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I. NUCLEAR REACTION STUDIES

A. INSTRUMENTATION

1. Cyclotron. (D. J. Tendam) The cyclotron is operating satisfactorily and no major modifications have been made during the past year. About six weeks of running time were lost while locating and repairing an internal water leak in the dee cooling and electronic troubles in the oscillator power supply.

2. Reaction Chamber: Modifications and Additions. (D. R. Ober, B. T. Lucas and O. E. Johnson) During the past year several accessory units have been designed and constructed which will extend the utility of the 30-in. reaction chamber which has been described in Progress Reports Nos. 11 through 14.

A multi-counter head containing four (E, dE/dx) counter telescopes has been completed. This unit will make possible the simultaneous determination of charged-particle spectra at each of four laboratory observation angles separated by 10° . Each of the constituent telescope assemblies consists of two silicon surface-barrier detectors (a thick, deeply depleted E-counter, and a very thin, totally depleted ΔE -counter), defining aperture system, and absorber assembly for the degradation of particle energy when required by experimental circumstances. In addition, provision has been made for the convenient energy calibration and alignment of each of these units.

The construction of a cylindrical (1-9/16" diameter by 3/4" height) gas target cell is essentially completed. The cell has been designed so that it can be quickly and conveniently introduced through the existing reaction chamber vacuum lock, placed in position, and put in operation without breaking the vacuum. The geometry of the cell, when used with the new multi-counter head and specially designed counter defining apertures, will allow observation angles up to 12.5° of the beam line. The use of a gas target cell requires a special

primary beam collimator system. This unit has also been completed.

3. Multi-Detector Electronic Spectrometer System. (D. R. Ober and O. E. Johnson) The component electronic units have been constructed for a system incorporating a two-dimensional multi-channel analyzer that will make it possible to simultaneously determine the differential spectra for charged particles at each of four laboratory observation angles separated by 10° . The system has been designed such that it may be extended to incorporate a particle identification capability in one or more of the four channels. The component units are presently under test. It is expected that the system will be assembled and put into general laboratory use by late summer.

4. Particle Spectrograph. (J. W. Hemsky and C. L. Wiley) With the determination of the absolute solid angle of the spectrograph focal surface, the initial calibration of the instrument is complete. The procedure for and the results of the entire spectrograph calibration are contained in a detailed report (see appended document No. 13).

5. Accelerator Plans. Funds for a 15 MeV two-stage tandem Van de Graaff accelerator have been made available by the National Science Foundation within the past month. Details of the installation are now being worked out with the architectural firm and the High Voltage Engineering Corporation.

B. AN EXPERIMENTAL STUDY OF THE $(2n+1)$ RULE USING THE (d, α) REACTION ON F^{19} , Na^{23} , Al^{27} AND P^{31}

S. W. Gosper* and O. E. Johnson

This study has been completed and no extension of this type of investigation is planned at this time. A full report of this work, based on the

preprint appended to Progress Report No. 15, has been published¹⁾.

* Present address: Lawrence Radiation Laboratory, University of California, Berkeley, California.

1) See appended document No. 1.

C. SOME 9.3-MeV (d, α) DIFFERENTIAL CROSS SECTIONS FOR F^{19} , Na^{23} , Al^{27} AND P^{31}

S. W. Cospers*, B. T. Lucas and O. E. Johnson

A plane-wave analysis of these (d, α) experimental angular distributions has been completed. Detailed reports on the experimental measurements and plane-wave analyses, based on the preprints appended to Progress Report No. 15, have been published¹⁾. Although no further experiments of this type are planned, the feasibility of distorted wave analyses of these data is under consideration.

* Present address: Lawrence Radiation Laboratory, University of California, Berkeley, California.

1) See appended documents Nos. 1 and 6.

D. ELASTIC AND INELASTIC SCATTERING OF 9.8-MeV DEUTERONS FROM P^{31}

B. T. Lucas and O. E. Johnson

The differential cross sections for (d, d_n) reactions which leave P^{31} in its ground and lowest three excited states (1.265 MeV, 2.232 MeV and 3.133 MeV) have been measured at an incident energy of 9.8 MeV.

The (σ_E/σ_R)-ratio for the elastic scattering has one pronounced maximum at about 128° but exhibits a somewhat irregular oscillatory structure

forward of 100° . The d_1 and d_2 cross sections are remarkably similar in shape, both rising monotonically forward of about 55° and decreasing monotonically at extreme backward angles with prominent maxima in the vicinity of 75° and 140° . The d_3 cross section has a weak maximum at about 110° and is roughly out of phase with the d_1 and d_2 cross sections. Although the d_1 and d_2 cross sections are clearly in phase, there appears to be no distinct phase relation between them and the d_0 cross section, an observation in contrast to the distinct phase relations usually observed in alpha-particle scattering.

The elastic angular distribution was analyzed in terms of a nuclear optical model with a four-parameter Saxon potential using the computer program briefly described in Progress Report No. 15. Three distinct sets of parameters were found which give moderately good fits to the data for angles less than 150° . It was further observed that the fits achieved in the present study using this simple four-parameter Saxon potential are quantitatively as good as those reported by previous investigators^{1, 2)} who used various six-parameter potentials in the analysis of data corresponding to target nuclei of the same nominal mass but higher incident energies.

The d_1 and d_2 cross sections were analyzed in terms of the distorted wave (DW) theory using a simple collective-model description for the excited states of P^{31} and the optical-model parameters determined through the analysis of the elastic scattering data. The computer program used was developed at this laboratory and was briefly described in Progress Report No. 14. The DW predictions for the d_1 and d_2 cross sections reproduce the general features of the data over a fairly wide angular range, the largest discrepancies occurring at small angles.

The close similarity in shape of the d_1 and d_2 experimental cross sections and the fact that the DW theory fits them both equally well suggests

that the same (collective) interaction mechanism is operative in both cases. The marked dissimilarity between the d_3 cross section and either the d_1 or d_2 cross sections, however, suggests a different type of mechanism for the excitation of the 3.133-MeV state.

A complete report of the results of this investigation which is based on the attached preprint³⁾ has been accepted for publication in The Physical Review.

-
- 1) C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).
 - 2) E. C. Halbert, Nuclear Physics 50, 353 (1964).
 - 3) See appended document No. 10.

E. OPTICAL-MODEL AND DISTORTED-WAVE ANALYSES OF SOME 18 MeV ALPHA-PARTICLE SCATTERING CROSS SECTIONS FOR Ar^{40} , S^{32} , P^{31} , Na^{23} AND Ne^{20}

B. T. Lucas, S. W. Cosper*, and O. E. Johnson

The 18-MeV (α, α_n) cross sections for some states of Ne^{20} (Gnd., 1.632-MeV), Na^{23} (Gnd., 0.439-, 2.080-MeV), P^{31} (Gnd., 1.265-, 2.232-MeV), S^{32} (Gnd.), and Ar^{40} (Gnd., 1.462-MeV) have been analyzed in terms of the nuclear optical model (OM) and distorted-wave (DW) theory. The OM computer program, the preliminary stages of the OM analyses, and the DW computer program developed at this laboratory have all been briefly described in Progress Reports Nos. 14 and 15.

A Saxon-Woods, four-parameter potential together with a Coulomb potential corresponding to a uniformly charged sphere of radius $1.2 A^{1/3} F$ was used in the analyses of the elastic scattering data. Several distinct sets of parameters were found which were judged to give subjectively equivalent forward-angle fits. A detailed comparison of the forward-angle fits achieved

for the present 18-MeV data (A^{40} , P^{31} , S^{32} , Na^{23}) and 28-MeV (Si^{28} , Al^{27} , Mg^{24}) data¹⁾ reveals that although quantitative agreement between measurement and theory is found in the lower-energy study, the fits are definitely poorer than those of the higher-energy investigation. In view of the fact that the nuclei in the 28-MeV study are generally lighter than those studied at 18 MeV, it is suggested that the dominant factor in the deteriorated agreement between experiment and theory in the present study is the reduced alpha-particle energy, and that 18 MeV is marginal for an optical-model description. However, the observation that the 18- and 28-MeV fits for Ne^{20} appear to be relatively poor, but of comparable quality suggests that an A value of 20 is somewhat marginal. With decreasing A , it can be categorically stated that the angular range over which the fits are qualitatively good becomes smaller.

