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Level Structure of Cr$^{53}$

by

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I. Introduction

The purpose of the experiments described in this thesis was to develop a good particle-gamma coincidence system ultimately making use of an I.B.M. 1401 computer as a two dimensional pulse height analyzer and to use this system to determine energy levels and gamma schemes for the Cr$^{53}$ nucleus. Targets of natural chromium and enriched Cr$^{52}$ were bombarded with 4.0 MeV deuterons from the Rice University 6.0 MeV van de Graaff accelerator. The protons produced in the Cr$^{52}$(d,p)Cr$^{53}$ reaction were detected by a surface barrier detector while the gamma rays were detected by a NaI(Tl) crystal. The gamma decay schemes of ten excited states of Cr$^{53}$ have been determined in this experiment and spin and parity assignments have been made to six of them. Additional confirmation of the existence of a level in Cr$^{53}$ at 1.54 MeV has been obtained from a study of the Cr$^{53}$(p,p',γ)Cr$^{53}$ reaction.

Prior to the start of this experiment there was a considerable amount of experimental information available on the level structure of Cr$^{53}$ but with a number of unresolved questions which remained to be answered. Levels had been reported from various experiments at 0.560, 1.008, 1.29, 2.32, 2.69, 3.20, and 3.65 MeV$^{(1)}$. Additional levels had been observed by some groups at 1.54 and 1.97 MeV. One of the original purposes of this experiment was to confirm the existence of these two levels. A sensitive test for the existence of these levels in Cr$^{53}$ would be a particle-gamma coincidence measurement in the Cr$^{52}$(d,p)Cr$^{53}$ reaction. There are a number of factors which make a particle-gamma coincidence measurement a good method for confirming the existence of levels in a particular nucleus. In an experiment in
which only particle groups are observed there may be a certain contami-
nation in the target which would give a particle group of the same en-
ergy as the particle group leading to the particular level under inves-
tigation. Hence it may be difficult to determine whether or not a par-
ticle group is due to a contaminant or to the nucleus under investiga-
tion. Similarly in an experiment in which only gamma rays are detected
it may be extremely difficult to determine a unique level scheme, or
even whether or not a gamma ray is from the nucleus under investiga-
tion. This difficulty is particularly pronounced in the cases of
weakly excited levels with complex decay schemes. By observing the
particle groups and the gamma rays in coincidence, however, one places
a rather severe requirement on the assignment of a level to a particu-
lar nucleus. Not only must one observe a particle group of the proper
energy to correspond to excitation of a particular level in a particu-
lar nucleus, but one must also observe a coincident gamma spectrum
with gamma ray energies consistent with the excitation of the level in
question. In the case of a ground state gamma transition the energy
of the gamma ray must be equal to the energy of the excited state in-
volved. In the case of a cascade to one or more lower excited states,
the different gamma rays which are observed must be identifiable in
terms of lower known excited states. The sum of the energies of the
members of a suspected cascade must be equal to the excitation energy
of the level in question. Moreover, the intensities of each of the
members of a cascade must be the same after correcting for the varia-
tion of the detector efficiency with gamma ray energy, except for pos-
sible angular correlation effects. The two levels at 1.54 and 1.97
Mev have definitely been assigned to Cr\textsuperscript{53} from the results of this
experiment.

Recent results on the $^{52}\text{Cr}^{52}(d,p)^{53}\text{Cr}^{53}$ reaction using a broad range magnetic spectograph at Copenhagen (2) and at M.I.T. (3) indicate a considerably more complex spectrum for $^{53}\text{Cr}$ than had been previously reported, particularly at higher excitation energies. Values of $l_n$ have been determined by Sperduto, et al. (3) for those levels which exhibit strong stripping patterns. By using these results in conjunction with the gamma decay data obtained in the present experiment spin and parity assignments have been made for seven levels in $^{53}\text{Cr}$. 

