and one linear term, and four exponential decay components, there is insufficient space to discuss these relations here.

Having accumulated evidence that for the Harshaw sample of KCl, F-center growth and decay consists of more or less independent components, one would like to determine the physical processes that produce this situation. Unfortunately, linear, exponential, and saturating exponential components describe such a large number of kinetic processes that the fact that they are observed does not helpfully restrict the number of processes that have to be considered. However, the data given here together with the low dose rate results[3] appear to favor one class of plausible processes. Namely, for each F-center growth component there are holes trapped in one of four or more different kinds of hole traps. Some of these traps might be observable as V centers.[3] Thus, each component corresponds to a single kind of trap, or distribution of traps having similar hole capture, thermal hole untrapping, and hole-electron recombination properties. In addition to these properties the parameters describing each component are functions—in a way that is not necessarily simple—of the ionization-produced electron and hole concentration, the hole capture and hole-electron recombination cross section, and other interactions such as the presence of efficient recombination centers. There are other, both simple and more complicated, mechanisms that would lead to the observed kinetics. At this time it is apparent that additional measurements are necessary before these growth and decay observations can be definitely attributed to specific processes.

In conclusion, it is essential to emphasize that the results given above show there are important differences between coloring-curve data obtained during irradiation and data obtained by irradiating a sample and then transferring it to a spectrophotometer for measurement at a later time. However, the results given here illustrate only the more important differences. They refer to only one center in one kind of crystal (one boule of KCl from Harshaw) at one temperature and dose rate. In addition, even if these experimental conditions are kept constant, variation in other parameters, such as straining prior to irradiation, affect the growth and decay curves. Studies on additional factors affecting the growth and decay curves will be reported shortly.

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SPIN-WAVE DISPERSION RELATIONS IN GADOLINIUM*

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Spin-wave dispersion relations have been measured in high-symmetry directions for metallic Gd. Analysis shows that at least five interplanar constants are required for a satisfactory fit to the data. The energy gap at $q = 0$ is unmeasurably small. In the c direction the measured dispersion curve gives directly the Fourier-transformed exchange interaction $J(0)-J(q)$. This exhibits no other extreme value except that at the origin.

The spin-wave dispersion relation has been measured for the three high-symmetry a, b, and c directions in gadolinium metal at 78°K, by neutron inelastic-scattering measurements. These measurements were carried out by means of the triple-axis spectrometer located at the High Flux Isotope Reactor. Both constant-q and constant-E modes of operation were employed. The specimen is a single crystal, grown in this laboratory, of gadolinium highly enriched (99.99%) in the low capturing isotope ^{160}Gd. As finally isolated, the crystal has the form of a half-disk weighing 23 g. The total neutron cross section at $\lambda = 1.07$ Å is 20.3 b.

Gadolinium is one of the simplest magnetic materials known and as such is an ideal candidate for inelastic neutron scattering measurements. It is a simple ferromagnet below its Curie point of 300°K and at 78°K it has developed nearly its full magnetic moment of $7.0\mu_B$. The metal be-

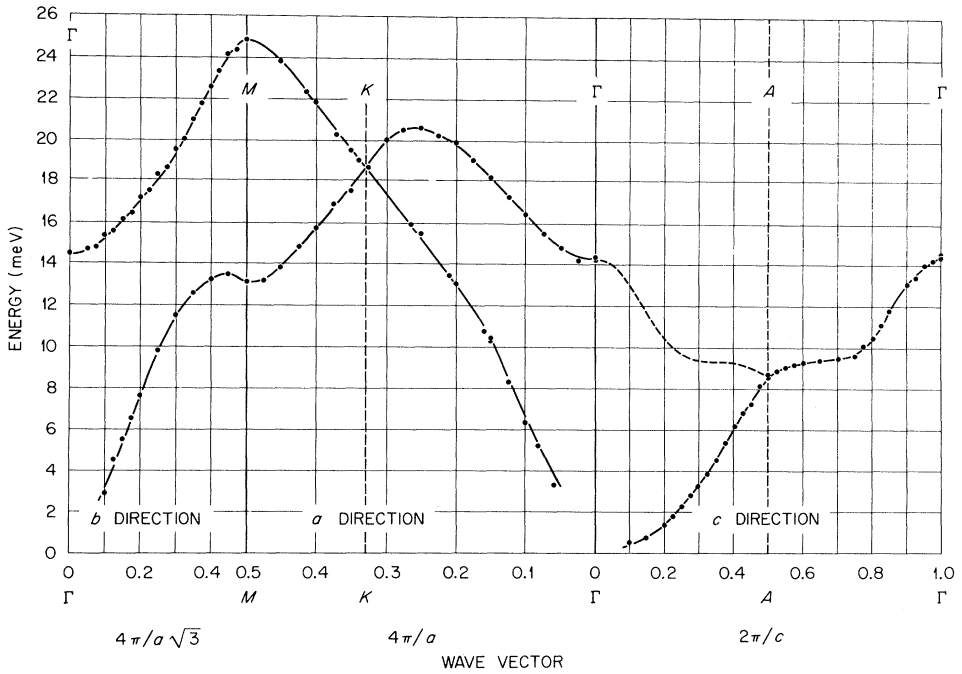

FIG. 1. Magnon dispersion curves for ^{160}Gd at 78°K.

haves as if it contained tripositive ions in $^8S_{7/2}$ states; accordingly, the influence of the crystalline anisotropy and of anisotropic exchange on the dispersion curves can be expected to be small, and the dispersion curves can be taken to be a direct measure, at least in the c direction, of the exchange energy.