The distorted-wave angular distributions are in fair agreement with the experimental data at the more forward angles in that they generally reproduce the positions of two or more of the maxima. Although for larger angles, the quality of the fits deteriorates in so far as detail is concerned, the calculated curves do follow the general trend of the data. For the inelastic angular distributions, the quality of the fits is poorer and the angular range over which the fits are acceptable is smaller than for the corresponding elastic cross sections.

A complete report of this investigation has been published in The Physical Review²⁾.

* Present address: Lawrence Radiation Laboratory, University of California, Berkeley, California.

1) G. R. Satchler, Nuclear Physics 70, 177 (1965).

2) See appended document No. 8.

F. THE $\text{Na}^{23}(\alpha, d)\text{Mg}^{25}$ AND $\text{P}^{31}(\alpha, d)\text{S}^{33}$ REACTIONS AT 18.7 MeV

B. B. Srivastava, S. W. Cospers*, and O. E. Johnson

The experimental investigation of the (α, d) reaction has been extended from the original study on Al^{27} (see Progress Report No. 15) to include Na^{23} and P^{31} . The 18.7-MeV differential cross sections for the (α, d) reactions leading to the ground and 0.584-MeV states of Mg^{25} , and the ground and 0.841-MeV states of S^{33} have been measured in the angular range from 15° to 170° at 5° intervals.

The targets were prepared by vacuum evaporation of sodium hydride ($266 \mu\text{g}/\text{cm}^2$) and phosphorous ($642 \mu\text{g}/\text{cm}^2$) onto thin ($10\text{--}20 \mu\text{g}/\text{cm}^2$) Formvar films. The spectrometer system incorporated a $(E, dE/dx)$ counter telescope consisting of two silicon surface barrier detectors, a multi-channel pulse-height analyzer, and a particle identification system. Particle identification was made on the basis of the approximate proportionality between the particle's mass and its $(E \times \frac{dE}{dx})$ product.

The angular distributions are unique in overall shape, however, all, except the one corresponding to the 0.841-MeV state of S^{33} , show forward peaking. This differential cross section has an oscillatory structure somewhat similar to those observed for stripping reactions. In contrast to the behavior of the P^{31} cross sections, those of Na^{23} tend to peak strongly at backward angles.

Up to the present time, only the analysis of the $\text{P}^{31}(\alpha, d)\text{S}^{33}$ data has been completed. These data have been analyzed in terms of the simple knock-out model of Tobocman¹⁾ using a cut-off distorted-wave code due to Gibbs et al²⁾. Considerably more than the gross structure of the experimental angular distributions are reproduced by the fitted theoretical curves--a result which is

particularly surprising in view of the distinctly different general character of these cross sections. The experimental data requires that the ground state of P^{31} be described as the bound two-body system (a Si^{29} core in its ground state and a deuteron) with a relative orbital angular momentum 0 and the final nucleus S^{33} (a Si^{29} core in its ground state and an alpha particle) with relative orbital angular momenta 2 and 0 for the ground and 0.841-MeV state, respectively. A preliminary oral report on these results was presented at the 1966 Washington, D. C. meeting of the American Physical Society³⁾. A more detailed report on the results of this investigation is in preparation.

Because of the modest success in achieving a description of the $P^{31}(\alpha, d)S^{33}$ angular distributions with this rather simple model, similar analyses of the $Na^{23}(\alpha, d)Mg^{25}$ data have been recently initiated but no results are available at the present time.

* Present address: Lawrence Radiation Laboratory, University of California, Berkeley, California.

- 1) W. Tobocman, Theory of Direct Nuclear Reactions (Oxford University Press, London, 1961), p. 30.
- 2) W. R. Gibbs, V. A. Madsen, J. A. Miller, W. Tobocman, E. C. Cox and L. Mowry, Direct Reaction Calculation - NASA TN D-2170 (National Aeronautics and Space Administration, Washington, D. C., 1964).
- 3) B. B. Srivastava, S. W. Cosper and O. E. Johnson, Bull. Am. Phys. Soc. 11, 333 (1966).

G. THE REACTION $S^{32}(\alpha, p)Cl^{35}$ AT 19.2 MeV

D. L. Deardorff and O. E. Johnson

The angular distributions of protons from the reaction $S^{32}(\alpha, p)Cl^{35}$ which leave Cl^{35} in its ground and lowest two excited states (1.220- and 1.762-MeV) have been measured over the angular range from 10° to 170° . The targets were fabricated from a lamination of thin Formvar films which were produced from a solution containing dissolved elemental sulphur and had a nominal areal density of $250\mu\text{ gm/cm}^2$. The spectrometer system incorporated a $(E, dE/dx)$ counter telescope consisting of a thin silicon surface barrier detector (ΔE) and a Li-drifted silicon detector ($E-\Delta E$), a multi-channel pulse-height analyzer, and a particle identification system. Proton identification was accomplished by imposing appropriate upper and lower limits on ΔE and $(E-\Delta E)$.

The angular distributions are all somewhat oscillatory but are unique in overall shape. Some evidence was found for a rather strong energy dependence in the cross sections at 150° . The results of further investigation suggest that these differential cross sections become more strongly energy dependent with increasing observation angle. No analysis has been undertaken.

H. COMPUTER PROGRAMS

During the past year several useful computer programs have been developed which will facilitate the execution of measurements and the reduction of experimental data. These programs have been written in IBM 7090/7094 Fortran II language.

1. Non-Relativistic Kinematics for Nuclear Reactions--Two-Body Final States. (B. T. Lucas) The program calculates the energy, E_3 , of the "light" final-state particle for angles of emission, θ_3 , between 0° and 180°

(except when the kinematics imposes an upper limit on θ_3) with an angular increment that is specified as input information. Also calculated are the quantities: $dE_3/d\theta_3$, dE_3/dE_1 (where E_1 is the incident energy); the center-of-mass angle; the solid-angle ratio between the laboratory and center-of-mass systems; the angle of emission of the "heavy" final-state particle and its energy (θ_4 and E_4 , respectively); and the quantity $dE_4/d\theta_4$. Nine values of the excitation energy of the final nucleus may be entered on one input card and run sequentially.

2. Non-Relativistic Reaction Kinematics for Nuclear Reactions--Three Body Final States. (B. T. Lucas) When a nuclear reaction involving three particles in the final state is observed in such a way that coincidences are required between two of the three particles emitted at fixed angles θ_1 and θ_2 , the corresponding energies E_1 and E_2 will lie on a continuous curve. The program calculates this kinematic locus (E_1, E_2) for the coincident events corresponding to fixed pairs of angles (θ_1, θ_2). Also calculated are the energy and angle of the third particle and the phase-space factors $N(E_1, \theta_1, \theta_2)$, $N(E_2, \theta_1, \theta_2)^{1)}$. Up to eight pairs of angles (θ_1, θ_2) may be entered on one data card and run sequentially.

3. Finite Target Thickness Calculation. (B. B. Srivastava) The program can calculate the target thickness from a knowledge of the energy lost by a heavy charged particle of known mass, charge, and initial energy in passing through it. The target may be a mixture and/or compound of known relative constitution consisting of a maximum of five different elements. In the program, the total energy loss is partitioned into a number of small, equal energy intervals, the stopping power, dE/dx , is assumed constant in each energy increment and an equivalent thickness (areal density) is calculated, the thickness of these slabs is totaled to give the target thickness. In the output are included:

the dE/dx for each constituent element and the total dE/dx for the mixture in each of the energy intervals; the areal density corresponding to each energy interval, and the accumulated areal density up to each energy interval.