II. Experimental Apparatus

The scattering chamber used in all phases of this experiment has been previously described in detail (4). It consists simply of a circular brass cylinder 4 inches high and 8 1/2 inches in diameter with a small air cooled diffusion pump attached to a pumping port on the chamber. A slit system placed in front of the chamber provides for alignment of the beam. A ruled quartz may be placed in the target position and the slits and chamber position may be adjusted so that a 1 mm$^2$ spot is obtained at the center of the quartz. The slits used to define this beam spot are either tantalum or tantalum covered with gold. A high Z material is used to define the beam in order to take advantage of the large reduction in cross section for deuteron induced reactions because of the large Coulomb barrier, thereby reducing possible gamma ray and neutron background from the slits. The quartz is then removed from the chamber and replaced by the target which may be rotated to any desired angle with respect to the beam axis. In these experiments the target was kept at 45 degrees with respect to the beam.
axis. One modification was made to allow the beam to pass through the chamber and be stopped on a gold disc located several feet away from the gamma detector to prevent an excessive amount of background which might be produced by stopping the beam in the chamber.

The gamma ray detector used in all phases of this experiment was a 3" x 3" NaI(Tl) crystal with a voltage of 1000 volts on the photomultiplier. The NaI crystal was used in different geometrical configurations in the different phases in this experiment. In an attempt to minimize background in the gamma ray detector from the slits or other sources a 3" thick lead shield was placed around the crystal. However, the gamma ray counting rate in the crystal with a 4.0 MeV deuteron beam on a natural Cr target was not significantly reduced by the addition of this shield, indicating that most of the counting rate was from the target. The addition of the shield had an undesirable effect in that the resolution of the gamma ray detector was somewhat poorer with the shield than without it. As a result it was decided to conduct these experiments without shielding the gamma detector.

The particle detector used in these experiments was a solid state surface barrier detector, Molechec M-700-50F with an area of 50 mm² and a depletion depth of 665 microns. The detector was mounted on a movable stand which could be placed 1 1/2" from the target in order to get a sufficiently high counting rate for weakly excited states.

III. The Cr(α,p γ) Reaction

In the first series of experiments a natural chromium foil, which had been prepared by electroplating chromium on to a thin nickel foil
and etching away the nickel, was bombarded with 4.0 MeV deuterons from the Rice University 6 MeV Van de Graaff accelerator. The protons from the $\text{Cr}^{52}(d,p)\text{Cr}^{53}$ reaction ($Q=5.718$ MeV) were observed at 90 degrees with respect to the beam axis. The gamma ray detector was placed directly above the scattering chamber 2 1/4" from the center of the target. Pulses from the photomultiplier were fed through a White cathode follower into the input of a Cosmic double-delay-line-clipped amplifier, model 901. The pulses from the particle detector were fed through a Tennelec preamp into a second Cosmic amplifier. The amplifiers have two outputs available - a prompt output and a delayed (2 $\mu$ seconds) output. The prompt outputs were fed to a Cosmic Model 801 Multiple Coincidence Unit used for fast-slow coincidence requirements. In this experiment windows were set around the various particle groups corresponding to excited states in $\text{Cr}^{53}$ and the coincident gamma ray spectra were observed in the Nuclear Data 1024 channel analyzer used in multiplex mode of operation as two 256 channel analyzers.

True and accidental coincidences were measured simultaneously by the following technique. The prompt output of the amplifier used for detecting gamma rays was fed into one Cosmic coincidence module. The prompt output of the other amplifier was paralleled into two Cosmic modules, one of which has a $0.4 \mu$ second delay at the input, and hence recorded only accidental coincidences. Windows were set around the same particle group in these two modules and each module was put in fast-slow coincidence with all gamma ray pulses from the first module. A block diagram of the experimental arrangement is shown in Fig. 1. The total number of coincidences between gamma rays, and particles within the window is obtained from coincidence output 1, while the
Figure 1