The observed neutron groups were well defined and quite strong with peak intensities ranging from fifty to a thousand counts per minute. Phonon scattering was separated from that of the magnons by appropriately discriminatory scans at 78°K, and by separate room-temperature phonon studies. An uncertainty of 0.08 meV in the measured magnon energies was assigned.

The measured dispersion curves are shown in Fig. 1. It may be noted that these are similar to those observed in ferromagnetic terbium by Bjerrum Møller and Houmann[1] with the important exception that the energy gap at $q=0$ for magnons propagating in the c direction is unmeasurably small. Moreover, the maximum energy transfers are appreciably higher than those in terbium. The same degeneracies observed at the crossing of the optic and acoustic branches in the a direction are to be noted.

These dispersion curves have been analyzed, as were those of terbium, in terms of the Fourier-transformed exchange parameters

$$J^{s,d}(q)=\sum_{\vec{r}_l} J(\vec{r}_l)\exp(i\vec{q}\cdot\vec{r}_l), \tag{1}$$

where the superscripts signify that the sum is to be taken over atoms on the same (s) or different (d) sublattices.

The model Hamiltonian chosen is the following simple expression which is appropriate, to a first approximation, to gadolinium:

$$H=-\sum_{l>m} J(\vec{r}_l-\vec{r}_m)\vec{S}_l\cdot\vec{S}_m. \tag{2}$$

In the c direction, the measured dispersion curve is directly related to $J(0)-J(q)$ in that direction. From this, the interplanar exchange parameters have been obtained by a least-squares procedure. In the a and b directions the acoustic- and optic-branch data can be combined and yield after analysis the corresponding interplanar constants (or a combination of them for the case of different sublattices in the b direction).

The results of the analysis are summarized in Table I. These constants show a qualitative similarity to those derived from data obtained for ferromagnetic terbium, even to the extent that the same constants go negative in the two cases. There are distinct quantitative differences, how-

Table I. Interlayer exchange parameters for gadolinium at 78°K. All constants are expressed in meV except those for J_d in the b direction which are $(\text{meV})^2$.

	a		b		c
	s	d	s	d	
J_1	0.713	0.773	0.789	0.391	0.893
J_2	0.341	−0.146	0.054	0.494	0.092
J_3	0.106	0.125	0.040	0.012	0.097
J_4	0.027	0.036	0.008	0.113	−0.131
J_5	0.030	0.029	0.007	0.032	0.032

ever.

The magnetic structures of the rare earths heavier than gadolinium as well as of certain alloys of gadolinium with yttrium and with other rare earths exhibit periodic structures whose characteristic wave vectors are directed along the c axis. In gadolinium, as in terbium, the curve $J(0)-J(q)$ along the c direction exhibits a single minimum at $q=0$.

These experiments on gadolinium will be carried to temperatures close to the Curie point, and to 4.2°K to study the variation of the exchange constants and of the magnon lifetimes with temperature. The growth of single-crystal helical Gd-Y is in progress, and a comparative study of ferromagnetic Gd with helical Gd will be made.

It is a great pleasure to acknowledge the cooperation of Dr. George Rogosa, U. S. Atomic Energy Commission, in authorizing the separation of the isotopic sample, and of the Stable Isotopes Division, Oak Ridge National Laboratory, in carrying it out. The metal was produced by D. E. LaValle and the crystal grown by A. H. Millhouse to whom we express our thanks.

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POSSIBLE SCHEME FOR ANALYZING DIRECT NUCLEAR REACTIONS*

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A technique of data analysis familiar in nucleon-nucleon scattering is proposed for use in the extraction of spectroscopic information from direct nuclear reactions. The method is shown to be successful in analyzing some artificial data generated by a soluble three-body model of deuteron stripping.

The use of distorted wave (DW) theories[1] for the extraction of accurate single-particle widths from direct reactions is hampered by a number of uncertainties and ambiguities inherent in such reaction theories. It is the purpose of this paper to discuss and test an alternative scheme that avoids a detailed reaction theory and thus offers the hope of more accurate nuclear structure information.

The proposed procedure is based on the so-called "modified phase-shift analysis" method that is standard in the study of nucleon-nucleon scattering.[2] In N-N scattering the method proceeds as a conventional phase-shift search except that the scattering amplitudes in the high partial waves are assigned values determined by the theoretically unambiguous one-pion-exchange (OPE) contribution. Thus, the amplitudes in the low partial waves are represented by free parameters to be fixed by comparison with experimental data, whereas in the high partial waves it is argued that the OPE pole dominates the amplitude for these small-momentum-transfer collisions. This technique of data analysis has yielded[3] an essentially unique set of N-N phase shifts as well as a consistent value for the π-N coupling constant.

We now would like to apply this method to a direct reaction such as deuteron stripping ($d+A \rightarrow p+B$). Here the analogs of the OPE amplitude and the π-N coupling constant are the plane-wave Born approximation (PWBA) for stripping and the single-particle width for the residual nucleus B. We then proceed as in the N-N case and construct a stripping amplitude containing free parameters in the low partial waves while in the high partial waves we insert the PWBA with allowance for a free overall normalization constant that can be taken to be the single-particle width or spectroscopic factor for the residual nucleus. These free parameters are then determined by the usual search procedures that minimize devia-