As an option the program can calculate the energy lost by a heavy charged particle of known mass, charge, and initial energy in passing through a given slab of material of thickness. In this case, the total thickness of the slab is partitioned into a number of small equal increments. The energy loss is then calculated in a straightforward manner. The output in this mode of operation includes: the energy loss in each increment; the accumulated energy loss up to each increment; and the total dE/dx appropriate to each increment for the mixture and each of the constituent elements.

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- 1) For a definition of these quantities, see W. D. Simpson, J. D. Bronson, W. R. Jackson, and G. C. Phillips, Rev. Mod. Phys. 37, 523 (1965).

L. INVESTIGATION OF THE LOW-ENERGY TRIPLET LEVELS IN THE ¹⁹F NUCLEUS BY MEANS OF THE ELASTIC AND INELASTIC SCATTERING FROM ¹⁹F OF 18.5 MeV ALPHA PARTICLES

C. L. Wiley

The experimental aspects of the ¹⁹F(α , α')¹⁹F scattering experiment are completed. Angular distributions for the ground state and the first six excited states of the ¹⁹F nucleus were measured in angular increments of 5° between laboratory angles of 15° and 155°. The targets, fabricated from Kynar*, were nominally 50 μ gm/cm² thick. The raw data from the experiment have now been extracted from the nuclear-track emulsions, and the reduction of this data to center-of-mass cross sections and the corresponding angular distributions is in progress.

* Courtesy of the Pennsalt Chemicals Corporation, Philadelphia, Pennsylvania.

J. ISOBARIC SPIN CONSERVATION IN THE REACTION $^{40}\text{Ca}(d, \alpha)^{38}\text{K}$

J. W. Hemsky

Plates were used to measure the angular distributions of alpha particles from the reaction $^{40}\text{Ca}(d, \alpha)^{38}\text{K}$ which leave the ^{38}K nucleus in its ground state (3^+ , $T=0$) and its first four excited states (0^+1 at 0.129 MeV, 1^+0 at 0.456 MeV, 1^+0 at 1.201 MeV and 2^+1 at 2.406 MeV)¹⁾. These angular distributions are shown in Figures 1-5, respectively. The standard errors of the cross sections due to uncertainties in solid angle, charge collection, and target thickness amounted to $\approx 10\%$. Counting statistics and plate reading errors are only about 7% for the $T=0$ data, but make up the major part of the error in the $T=1$ data as can be seen in Figures 2 and 5.

While this experiment was in progress, the angular distribution of the transitions to the three $T=0$ states were measured at a deuteron energy of 14.8 MeV by Micheletti and Mukherjee²⁾ and a deuteron energy of 11.4 MeV by Wakatsuki et al., as reported by Lin and Yoshida³⁾. Since these distributions were measured earlier by Janecke⁴⁾ for a deuteron energy of 7.7 MeV, the information at 9.2 MeV will just fill the gap between 7.7 and 11.4 MeV.

The angular distribution of the transition to the 0^+1 state for a deuteron energy of 9.20 MeV, as shown in Figure 2, is nearly symmetrical about 90° which may indicate that the reaction proceeds predominately, if not entirely, by compound-nucleus formation. According to the selection rules for two-particle (d, α) stripping⁵⁾, direct transitions from a 0^+ to a 0^+ state by this mechanism are not allowed. The distribution is, however, far from isotropic. Meyer-Schutzmeister et al.⁶⁾ observe similar angular distributions for the α -particles emitted in the transitions to the 1.74-MeV 0^+1 state of ^{10}B in the $^{12}\text{C}(d, \alpha)^{10}\text{B}$ reaction for deuteron energies from 9 to 11 MeV. They also find a decreasing yield with increasing energy in this range which is in

Fig. 1 Angular distributions of alpha particles leading to the $3^+, 0$ ground state of K^{38}

Fig. 2 Angular distributions of alpha particles leading to the $0^+, 1$ first excited state of K^{38}

Fig. 3 Angular distributions of alpha particles leading to the $1^+, 0$ second excited state of K^{38}

Fig. 4 Angular distribution of alpha particles leading to the $1^+, 0$ third excited state of K^{38}

Fig. 5 Angular distribution of alpha particles leading to the $2^+, 1$ fourth excited state of K^{38}

agreement with the trend shown by comparing the data of Janecke⁴⁾ for a deuteron energy of 7.7 MeV with the present data at 9.20 MeV. A possible explanation for both cases is that one approaches with increasing energy, the "dynamic condition" $\langle H_c \rangle \ll \langle \Gamma \rangle$, where $\langle H_c \rangle$ is the average matrix element of the Coulomb forces which mix the isobaric spins of states with the same spins and parity and $\langle \Gamma \rangle$ is the average widths of these levels in the compound nucleus, for small isobaric spin impurities in the compound nucleus which results in a better degree of conservation of isobaric spin. The transition for a deuteron energy of 9.20 MeV was found to be inhibited by a factor of 3 due to the conservation of isobaric spin in contrast to the complete violation at lower energies as found by Hashimoto and Alford⁷⁾ at deuteron energies of 3.3 - 4.1 MeV and Janecke⁴⁾ at 7.7 MeV. The strong variation of the differential cross section is due to the restrictions on angular-momentum combinations. Following Blatt and Biedenharn⁸⁾, one obtains an expression for the experimental cross section in terms of $(P_J^1)^2$ and related cross terms where the index J only is needed to characterize the transition amplitude because the channel spins are fixed and the channel orbital angular momenta are both determined by $J(l=l'=J)$. The expression is in the process of being fitted with a maximum J of 4 and the results will be shown in a paper which will be submitted soon.

The angular distributions of the 2^+1 transition, as shown in Figure 5, is asymmetrical about 90° and has forward peaking, which may indicate the presence of a direct-interaction mechanism. It is estimated that the direct interaction contributes about 40% to the observed cross section. Again, as in the 0^+1 transition, the cross section decreased in going from 7.7 to 9.20 MeV deuterons.

It is concluded that care must be taken when considering possible reaction mechanisms contributing to the transition to an isobaric-spin forbidden

level. In particular, if one tries to find the predicted maximum of the isobaric spin violation due to mixing in the compound nucleus, any possible direct interaction component must be taken into account. Also estimations of isobaric spin impurities from measurements of the cross section at just one of two angles can be very misleading, even if there is no direct-interaction component in the transition as seen in Figure 2. The assumption of isotropy would obviously be very inappropriate here.

-
- 1) Progress Report No. 15, 1965, p. 2-3.
 - 2) S. Micheletti and P. Mukherjee, Nuclear Physics 63, 504 (1965).
 - 3) C. L. Lin and S. Yoshida, Prog. Theoret. Physics (Kyoto) 32, 885 (1964).
 - 4) J. Janecke, Nuclear Physics 48, 129 (1963).
 - 5) N. K. Glendenning, Nuclear Physics 29, 109 (1962).
 - 6) L. Meyer-Schutzmeister, D. Von Ehrenstein and R. G. Allas, to be published.
 - 7) Y. Hashimoto and W. Parker Alford, Phys. Rev. 116, 981 (1959).
 - 8) J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. 24, 258 (1952).

II. COULOMB EXCITATION STUDIES (Tandem Van de Graaff Generator)

Multiple Coulomb Excitation and the Reorientation Effect

An experimental investigation is underway of a new method for the determination of nuclear electric quadrupole moments. This method involves the use of energetic (25 MeV) heavy particle beams (O_2) which are obtained from the Argonne National Laboratory Tandem Van de Graaff generator. The associated experimental equipment consists of coincidence particle detection systems.

The reorientation effect as proposed by G. Breit et al.¹⁾ is a model independent method for the determination of the sign and magnitude of the electric quadrupole moment of excited nuclear states. All conventional methods for the determination of electric quadrupole moments of any nuclear state measure the product of $\pm |Q \frac{\partial E}{\partial z}|$ where Q is the quadrupole moment of the state and $\frac{\partial E}{\partial z}$ represents, for example, an axially symmetric electric field gradient set up by the electronic environment around the nucleus. In general, $\frac{\partial E}{\partial z}$ is uncertain by 20% to 100%. This uncertainty in $\frac{\partial E}{\partial z}$ makes all values of Q extracted from such measurements uncertain by 20% to 100%.