SCHEMATIC DIAGRAM OF THE ELECTRONIC EQUIPMENT

For an explanation refer to the text.
number of accidental coincidences is obtained from coincidence output
2. The resolving times for the coincidence modules may be varied from
20 to 100 nanoseconds - in this experiment a resolving time of 25
nanoseconds was used for each module. The two particle modules were
matched for resolving times by inserting the delay in both modules so
that only accidental coincidences were recorded and then varying the
resolving time until the counting rate was the same. The Cosmic mod-
ules also have variable delays (0 to 0.3 μsec) to compensate for any
differences in delay in the electronic equipment associated with the
detection of the gamma rays or the particles. The proper delay settings
were obtained by measuring particle – gamma coincidences from the 3.09
MeV state in C\textsuperscript{13} formed in the C\textsuperscript{12}(d,p) C\textsuperscript{13*} reaction and varying the
delay setting until the center of a flat maximum in the coincidence
counting rate was determined.

The delayed output of the amplifier used for detecting gamma rays
was paralleled into the two sides of the Nuclear Data 1024 channel
analyzer. A variable attenuator was used on the input to one side of
the Nuclear Data in order to provide a continuously variable gain con-
trol so that the gamma spectra taken in the two sides could be super-
imposed. One side was gated by the "total" coincidence pulses from
output 1 and the other was gated by the accidental coincidence pulses
from output 2. The two spectra were subtracted to give the true gamma
spectrum in coincidence with a particular particle group. The results
obtained when natural Cr was bombarded with 4 MeV deuterons is shown
in the following graphs.

Fig. 2 shows the "singles" particle spectrum observed at 90 degrees
with respect to the beam with the peaks attributed to the Cr\textsuperscript{52}(d,p) Cr\textsuperscript{53}
Figure 2

Particle spectrum observed at 90 degrees when a natural chromium foil is bombarded with 4.0 MeV deuterons.
reaction indicated. Windows were set around each of these peaks and the coincident gamma spectra were determined as previously described. The different spectra were taken for varying lengths of time and with different gains so that a direct comparison between any two cannot be made.

Fig. 3 shows the gamma ray spectrum in coincidence with the protons leaving Cr$^{53}$ in its first excited state at 560 KeV, showing the 560 KeV transition to the ground state.

Fig. 4 shows the gamma spectrum in coincidence with the protons corresponding to the 1.008 MeV state in Cr$^{53}$. The gamma spectrum contains a strong peak at 1.01 MeV but no statistically significant peaks at 0.560 MeV or 0.450 which would correspond to a cascade through the first excited state.

The gamma spectrum from the 1.29 MeV state in Fig. 5 shows peaks corresponding to gamma rays of energy 1.29, 1.01, and 0.83 MeV. The 1.29 MeV gamma can be attributed to a transition to the ground state of Cr$^{53}$. The 1.01 MeV gamma ray may be due to a cascade through the second excited state of Cr$^{53}$. Unfortunately the first member of this cascade, namely the 0.28 MeV gamma ray cannot be observed because of the sharp drop-off in detection efficiency of the coincidence unit for small pulse heights. In this particular experiment, if the amplifier gain is increased in an attempt to observe low energy gamma rays, there are a sufficient number of large pulses to saturate the amplifier and produce unreliable operation of the coincidence unit. It was decided to run with the lower gain and sacrifice the gamma rays below 300 KeV, especially since the low energy background was quite high under any circumstance. The peak at 0.83 MeV is most likely from the
Figure 3

Gamma Spectrum in coincidence with protons leaving Cr$^{53}$ in its first excited state at 0.56 MeV, following the Cr$^{52}$(d,p) Cr$^{53}$ reaction.
Figure 4

Gamma ray spectrum in coincidence with the protons leaving Cr$^{53}$ in its second excited state at 1.01 MeV.
Figure 5

