum of the second parameter associated with this interval can be obtained. With the address information the only way to extract the useful information is to select the regions of interest by selecting intervals along either parameter and obtain the spectrum along the other. Often with intelligent programming after a careful determination of the regions

of interest it is possible to obtain the useful information in only one run at the computer.

In decay curve analyses obtained by following the radioactive growth or decay of a sample the least-squares method is employed and the CLSQ program of Cumming ¹⁶⁾ is widely used. This program assumes independent activities in the sample and a function of the form

$$A(t) = c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t} + \dots, c_n e^{-\lambda_n t},$$

where $c_1, c_2, \dots, c_n$ are independent constants, is fit to the experimental curve.

We have written, debugged, and used a program in which relations between the coefficients $c_1, \dots, c_n$ must be satisfied as required by the laws of radioactive growth and decay when the parent and the daughter are both present in the sample. These additional relationships must be satisfied if the least-squares solution is to be acceptable. This was done by imposing these relations as additional constraints and solving the least-squares equations by introducing by appropriate Lagrange multipliers. It should be noted, however, that in these equations of constraint the relative counting efficiencies of the related activities must be known. This program will calculate only the constants $c_1, c_2, \dots, c_n$ with the constraint but it will not determine the decay constants.

We are presently working on a program to fit by least squares a series of Legendre polynomials to the experimental angular distributions.

(D. G. Sarantites, S. Greene)

References

1. N. T. Porile, Phys. Rev. 115 (1959) 939.
2. S. Fukushima, S. Hayashi, S. Kume, H. Ikamura, K. Otozai, K. Sakamoto, and Y. Yoshizawa, Nucl. Phys. 41 (1963) 275.
3. D. G. Sarantites and B. D. Pate, "Angular Momentum Effects in the Compound-Statistical Model for Nuclear Reactions: Monte Carlo Calculations of Excitation Functions (Part I)", preprint accompanies this report.
4. F. G. Perey, Phys. Rev. 131 (1963) 745.
5. R. Hofstadter, Rev. Mod. Phys. 28 (1956) 215.
6. D. G. Sarantites, "Angular Momentum Effects in the Compound-Statistical Model for Nuclear Reactions: The Importance of the Fermi-gas Model Parameters on Calculated Excitation Functions Part II)", preprint accompanies this report.
7. D. G. Sarantites, "On the Effect of Gamma-ray Competition in Statistical Model Calculations of Isomer Yield Ratios", preprint accompanies this report.
8. C. T. Bishop, J. R. Huizenga and J. P. Hummel, Phys. Rev. 135 (1964) B401.
9. R. M. Eisberg, G. Igo and H. E. Wegner, Phys. Rev. 100 (1955) 1309.
10. C. Hurwitz, S. J. Spencer, R. A. Esterlund, B. D. Pate and J. B. Reynolds, Nucl. Phys. 54 (1964) 65.
11. D. B. Thomson, Phys. Rev. 129 (1963) 1649.
12. C. Hurwitz, Ph.D. Thesis, Washington University (1964), unpublished.
13. A. deShalit, Phys. Rev. 122 (1961) 1530.
14. J. Kantele and R. W. Fink, Nucl. Phys. 43 (1963) 187.
15. J. Svedberg and G. Andersson, Nucl. Phys. 48 (1963) 313.
16. J. B. Cumming, Brookhaven National Laboratory Report BNL-6470, unpublished (1962).

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 $U = 26,15 \text{ MeV}$