1) G. Breit et al., Phys. Rev. 103, 727 (1956).

A. INSTRUMENTATION

1. Scattering Chamber. (G. Schilling and R. P. Scharenberg) An 18-inch scattering chamber has been constructed. The chamber has provisions for 3 movable arms and a target changing mechanism. The top plate of the chamber houses a 5-inch by 4-inch NaI (Tl) crystal. A special beam collimator has been built to facilitate quick beam adjustments at the Argonne machine.

2. Shared-Time Electronic System. (G. Schilling, R. P. Scharenberg and P. C. Simms) Suitable electronic systems have been designed and constructed, which allow the use of up to four solid state particle detectors. The heart of the system is an exclusive "Or" gate with a small 10^{-8} second overlap time. The circuit was suggested by P. C. Simms. The electronic system also gives automatic accidental coincidence correction and addresses a 400-channel analyzer in a four fold selective storage mode.

3. Target Vacuum System. (J. W. Tippie) A four-inch general purpose vacuum system has been constructed for target preparation. Vacuums of 10^{-6} mm Hg are reached in a matter of hours. With this facility, it is possible to vacuum deposit almost any metal. With this system, materials may be evaporated by resistance heating of boats, radiation or electron beam heating of crucibles, and electron beam melting on a water-cooled copper crucible. The vacuum system was designed in such a way that all leads into the vacuum system are on a single base plate. With this construction it is possible to change evaporation techniques by simply interchanging base plates or by inserting the required leads into the base plate on the system. Provision has also been made for both heating and cooling of the substrate. Substrate temperatures between liquid nitrogen temperature and about 500°C are possible.

4. Target Preparation for Argonne Experiments (J. W. Tippie) Separated isotope Cd^{114} targets of from 50 to $300\text{ }\mu\text{g}/\text{cm}^2$ on 50 to $100\text{ }\mu\text{g}/\text{cm}^2$ copper backings have been produced for the reorientation experiments at Argonne. The copper backings are made by evaporating a thin ($\sim 30\text{ }\mu\text{g}/\text{cm}^2$) layer of NaCl onto a glass slide followed by copper. During the evaporation, the glass slide is held at about 200°C , to stress relieve the copper foil. The slides with the copper foil are then cooled to liquid nitrogen and the Cd is evaporated. This is necessary since the Cd vapor will not condense uniformly

on room temperature surfaces. The composite film is then floated off on water and mounted on target holders. Since Cd has a high vapor pressure, it is necessary to evaporate a thin (about $20 \mu\text{g}/\text{cm}^2$) copper evaporation shield on top of the exposed Cd to prevent evaporation of the Cd during an experiment due to beam heating of the foil.

A target thickness measuring system has been constructed which can measure target thicknesses of from about 10 to $500 \mu\text{g}/\text{cm}^2$ to an accuracy of several $\mu\text{g}/\text{cm}^2$. This system consists of observing the energy shift of α -particles from an Am^{241} source when the target is placed between the α -source and a solid state detector.

B. REORIENTATION EFFECT IN Cd^{114}

G. Grissmer, R. P. Scharenberg, G. Schilling and J. W. Tippie

The differential cross section for Coulomb excitation can be written¹⁾

$$d\sigma_{E_2} = P(\theta) d\sigma_R$$

where $d\sigma_R$ is the Rutherford cross section, $P(\theta)$ is the probability of excitation and can be expressed to first order by the expression

$$P(\theta) = a(\theta) + b(\theta)\lambda$$

where $\lambda = CQ$. $a(\theta)$, $b(\theta)$ and c are known expressions and Q is the quadrupole moment of the excited nuclear state.

Measurement of $P(\theta)$ and deviations from $a(\theta)$ can give the sign and magnitude of the quadrupole moment of the excited nuclear state. Preliminary results are shown in Figure 1.

The experimental points show a deviation from the $a(\theta)$ curve. The magnitude of the deviation is about 10% at the larger scattering angles in

agreement with De Boer et al²⁾.

The experimental points have not been corrected for a small number of counts due to Coulomb excitation of the Cu vapor shield and multiple excitation. The method of measuring the angular distribution $P(\theta)$ can eliminate the need for normalization measurements using α particles.

1) K. Alder et al., Rev. Mod. Phys. 28, 432 (1956).

2) J. De Boer et al., Phys. Rev. Letters 14, 564 (1965).

III. ANGULAR CORRELATION STUDIES

A. HIGHER ORDER EFFECTS IN β - γ CORRELATIONS INVOLVING ALLOWED β -TRANSITIONS*

S. Cipolla, Z. W. Grabowski, H. M. Naser and R. M. Steffen

(Abstract of paper published in The Physical Review 146, June (1966))

Higher order effects in allowed β -transitions may be generated by the interference of the allowed Gamow-Teller components with second-forbidden components. In strongly hindered β -transitions, this interference effect is expected to give rise to β - γ directional correlations with measurable anisotropies. The β - γ directional correlations of the hindered allowed β -transitions ($\log ft > 8$) in the deformed nuclei Eu^{152} , Eu^{154} and Tb^{160} were studied. The β -correlation factor A_2^β , which characterizes the β -transition in the expression for the β - γ directional correlation $W(\theta) = 1 + A_2^\beta A_2^\gamma \cdot P_2(\cos \theta)$, were found to be vanishingly small in all cases, except Tb^{160} . The results are:

$A_2^\beta = -0.017 \pm 0.012$ for the 0.70 MeV β -transition of Eu^{152} ($\log ft = 10.6$);

$A_2^\beta = +0.016 \pm 0.020$ for the 0.20 MeV β -transition of Eu^{152} ($\log ft = 9.6$);

$A_2^\beta = 0.007 \pm 0.006$ for the 0.58 MeV β -transition of Eu^{154} ($\log ft = 10.0$) and

$A_2^\beta = +0.05 \pm 0.02$ for the 0.566 MeV β -transition of Tb^{160} ($\log ft = 8.1$). A summary of all known β - γ directional correlation measurements on allowed β -transitions is presented and the implications of the results are discussed. In most cases, the experimental results suggest that the effects that cause the reduction of the allowed matrix elements are also operative in reducing the second-forbidden matrix elements.

* See appended document No. 9.

B. CONVERSION ELECTRON PARTICLE PARAMETERS IN MEDIUM-HEAVY NUCLEI

H. Naser, Z. W. Grabowski and R. M. Steffen

Recently, serious discrepancies between theory and experiment have been reported for the internal conversion electron particle parameters of some E2 transitions in medium-heavy nuclei¹⁾. The deviations of the reported results are difficult to explain on the basis of nuclear structure effects (e. g. penetration matrix elements).

A systematic study of conversion electron (e^-) particle parameters seems very desirable and such a program has been started. The lens spectrometer which has been described in previous progress reports has been modified for e^- - γ directional correlation experiments. NaI(Tl) scintillation counters as well as Li-drifted Germanium detectors are being used for the detection of gamma radiation. The operation of the instrument is automatic and data are being accumulated 24 hours a day.

The calibration of the instrument with the isotropic β - γ directional correlation of Co^{60} showed no instrumental asymmetries within 0.3 percent.

An investigation of the e^- -particle parameters of the 0.122 MeV and the 0.245 MeV transition in Sm^{152} following the decay of Eu^{152} (see Figure 1) is in progress. The Eu^{152} sources were prepared by vacuum volatilization of Eu_2O_3 onto an Al foil of $200 \mu\text{g}/\text{cm}^2$ thickness. The sources were approximately $50 \mu\text{g}/\text{cm}^2$ thick.