Gamma ray spectrum in coincidence with the protons leaving Cr$^{53}$ in an excited state at 1.29 MeV.
Cr$^{53}$ (d,p) Cr$^{54}$ reaction ($Q = 7.49\text{MeV}$). There are several closely spaced levels at 3 MeV excitation energy in Cr$^{54}$ which decay to the first excited state at 0.832. The particle groups from these levels should fall at about the same position as the proton group to the 1.29 MeV state in Cr$^{53}$. Hence one might expect a significant contribution to the gamma ray spectrum in the case of weakly excited states of Cr$^{53}$ since the isotopic abundance of Cr$^{53}$ is 9.55%, compared to 83.76% for Cr$^{52}$.

Fig. 6 shows the gamma ray spectrum in coincidence with the 1.54 MeV state in Cr$^{53}$. Peaks are observed at .540, 0.83, 1.01, and possibly 1.29 MeV. The peaks at .540, and 1.01 could correspond to a cascade through the 1.008 MeV state. There may also be a weak branch to the 1.29 MeV state. The peak at 0.83 MeV is once again most likely due to Cr$^{53}$(d,p) Cr$^{54}$.

Fig. 7 shows the gamma spectrum in coincidence with the particle group corresponding to excitation of the 2.32 MeV state in Cr$^{53}$. The spectrum clearly indicates that the 2.32 MeV state decays predominantly to the ground state with no other statistically significant peaks observed.

The decay of the 2.69 MeV state, on the other hand, is considerably more complex as is shown in Fig. 8. Gamma rays of 0.560, 1.008, 1.32, 1.68, 2.14, and 2.69 MeV are observed. The gamma rays at .560 and 2.14 MeV correspond to a cascade through the first excited state of Cr$^{53}$. The gamma rays at 1.008 MeV and 1.68 MeV correspond to a cascade through the second excited state of Cr$^{53}$. The gamma ray at 2.69 MeV is the direct transition to the ground state. The broad peak at
Figure 6

Gamma ray spectrum in coincidence with the protons leaving Cr$^{53}$ in an excited state at 1.54 MeV.
Figure 7
Gamma spectrum in coincidence with the protons leaving Cr$^{53}$ in an excited state at 2.32 MeV.
Figure 8

Gamma ray spectrum in coincidence with the protons leaving Cr\textsuperscript{53} in an excited state at 2.69 MeV.
1.32 MeV may be due to two unresolved gamma rays of energy 1.29 and 1.40 MeV corresponding to a cascade through the third excited state of Cr$^{53}$. There is also some indication of a gamma ray at 0.830 MeV, which could be due to the Cr$^{53}$(d,p)Cr$^{54}$ reaction.

In all these measurements calibration points were obtained using standard sources placed near the NaI(Tl) crystal with the beam on the target since it was observed that the position of gamma peaks was shifted slightly in the presence of high counting rates. The sources used were Bi$^{207}$ which has strong gamma rays of 0.570 MeV and 1.07 MeV, Cs$^{137}$ which has a gamma ray of 0.662 MeV, Co$^{60}$ which has gamma rays at 1.17 and 1.33 MeV, and the 0.511 MeV positron annihilation radiation which was always present. Because of possible small errors in the calibration under different beam conditions and the weakness of the gamma transitions involved in the decay of the 1.54 MeV state, it is difficult to rule out the possibility that the 1.54 MeV level decays to the 0.510 MeV state. What is needed is a method of obtaining calibration points and coincidence spectra simultaneously. This may be achieved by using two dimensional analysis techniques as will be discussed later.