The e^- -particle parameters are computed from the measured e^- - γ directional correlation, which can be represented by the function

$$W(\theta) = 1 + A_2(e^-) \cdot A_2(\gamma) P_2(\cos \theta) + A_4(e^-) A_4(\gamma) P_4(\cos \theta)$$

${}^{152}_{89}\text{Eu}$

Fig. 1 Decay of Eu^{152}

where $A_k(\gamma)$ are the γ -directional correlation factors and $A_k(e^-)$ are the internal conversion correlation factors. For pure 2^L multipole transitions, the latter can be expressed in the form

$$A_k(e^-) = b_k(L L; e^-) F_k(L L I' I)$$

where $b_k(L L; e^-)$ is the e^- -particle parameter and $F_k(L L I' I)$ is an F-coefficient. The value of $A_k(\gamma)$ is extracted from γ - γ directional correlation experiments.

The preliminary results of the e^- - γ directional correlation experiments are summarized in Table 1. The data are not corrected for scattering in the source.

The e^- -particle parameter of the 0.345 MeV transition in Gd^{152} agrees well with theory, whereas the experimental e^- -particle parameters observed in the 0.245 MeV - 0.122 MeV cascade of Sm^{152} show large deviations. The e^- -particle parameter of the 0.245 MeV transition as observed in the 0.872 MeV - 0.245 MeV cascade, however, agrees with the theoretical predictions. A natural explanation of this apparent inconsistency would be the presence of a strong perturbation of the 0.245 MeV - 0.122 MeV correlation in the solid $Eu_2 O_3$ source. No evidence of such a perturbation was found, however, in measuring the γ - γ correlation of this cascade in the same source (see next section). Another explanation could be found in scattering effects in the source. The fact, that the particle parameters of electrons with the smallest energies show the largest deviations, points to this possibility. For this reason, the experiments are being repeated with sources of $7 \mu g/cm^2$ thickness, prepared in the Argonne Isotope Separator. Scattering effects would not, however, explain the good agreement of the b_2 and b_4 particle parameters of the 0.245 MeV transition

TABLE 1

Preliminary experimental results of e^- -particle parameter measurements
on Eu^{152}

Transition	Observed Cascade	$b_2(22, e_k^-)$		
		Theory	Hamilton et al.	Present Work
<u>Gd¹⁵²</u>				
$2^+(E2) 0^+$ 0.345 MeV	$0.782\gamma - 0.345 e_k^-$	1.60	1.58 ± 0.17	1.74 ± 0.23
<u>Sm¹⁵²</u>				
$2^+(E2) 0^+$ 0.122 MeV	$0.245\gamma - 0.122 e_k^-$	1.89	1.65 ± 0.17	0.91 ± 0.07
	$1.416\gamma - 0.122 e_k^-$	1.89	-	0.88 ± 0.04
$4^+(E2) 0^+$ 0.245 MeV	$0.245 e_k^- - 0.122\gamma$	1.72	1.05 ± 0.16	0.90 ± 0.14
	$0.872\gamma - 0.245 e_k^-$	1.72	-	1.8 ± 0.4
		$b_4 = -0.8$		$b_4 = -0.8 \pm 0.5$

with theory, as is observed in the 0.872 MeV - 0.245 MeV cascade. A systematic study of all e^- - γ and γ - γ directional correlations in the decay of Eu^{152} is in progress.

1) J. H. Hamilton et al., Phys. Rev. Letters 14, 567 (1965).

C. GAMMA-GAMMA DIRECTIONAL CORRELATION MEASUREMENTS WITH Ge(Li)-DETECTORS

A. J. Becker and R. M. Steffen

In order to extend the high-resolution capabilities of lithium-drift germanium gamma-ray detectors to directional correlation measurements, an apparatus has been constructed which utilizes two such semiconductor detectors. At present, two 5 mm intrinsic-depth RCA Victor, Ltd., detectors are being used with Goulding-designed, home-built preamplifiers, two ORTEC Model 220 Linear Pulse Analysis Systems (including amplifiers, fast-slow coincidence circuits, delay amplifier and linear gate) and an RIDL Model 34-12B 400-channel analyzer.

It was found necessary to use a multi-channel analyzer for the measurements to enable a more accurate determination of the unwanted addition of Compton-scattering events to those of the peaks under consideration. An auxiliary circuit was constructed to allow the simultaneous measurement of the true-plus-chance coincidences and of only the chance ones. Events from each of the two categories are routed into separate subgroups of the analyzer, allowing for channel-by-channel analysis. A block diagram of the arrangement is shown in Figure 1.

The large amount of data accumulated with the 400-channel analyzer are analyzed by the IBM 7094 computer. Programs for the extensive analysis, including peak shift corrections, "under peak" corrections, least square fits,

Fig. 1 Block diagram of Ge(Li) γ - γ Angular Correlation Electronics

etc., have been developed and tested.

The directional correlation of the 0.245 MeV - 0.122 MeV γ - γ cascade in Sm^{152} was measured with the same sources (Eu_2O_3) which were used in the e^- - γ directional correlation measurements described in the preceding section. After a careful correction for the Compton background under the 0.122 MeV and 0.245 MeV peaks, the following result for the anisotropy $A = [W(180^\circ)/W(90^\circ)]/W(90^\circ)$ was obtained

$$A'_{\text{exp}} = 0.155 \pm 0.013$$

This anisotropy value is not corrected for the finite solid angle of the Ge(Li) detectors. The theoretical value for the unperturbed 4-E2-2-E2-0 γ - γ directional correlation is

$$A'_{\text{th}} = 0.148 \pm 0.004$$

where the finite solid angle of the experimental arrangement has been taken into account. The error in the "theoretical" value reflects the uncertainty in the finite solid angle correction. Liquid sources (dilute aqueous solution of EuCl_3) which display unperturbed correlations for intermediate state lifetimes of 5 ns or less, show the same anisotropy as above. Thus the directional correlation as measured with the solid Eu_2O_3 sources is not perturbed.

It was noted that the "under peak" corrections are of great importance in the case of the Sm^{152} γ - γ directional correlation measurements, since the "under peak" background shows a considerable negative anisotropy in its directional correlation.

Previous measurements of the 0.624 MeV - 0.513 MeV γ - γ directional correlation in Pd^{106} with scintillation counters gave results which were almost, but not quite, in agreement with the correlation function for a 0-E2-2-E2-0

cascade. The lack of perfect agreement was attributed to the contribution of the 0.612 MeV - 0.513 MeV γ - γ cascade. Since we are interested in measuring the g-factor of the 0.513 MeV excited state of Pd^{106} using the internal fields in ferromagnetic foils, accurate knowledge of the 0.624 MeV - 0.513 MeV γ - γ directional correlation is important. In addition, the very pronounced directional correlation of the Pd^{106} gamma rays is well suited to study the finite solid angle corrections for solid state detectors. The absolute finite solid angle correction is determined by measuring the directional correlation of annihilation radiation whose energy is relatively close to the energies of the Pd^{106} gamma rays of interest.

A least square fit of the preliminary experimental data as obtained with two Ge(Li) detectors gives for the directional correlation coefficients of the 0.624 MeV - 0.513 MeV γ - γ cascade of Pd^{106} :

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

$$A_{22 \text{ exp}} = 0.242 \pm 0.055$$

$$A_{44 \text{ exp}} = 0.905 \pm 0.088$$

as compared to the theoretical result for a 0-E2-2-E2-0 cascade:

$$A_{22} = 0.3571$$

$$A_{44} = 1.143$$

More accurate data and a more comprehensive study of the under-peak and solid angle corrections are needed, before any definite conclusions can be drawn from the data. The measurements are still in progress.

D. DIRECTIONAL CORRELATION MEASUREMENTS INVOLVING CONVERSION ELECTRONS

D. L. Coppage and R. M. Steffen

The electron-electron directional correlation equipment has been modified for use as a gamma-electron directional correlation apparatus by the addition of a sodium iodide scintillation detector of a standard type. The use of lucite for the main vacuum chamber permits the observation of very low energy gamma rays and enhances the versatility of the instrument, which is now suitable for both electron-electron and gamma-electron directional correlations. Another alteration completed some time ago was the addition of apparatus for the cooling of the lithium-drift silicon detectors by the use of liquid nitrogen. Presently under consideration, are plans to use a multichannel analyzer with punched paper tape output, which is in a form easily convertible to IBM magnetic tape and which should facilitate the handling of the data.

The present experimental studies are directed at clarifying discrepancies in the theory of internal conversion. New computations¹⁾ of conversion coefficient and b_2 -particle parameter data show considerable deviations from the calculations of Rose²⁾ and Sliv³⁾, particularly for $L = 4$.

The cases presently under consideration involve high multipolarity transitions in Pb^{207} , Te^{123} and Hg^{197} . Preliminary measurements for the 1.063 MeV $e^-_k - 0.560$ MeV γ directional correlation in the decay of Bi^{207} give the following results for the directional correlation coefficients

$$A_{22}(e^-, \gamma) = 0.219 \pm 0.007$$

$$A_{44}(e^-, \gamma) = -0.01 \pm 0.01$$

The theoretical results for a point nucleus approximation are:

$$A_{22} = + 0.230$$

$$A_{44} = - 0.022$$

The measurement of the corresponding $e_L^- - \gamma$ directional correlation is in progress and the data will be analyzed in terms of the new internal conversion theory of Pauli¹⁾.

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- 1) H. C. Pauli, Ph.D. Thesis, University of Basel (Switzerland), unpublished.
 - 2) See, e.g., α -, β -, γ -Ray Spectroscopy (K. Siegbahn, Ed.), North-Holland Publishing Company, Amsterdam 1965, p. 887.
 - 3) *ibid.*, p. 1639.

E. K-FORBIDDEN BETA-TRANSITIONS

S. Cipolla and Z. W. Grabowski

In the adiabatic approximation, the quantum number K (projection of the total angular momentum on the symmetry axis) is a constant of the motion for a deformed nucleus. This approximation holds exactly in the limit of very small rotational frequencies. In the "rotational" nuclei, the adiabatic approximation is good only to the first order and in general the nuclear wave functions will contain terms with different K -values. Evidence for a coupling between the bands with a different K -value comes mainly from the analysis of gamma-ray branching ratios and rotational energies. A most direct evidence for band mixing is the occurrence of K -forbidden transitions.

At present, the first-forbidden beta-decay of Tb^{160} ($K = 3$) to the first excited 2^+ rotational state ($K = 0$) in Dy^{160} is under investigation. The decay of Tb^{160} provides also a possibility of comparing this decay with the first-

forbidden beta-decay in the 2^+ vibrational state in Dy^{160} (at 966 keV) which is K-allowed. Measurements on these two beta decays, by means of the beta-gamma directional correlation, are in progress. The preliminary results, in terms of the coefficients in the beta-gamma directional correlation function are:

1.75 MeV β - 0.087 MeV γ cascade:

E_β (MeV)	$A_{22}(\beta-\gamma)$
1.15 - 1.30	$+0.033 \pm 0.002$
1.30 - 1.45	-0.028 ± 0.002
1.45 - 1.60	-0.043 ± 0.003
1.60 - 1.75	-0.064 ± 0.007

These values are not corrected for the γ - γ coincidence background nor for the competing 1.55 MeV β - 0.197 MeV γ cascade. Measurements of these interfering effects are currently being done.

F. AUTOMATIC DATA RECORDING SYSTEM

P. C. Simms

An automatic data recording system has been developed for the general use of the group. The block diagram of the electronics is shown in Figure 1. The system is very flexible and reliable, and still it can be built for a small fraction of the cost of commercial equipment. The system is composed of decade counting cards, input cards, and control cards which permit the system to print out data on a Teletype TC-33 page printer and paper tape punch. Any counting configuration can be set up by inserting the desired number of cards in a prewired card file. Each card file will accept 19 cards, and any number of card files can be operated by one master control unit. Any combination of input and count cards may be used. For example, with a single file, one could

Fig. 1 Simplified Block Diagram of Automatic Data System

have 9 one-digit scalers (9 count cards and 9 input cards), or a single 18-digit scaler could be obtained with one input card and 18 count cards. No wiring changes are required to change the counting configuration. The master control unit transfers the data from each card to the printer-punch in a serial fashion. A printout circuit on the input card can be used to write identification numbers or to generate functions (space, tabulate, etc.) for the printer.

The count card has a 10 MC scaler section. The output from the printing section is a 1-2-4-8 BCD code. Four lights are also provided on the front of the card. Inexpensive plastic transistors and micrologics are used in the electric circuits. The printout sequence is DC controlled so that it cannot be interrupted by external interference.

The input card has three sections. The discriminator section will accept positive or negative pulses from 100 mv to 100 volts. The circuit is very insensitive to the input pulse shape and width. The pulse pair resolution of the input is fixed by a separate circuit. The resolution is usually set for 200 nsec to insure that any pulse accepted by the input board will be counted by the scaler. The pulse pair resolution is stable to within 2 nsec, so that the counting loss with random input pulses is constant. The third stage of the input board generates the pulse for the following count card. The counter is turned off by inhibiting this generator. This stage is also used to insert a test pulse into the system.

There is a test pulse generator in the master control unit. When this test generator is turned on, all regular inputs are turned off automatically, and the same test pulse is presented to all input boards in the system. Therefore, in the test mode, all scalers should count at the same rate. The complete system can be tested in a few seconds without changing any connections.

The master control unit has several additional functions. It controls

the readout process. The time required to cancel the preceding readout and initiate a new readout is approximately 2 μ sec. Thus the readout time of the system is entirely limited by the printing device. The master control has an electronic timer which can be operated from the 60 cycle AC line or from a plug-in crystal oscillator. The printer driving circuits are also in the master control unit. A serially coded pulse train is provided so that no modifications have to be made in the teletype printer. Since the master control unit is also made up of plug-in cards, any other type of readout device could be used by changing the readout card.

The master control unit has a flexible set of circuits to control external equipment. SCR switching circuits are used to operate motors and other electromechanical devices. Data can be added to the printed record by grounding code lines which are connected to the external equipment.

Very few circuits in the system require well-regulated DC power. Whenever regulated power is required, zener diodes are included on the printed circuit card. A system with 100 counting cards can be operated from a plus and minus 12 volt, 15 amp. supply. A commercial power supply which costs only \$200. is used.

Three systems are now in use in the laboratory. Two-hundred count cards, 50 input cards and 3 master controls have been built. Three more systems are being prepared. The cost of a system can be estimated in the following way (including parts and labor). Count or input card - \$25., master control - \$500., power supply - \$200., TC-33 - \$650.

Minor modifications of the circuits are being made before a description of the system is published. The failure rate has been so small that it was necessary to build a large number of cards before any weak points were evident.

G. ANGULAR CORRELATION HANDBOOK*

R. M. Steffen

A collection of formulae, tables and graphs useful to research groups engaged in experimental work on angular correlations was prepared. No derivations of formulae and few references to original work are given. It was not intended to write a review paper on angular correlation, but rather to make available to interested experimentalists, graphs, tables and formulae that are in constant use in the Purdue Nuclear Structure Laboratory.

This volume on unperturbed directional correlations is the first of four volumes. In the second volume, data on finite instrumental resolution and on scattering effects will be presented. The third volume will cover extranuclear perturbations of angular correlations and the fourth volume will contain data on polarization correlations.

* Appended document No. 14.

IV. GENERAL NUCLEAR SPECTROSCOPY

A. FABRICATION OF LITHIUM-DRIFTED GERMANIUM DETECTORS

A. J. Becker and J. C. Spencer

In order to permit large-scale use of lithium-drift germanium detectors for high-resolution gamma-ray spectroscopy, a fabrication technique for these detectors has been developed. The equipment necessary for diffusing, drifting and etching and cleaning crystals has been assembled and tested, using modifications of various techniques that have been employed successfully elsewhere.