IV. The Cr$^{53}$(p,p') Cr$^{53*}$ Reaction

As an additional check to confirm the existence of the 1.54 MeV level in Cr$^{53}$, a similar particle gamma coincidence measurement was performed using the Cr$^{53}$ (p,p') Cr$^{53*}$ reaction. A thin self-supporting Cr$^{53}$ foil was prepared by evaporating Cr$^{53}$ (using Cr$_2$O$_3$ enriched to 98.8% Cr$^{53}$) onto glass slides which had been coated with NaCl and then floating the foil off in water. This foil was bombarded with
5.4 MeV protons from the Rice University 6 MeV Van de Graaff. A slight-
differently experimental arrangement was used in this case, in an at-
tempt to balance the counting rate in the particle detector and the

gamma detector. The NaI(Tl) crystal was moved back to about 9" from
the center of the target and a block of paraffin with a 1" hole in the
center was placed between the crystal and the target. The brass top
of the scattering chamber was replaced by an aluminum top with a thin
center section 3" in diameter turned down to a thickness of 1/8".

A window was set around the particle group corresponding to ex-
citation of the 1.54 MeV level in Cr$^{53}$ and the gamma ray spectrum re-
corded as previously described. The results are shown in Fig. 9. The

gamma rays corresponding to the decay of the 1.54 MeV state through the
level at 1.008 MeV are indicated on the diagram. There is also a gamma
ray at 1.29 MeV which may be partially due to a transition to the level
at 1.29 MeV. However, the particle resolution in this experiment was
poor because of the extremely high counting rate from the elastic pro-
tons that produced a tail on the low energy side tending to smear the
particle groups together. As a result of this poor resolution, it was
difficult to be certain the window did not contain some of the 1.29
MeV state. At any rate, the experiment does show the same two peaks
corresponding to the cascade through the 1.008 MeV state as the Cr$^{52}$
(d,p) reaction and tends to strengthen still further the identification
of the 1.54 MeV state as a level in Cr$^{53}$.

V. The Cr$^{52}$(d,p) Cr$^{53}$ Reaction

Because of various ambiguities which might arise because of re-
actions involving less abundant isotopes of chromium present in natural
Figure 2
Gamma ray spectrum in coincidence with the protons leaving Cr$^{53}$ in an excited state at 1.54 MeV following the Cr$^{53}(p,p')$ Cr$^{53}$ reaction at a proton bombarding energy of 5.2 MeV.
chromium as has been previously noted, it was deemed necessary to repeat the (d,p) experiment using a self-supporting Cr$^{52}$ (99.97%) foil. The NaI(Tl) crystal was placed directly on the chamber in the shallow depression in the aluminum top used for the Cr$^{53}(p,p')$ Cr$^{53*}$ reaction. It was found, however, that the gamma resolution suffered in such a configuration, apparently due to the presence of a prohibitively large amount of low energy gamma radiation. A lead disc 2 mm. thick was placed in front of the crystal to preferentially discriminate against low energy gamma radiation, since the dominant gamma interaction mechanism at low energies is the photoelectric effect which varies as $Z^5$. The resultant gamma spectrum displayed a marked improvement in resolution.

At this time the development of the Rice University I B M 1401 computer for use as a two dimensional analyzer made it feasible to perform the experiment with Cr$^{52}(d,p \gamma)$Cr$^{53}$ using two dimensional analysis. The experimental arrangement for using the computer as a two dimensional analyzer is shown in Fig. 10. The pulses from the gamma and particle detectors are fed into the Cosmic amplifiers as before, but now the same signals are paralleled at the input to the Cosmic amplifiers and fed into two Hanner Non-Overload Amplifiers, Model N-302. The output signals from the Hanner amplifiers are delayed by 2.5 $\mu$sec, using HH 2500 delay line in order to compensate for the delay of 1 to 1 1/2 $\mu$ seconds from the Cosmic coincidence unit. The signals then proceed through two pulse stretchers into two Astodata series 3000 Analog to Digital Converters and then into the computer. The data is stored on magnetic tape and may be analyzed later into a two dimensional form of up to 1000x1000 channels with the particles along
Figure 10

Schematic diagram of the electronic equipment used in obtaining the two dimensional particle-gamma coincidence spectrum. This is the experimental arrangement used in the $\text{Cr}^{52}(d,p \gamma)\text{Cr}^{53}$ reaction.
one axis and the gamma rays along the other. The computer analyzer system is gated by a coincidence pulse from the Cosmic coincidence unit, thereby giving the total (true plus accidental) coincidence spectrum. Provision has also been made to gate the computer analyzer with an accidental coincidence pulse; in this case, the accidental coincidence pulse from the Cosmic unit as previously discussed was used. If the gate for the computer analyzer is opened by an accidental coincidence pulse, provision has been made to tag the record with an A B bit over the third digit in the x coordinate in order to identify the pulse as an accidental coincidence. Thus total and accidental coincidence spectra are taken simultaneously but may be analyzed separately and later subtracted to obtain the true coincidence spectrum.

There are many advantages in taking a two dimensional spectrum of all particles and all coincident gamma rays simultaneously. Perhaps the most obvious advantage is the tremendous saving in time over the previous method, since one can obtain all of the decay schemes for all of the observed energy levels at once. Moreover, there are several built in calibration points arising from the decay of the strongly excited levels. One of the most important advantages is that one may determine much more precisely to which level a state decays. This is particularly significant in the case of the 1.54 MeV level as will be discussed later. Possible errors due to gain shifts produced by drift in some of the electronic equipment will be evident from the strong groups present in the spectrum. Since the data is recorded on magnetic tape, one can analyze different sections of the tape separately and
correct for any gain shift which may have occurred.

The results obtained by bombarding a Cr\textsuperscript{52} target with 4.0 MeV deuterons are shown in the following series of figures. A beam current of 0.02 to 0.03 microamperes was used in order to maintain a good true to accidental coincidence ratio (about 10 to 1) and to avoid loss of resolution in the gamma detector because of high counting rates. The total time required to obtain the two dimensional coincidence spectrum was 65 hours.

An ungated particle spectrum obtained using the computer as a 1000 channel analyzer is shown in Fig. 11.

Fig. 12 shows a section of the two dimensional coincidence spectrum obtained in this experiment, giving the decay scheme of the first four excited states of Cr\textsuperscript{53}. This spectrum illustrates two of the principal advantages of the two dimensional coincidence technique. It is evident from this spectrum that the decay of the 1.54 MeV state is indeed to the 1.01 MeV state and not to the 0.56 MeV state. The other advantage of the two dimensional technique shown in this spectrum is the ability to identify peaks due to contaminants. The peak indicated by the dotted line corresponds to a gamma ray energy of 1.28 MeV. However, the particle group in coincidence with this gamma ray corresponds to the excitation of a level in Cr\textsuperscript{53} at only 1.01 MeV. Hence, the indicated peak must be from a contaminant which has a higher Q value for a (d,p) reaction than the Q value for the Cr\textsuperscript{52}(d,p) Cr\textsuperscript{53} reaction. A likely possibility for the origin of this peak is the Si\textsuperscript{28}(d,p) Si\textsuperscript{29} reaction leading to the first excited state of Si\textsuperscript{29} at 1.277 MeV. This reaction has a Q value of 6.253 MeV and would produce a particle
Figure 11

Particle spectrum observed at 90 degrees when Cr$^{52}$ is bombarded with 4.0 MeV deuterons.
Figure 12

Two dimensional particle-gamma coincidence spectrum obtained in the 
${\text{Cr}}^{52}(d,p \gamma ){\text{Cr}}^{53}$ reaction. The solid lines indicate the proton groups 
对应的到了 states in ${\text{Cr}}^{53}$. The rectangles indicate the 
gamma rays in coincidence with those proton groups. The dotted rec-
tangle indicates a particle-gamma coincidence peak due to a silicon 
contaminant.
group of the observed energy in coincidence with a 1.28 MeV gamma ray. This identification is confirmed by the observation of a peak in another section of the two dimensional spectrum corresponding to excitation of the second excited state of Si$^{29}$ at 2.027 MeV.