The main attempt has been to produce planar detectors with intrinsic-region depths up to 6 mm. Due to the relatively stringent solid-angle requirements of angular correlation experiments, no work on coaxial detectors has been attempted. Also, the significant increase in output-pulse rise-times with intrinsic-region thickness has set a practical upper limit for this depth of ~ 6 mm for coincidence work.

Up to the present time, six crystals have reached various stages of preparation. Two were derived from a Sylvania germanium ingot produced during the period in which that Company was experiencing difficulties in maintaining a low oxygen content in its material, and expectedly have shown an intrinsic-depth limit of 3-4 mm. These two have not been considered satisfactory for this reason. Using another Sylvania ingot, with better characteristics, four crystals have been derived. One, with surface area of $\sim 1 \text{ cm}^2$ and intrinsic depth of 5mm, has produced a resolution of 4.5 keV FWHM for the Cs^{137} 664 keV line with a system consisting of a Simtec preamplifier, ORTEC Model 220 amplifier, and RIDL Model 34-12B multichannel analyzer.

Presently, crystals with surface area $\sim 5 \text{ cm}^2$ are being drifted or cleaned.

A new problem involving an asymmetry in drift depth has arisen, and unfortunately seems to be inherent in the crystal. However, average intrinsic depths of 5 mm are still possible, and the crystals are quite satisfactory as detectors. A resolution of about 5 keV FWHM is obtained. Attempts are now being made to insure sufficiently clean crystal surfaces to limit the leakage current to less than 10 na. for 400-500 v bias, so as to improve the noise characteristics.

Techniques for the fabrication of thin-window germanium detectors employing a gold p-layer are presently under investigation. This method should be especially useful in bypassing the asymmetry difficulty that has recently arisen.

B. DECAY OF Eu^{145} *

John C. Hill

(Abstract of paper submitted to Phys. Rev. for publication (May 26, 1966))

The decay scheme of Eu^{145} was studied by means of the techniques of beta and gamma spectroscopy. The half-life was measured to be $5.93 \pm .1$ days. Thirty-three gamma transitions were identified by means of NaI and germanium gamma detectors and 180° magnetic spectrometers. Gamma-gamma coincidences were performed using both NaI and germanium detectors. Most of the transitions were incorporated into the decay scheme in a consistent manner. The multipolarity of several gamma transitions was determined from measurement of conversion coefficients, and a positron spectrum containing two branches was observed. The level scheme of Sm^{145} contains a first excited state at 0.895 MeV and a second excited state at 1.437 MeV. Above 1.5 MeV, the level density greatly increases. Levels with both even and odd parities were observed, and the energy between the ground states of Eu^{145} was determined to be about 2.75 MeV. Systematics for the first excited states

of nuclei with even proton number and neutron number near 82 are presented.

* See appended document No. 12.

V. THEORY

A. PERTURBATION OF ANGULAR CORRELATIONS BY RHOMBIC ELECTRIC FIELDS IN SINGLE CRYSTALS

E. Matthias* and R. M. Steffen

The influence of axially symmetric electric fields on angular correlations has been treated theoretically both for single crystal sources¹⁾ and for polycrystalline (powder) sources²⁾. It has been suggested earlier³⁾ that higher order effects, like non-axially symmetric (rhombic) electric field gradients and/or a finite distribution of interaction frequencies will modify the effects of the quadrupole interaction significantly. Stimulated by some recent experimental results⁴⁻⁶⁾, a theoretical analysis of the rhombic electric field interaction with and without the presence of applied magnetic fields was made.

The matrix elements of the Hamiltonian describing the rhombic quadrupole interaction in the presence of a magnetic field B (parallel to the quantization axis) is given by:

$$\begin{aligned}
 H_{mm} &= \omega_E \hbar \left\{ \frac{1}{2} (3 \cos^2 \beta - 1 + \eta \sin^2 \beta \cos 2\alpha) [3m^2 - I(I+1)] + \gamma m \right\} \\
 H_{mm \pm 1} &= \frac{3}{2} \omega_E \hbar \sin \beta \left\{ \cos \beta \mp \frac{\eta}{6} [(1 \pm \cos \beta) e^{2i\alpha} - (1 \mp \cos \beta) e^{-2i\alpha}] \right\} \\
 &\quad \times e^{\pm i\gamma} (2m \pm 1) [(I \mp m)(I \pm m + 1)]^{\frac{1}{2}} \\
 H_{mm \pm 2} &= \frac{3}{4} \omega_E \hbar \left\{ \sin^2 \beta + \frac{\eta}{6} [(1 \pm \cos \beta)^2 e^{2i\alpha} + (1 \mp \cos \beta)^2 e^{-2i\alpha}] \right\} \\
 &\quad \times e^{\pm 2i\gamma} [(I \pm m + 2)(I \pm m + 1)(I \mp m)(I \mp m - 1)]^{\frac{1}{2}}
 \end{aligned} \tag{1}$$

The symbols have the following meaning:

$$\omega_E = \frac{e Q V_{zz}}{4I(2I-1)\hbar} \quad \text{quadrupole frequency}$$

$$\gamma = \frac{\omega_L}{\omega}$$

$$\omega_L = \frac{\mu B}{I\hbar} \quad \text{Larmor frequency}$$

η = asymmetry parameter of the rhombic electric field gradient

α, β, γ Euler angles specifying the orientation of the crystal axis with respect to the quantization axes

The Hamiltonian matrix is diagonalized by a transformation U

$$U H U^{-1} = E \quad (2)$$

If the density operator of the intermediate nuclear state of a γ - γ cascade is denoted by $\rho(0)$ immediately after the observation of the first γ -radiation, the density operator at the time t is given by

$$\rho(t) = e^{-iHt/\hbar} \rho(t=0) e^{iHt/\hbar} \quad (3)$$

This result is valid if H does not contain the time t explicitly, as is the case in the static rhombic interaction we are concerned with. If we use as basis for the representation of H and ρ , the eigenstates $|n\rangle$ of H , Eq. (3) can be written in the form

$$\langle n | \rho(t) | n' \rangle = \langle n | \rho(0) | n' \rangle e^{i(E_{n'} - E_n)t/\hbar} \quad (4)$$

or in the usual $|Im\rangle$ representation that is appropriate for angular correlation calculations

$$\langle m | \rho(t) | m' \rangle = \sum_{m'', m'''} \langle m | \Lambda(t) | m'' \rangle \langle m'' | \rho(0) | m''' \rangle \langle m''' | \Lambda(t) | m' \rangle \quad (5)$$

where the $\langle m | \Lambda(t) | m'' \rangle$ are the matrix elements of the "evolution" operator

$$\Lambda(t) = e^{-iHt/\hbar} \quad (6)$$

i. e.

$$\langle m | \Lambda(t) | m'' \rangle = \sum_n \langle m | n \rangle e^{-iE_n t/\hbar} \langle n | m'' \rangle \quad (7)$$

The $\langle m | n \rangle$ are the elements of the unitary transformation U of Eq. (2). The perturbation coefficient $G_{k_1 k_2}^{N_1 N_2}(t)$ in the angular correlation function

$$W(\vec{k}_1, \vec{k}_2) = \sum_{k_1, k_2, N_1, N_2} A_{k_1}(1) A_{k_2}(2) G_{k_1 k_2}^{N_1 N_2}(t) [(2k_1+1)(2k_2+1)]^{\frac{1}{2}} \\ \times Y_{k_1 N_1}^*(\vec{k}_1) Y_{k_2 N_2}(\vec{k}_2) \quad (8)$$

can then be computed from Eqs. (1), (2), (5) and (7):

$$G_{k_1 k_2}^{N_1 N_2}(t) = \sum_{m, m''} (-1)^{2H+m+m''} [(2k_1+1)(2k_2+1)]^{\frac{1}{2}} \begin{pmatrix} I & I & k_1 \\ m' & -m & N_1 \end{pmatrix} \\ \times \begin{pmatrix} I & I & k_2 \\ m''' & -m'' & N_2 \end{pmatrix} \langle m | \Lambda(t) | m'' \rangle \langle m''' | \Lambda(t) | m' \rangle \quad (9) \\ = \sum_{m, m''} \sum_{n, n'} (-1)^{2H+m+m''} [(2k_1+1)(2k_2+1)]^{\frac{1}{2}} e^{-i(E_n - E_{n'})t/\hbar} \\ \times \begin{pmatrix} I & I & k_1 \\ m' & -m & N_1 \end{pmatrix} \begin{pmatrix} I & I & k_2 \\ m''' & -m'' & N_2 \end{pmatrix} \langle m | n \rangle \langle n | m'' \rangle \langle m''' | n' \rangle \langle n' | m' \rangle$$