The next three figures show the gamma decay schemes for ten excited states of Cr$^{53}$.

Fig. 13a shows the strong 560 KeV ground state transition from the first excited state of Cr$^{53}$.

Fig. 13b shows the decay of the 1.01 MeV state to the ground state with no indication of a decay to the first excited state.

Fig. 13c shows the decay of the 1.29 MeV state indicating a branch to the level at 1.01 MeV as well as a strong ground state transition.

Fig. 13d gives the decay of the 1.54 MeV state, indicating a decay through the 1.008 MeV level. In the previous experiment there was some difficulty in determining whether the 1.54 MeV state decayed to the 1.008 or to the 0.560 MeV level. Since the gamma energies for the two possible modes of decay are within 30 KeV of each other an accurate energy calibration was required. By taking a two-dimensional spectrum, the 560 KeV and 1.01 MeV gamma rays appear as strong peaks in coincidence with the first and second excited state proton groups and hence provide natural calibration points. By examining the spectra together, it is clear that one of the gamma rays from the decay of the 1.54 MeV state occurs at the same energy as the 1.01 MeV gamma ray, but the second gamma ray occurs at a slightly lower energy than the .560 MeV gamma ray. Therefore, one can assert with much greater certainty that the 1.54 MeV level decays to the 1.008 MeV level. There also appears to be a somewhat weaker branch to the 1.29 MeV level.
Figures 13, 14, and 15

Gamma ray spectra in coincidence with protons leading to ten excited states in Cr$^{53}$ as obtained in the Cr$^{52}$(d,p)Cr$^{53*}$ reaction. The levels in Cr$^{53}$ are indicated next to the gamma spectra with the observed gamma rays shown on the level diagram.
\( \text{Cr}^{52}(d,p\gamma) \text{Cr}^{53} \)

\( E_D = 4.00 \text{ MeV} \)
\( \theta_p = 90^\circ \)
\( \theta_\gamma = 90^\circ \)
The 1.97 MeV state is weakly excited and the statistics on the coincident gamma spectrum make it rather difficult to determine with any precision the decay scheme of this state. It is apparent, however, that the principal mode of decay is the transition to the ground state of Cr$^{53}$, as shown in Fig. 14a.

The gamma spectrum from the 2.32 MeV state, as shown in Fig. 14b, shows that the 2.32 MeV state decays overwhelmingly to the ground state, giving a strong 2.32 MeV gamma ray with the full energy peak and the one and two escape peaks, corresponding to the escape of one or both of the 511 keV positron annihilation gamma rays following pair creation in the NaI crystal. The peak observed at 0.511 MeV appears in all coincident gamma spectra which have a strong high energy gamma ray (greater than 2 MeV) as the principal mode of decay, including the $C^{12}(d,p \gamma) C^{13}$ spectrum used for calibration purposes. The most likely explanation for the origin of this peak is external pair creation in the material of the scattering chamber with subsequent detection of the 511 keV annihilation radiation. Since in this case the pair formation and annihilation radiation is produced by the 2.32 MeV gamma ray one can obtain a true coincidence between the 511 keV gamma ray and the protons leading to the 2.32 MeV state in Cr$^{53}$. The fact that this 511 keV peak increases with increasing primary gamma ray energy is consistent with this interpretation since the cross section for external pair formation increases with increasing gamma ray energy.

The decay of the level at 2.69 MeV is considerably more complex as is shown in Fig. 14c. Gamma rays are observed with energies of 0.560, 1.01, 1.68, 2.13, and 2.69 MeV and a broad peak centered at
1.35 MeV which may well be a partially resolved combination of gamma rays of energy 1.29 and 1.40 produced by a cascade through the level at 1.29 MeV. The gamma rays of 0.560 and 2.13 MeV are consistent with a transition to the first excited state of Cr$^{53}$. Those at 1.01 and 1.68 MeV are consistent with a transition to the second excited state of Cr$^{53}$. The gamma ray at 2.69 MeV is the ground state transition.