The perturbation coefficient (9) is being computed on the Purdue IBM 7094 computer for several cases of interest. The computer programs are completed and tested. In view of the many independent variables $l, k_1, k_2, N_1, N_2, \omega_E, \eta$ and γ , general tables of the perturbation coefficients would fill many volumes. The program will be run only for a selected choice of input parameters that are of particular interest to experimentalists.

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B. ROTATIONAL NUCLEAR STATES

S. M. Harris

A program is currently under way to investigate the deviations in the energy levels of high-spin states from the $I(I+1)$ rule in deformed nuclei. Previously, we have found that an excellent fit to the experimental data could be achieved by retaining higher order corrections in the extended cranking model¹⁾. At that time, the coefficients of the higher order corrections were treated as parameters. We are now trying to obtain estimates for these constants from first principles.

We have obtained a formula for the parameter C via perturbation theory. This expression contains a very complicated summation over intermediate states

since fourth-order terms are being considered. The calculation is performed within the framework of the unified model plus pairing. Both two and four quasiparticle intermediate states must be included. The complexity of the calculation dictates that computer use is necessary. This phase of the work is now in progress.

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C. NEUTRON-PROTON PAIRING FORCES

S. M. Harris

One of the major failings of the theory of pairing forces is the failure to include the forces acting between n - p $T=1$, $J=0$ pairs. Such forces would be expected to be important because of charge independence. Previous arguments asserting that such an interaction is unimportant because of the poor overlap between n - p wavefunctions have not been verified by calculation.

We have been investigating the generalization of the BCS scheme to the n - p case, but have not yet been able to generate a computational procedure comparable to that which exists when only one species is considered. We are attempting to apply the equation of motion method to this case which also has the added advantage of number conservation.

PUBLICATIONS

July 1, 1965 to June 30, 1966

(not including abstracts of papers presented at meetings)

1. A Study of Second Excited 2^+ States of Some Even-Even Nuclei by Beta-Gamma Angular Correlations, R. S. Raghavan, Z. W. Grabowski and R. M. Steffen. *Phys. Rev.* 139, B1 (1965).
2. Beta-Gamma Circular Polarization Correlation of Sb^{122} , Z. W. Grabowski, R. S. Raghavan and R. M. Steffen. *Nuclear Physics* 70, 170 (1965).
3. Search for Higher Order Effects in Allowed β -Transitions, Z. W. Grabowski, R. S. Raghavan and R. M. Steffen. *Phys. Rev.* 139, B24 (1965).
4. The Nuclear Matrix Elements in the First-Forbidden 2.2 MeV β -Transition of La^{140} , R. M. Singru, P. C. Simms and R. M. Steffen. *Phys. Rev.* 141, 1078 (1966).
5. Some (d, α) Differential Cross-Sections for Na^{23} , Al^{27} and P^{31} at about 9.3 MeV, S. W. Cospers, B. T. Lucas and O. E. Johnson. *Phys. Rev.* 139, B763 (1965).
6. Transverse Polarization of K-Conversion Electrons following the β -Decay of Au^{198} , R. L. Rasera and R. M. Steffen. *Phys. Rev.* 140, B1177 (1965).
7. Optical-Model and Distorted-Wave Analyses of Some 18-MeV Alpha-Particle Scattering Cross Sections for A^{40} , S^{32} , P^{31} , Na^{23} and Ne^{20} , B. T. Lucas, S. W. Cospers and O. E. Johnson. *Phys. Rev.* 144, 972 (1966).
8. Beta-Decay and Nuclear Structure, R. M. Steffen. *Proceedings of the Symposium on Solid State and Nuclear Physics, Calcutta, 1965.*
9. Lectures on Angular Correlations of Nuclear Radiations, R. M. Steffen. Tata Institute of Fundamental Research, Serial No. 24, Bombay (India).
10. Higher Order Effects in Allowed β -Transitions, S. Cipolla, H. Naser,

PUBLICATIONS (continued)

- Z. W. Grabowski and R. M. Steffen. Phys. Rev. 146, June 1966.
11. Elastic and Inelastic Scattering of 9.8 MeV Deuterons from P^{31} , B. T. Lucas and O. E. Johnson. Phys. Rev. 145, (1966).

~~LIST OF APPENDED DOCUMENTS~~

Reprints

Doc. No.

1. COO-1420-109 Experimental Study of the $2I+1$ Rule Using the (d, α) Reaction on F^{19} , Na^{23} , Al^{27} and P^{31} , S. W. Cosper and O. E. Johnson. Phys. Rev. 138, No. 3B, B610 (1965).
2. COO-1420-111 Study of Second Excited 2^+ States of Some Even-Even Nuclei by Beta-Gamma Angular Correlations, R. S. Raghavan, Z. W. Grabowski and R. M. Steffen. Phys. Rev. 139, B1 (1965).
3. COO-1420-112 Beta-Gamma Circular Polarization Correlation of Sb^{122} , Z. W. Grabowski, R. S. Raghavan and R. M. Steffen. Nuclear Physics 70, 170 (1965).
4. COO-1420-113 Search for Higher Order Effects in Allowed β -Transitions, Z. W. Grabowski, R. S. Raghavan and R. M. Steffen. Phys. Rev. 139, B24 (1965).
5. COO-1420-114 Nuclear Matrix Elements in the First-Forbidden 2.2 -MeV β Transition of La^{140} , R. M. Singru, P. C. Simms and R. M. Steffen. Phys. Rev. 141, 1078 (1966).
6. COO-1420-115 Some (d, α) Differential Cross Sections for Na^{23} , Al^{27} and P^{31} at About 9.3 MeV, S. W. Cosper, B. T. Lucas and O. E. Johnson. Phys. Rev. 139, B763 (1965).
7. COO-1420-116 Transverse Polarization of K-Conversion Electrons Following the β Decay of Au^{198} , R. L. Rasera and R. M. Steffen. Phys. Rev. 140, B1177 (1965).

8. COO-1420-119 Optical-Model and Distorted-Wave Analyses of Some 18-MeV Alpha-Particle Scattering Cross Sections for Ar^{40} , S^{32} , P^{31} , Na^{23} and Ne^{20} , B. T. Lucas, S. W. Cosper and O. E. Johnson, Phys. Rev. 144, 972 (1966).

Preprints

9. COO-1420-120 Higher-Order Effects in Allowed β -Transitions, S. Cipolla, Z. W. Grabowski, H. M. Naser and R. M. Steffen.
10. COO-1420-121 Elastic and Inelastic Scattering of 9.8-MeV Deuterons from P^{31} , B. T. Lucas and O. E. Johnson.
11. COO-1420-110 Beta-Decay and Nuclear Structure. R. M. Steffen.
12. COO-1420-118 Decay of Eu^{145} , John C. Hill.

Reports and Books

13. COO-1420-123 The Calibration of the Purdue Broad-Range, Magnetic Spectrograph and the Incident-Beam-Energy Analyzing Magnet, E. Bleuler, D. J. Tendam, J. W. Hensky and C. L. Wiley.
14. Angular Correlation Handbook