The decay of a level at 3.19 MeV gives gamma ray peaks at energies of 0.560 and 2.63 MeV consistent with a transition to the first excited state of Cr$^{53}$ as shown in Fig. 15d. There is also some indication of a somewhat weaker ground state transition of energy 3.19 MeV.

The next gamma spectrum is the decay of a level observed at about 3.60 MeV. The spectrum shows a strong gamma transition to the ground state and a peak at 511 KeV due to annihilation radiation as discussed in the case of the 2.32 MeV state. The small peak at 1.29 MeV is due to the fact that this level is not completely resolved from the next excited state at 3.70 MeV. The state at 3.70 MeV has a strong gamma ray transition to the 1.29 MeV state as is indicated by the observed gamma rays at 1.29 and 2.41 MeV.

In order to determine the branching ratios for the observed decay schemes the detection system efficiency must be determined as a function of gamma ray energy as is discussed in the next section.

VI. Determination of Detector Efficiency

The efficiency of the detection system has been measured as a function of gamma ray energy by measuring particle-gamma coincidences following (d,p) reactions to excited states of spin $1/2$ so that the
subsequent gamma decay is isotropic. The particular reactions chosen were the $^{16}\text{(d,p }\gamma^\prime)^{17}$ reaction and the $^{12}\text{(d,p }\gamma^\prime)^{13}$ reaction to the $1/2^-$ first excited states of $^{17}$ and $^{13}$ at 0.871 MeV and 3.09 MeV.

The relative gamma detection efficiency between these points was obtained using a Bi$^{207}$ source which has gamma rays of 0.570, 1.07 and 1.77 Mev.

In order to obtain branching ratios from a particular excited state one must know the efficiency of the detection system as a function of gamma ray energy. This information is also necessary to identify two gamma rays as being the two members of a cascade through an intermediate state. If the two gamma rays are the two members of a cascade they must have the same intensity except for possible angular correlation effects. In the present experimental arrangement these correlation effects are not expected to change the relative gamma ray intensities very much because of the large solid angle subtended by the NaI crystal.

The change in gamma ray detection efficiency as a function of gamma ray energy is due to a change in the relative importance of the various mechanisms by which the gamma rays interact with the NaI crystal. At low energies the principal means of interaction of the gamma rays with the NaI crystal is the photoelectric effect. For low energy gamma rays this produces a strong peak in the pulse height corresponding to the loss of the full energy of the gamma ray in the NaI crystal. For gamma rays less than 200 KeV there may also be a small peak in the pulse height spectrum below the full energy peak caused by the escape of the Iodine K-X ray following photoconversion of the incident gamma ray.
in the K-electron shell of the Iodine atom. In general for a 3"x3" crystal one would expect most of these X rays to be absorbed in the crystal and hence give a peak corresponding to the full energy loss of the incident gamma ray.

As one goes to gamma ray energies above a few hundred KeV, the dominant interaction mechanism is Compton scattering with the photo-electric cross section rapidly decreasing with increasing gamma ray energy. If a gamma ray interacts by means of the Compton effect, it may be scattered out of the crystal before losing all of its energy. Thus one obtains a continuous distribution in the pulse height spectrum. For sufficiently large NaI crystals the gamma ray may suffer multiple Compton scatterings and ultimately lose all its energy giving a full energy peak in the pulse height spectrum. The ratio of this full energy peak to the total number of gamma rays detected thus decreases with increasing gamma ray energy because of the decrease in the photoelectric cross section of the increased probability that a gamma ray will be Compton scattered out of the crystal before losing all its energy. Above 1.02 MeV an additional interaction mechanism can take place with increasing probability for higher energy gamma rays. This process is the creation of positron-electron pairs in the crystal. Since it requires 1.02 MeV to create a positron-electron pair this process is only possible for higher energy gamma rays, becoming significant above about 2 MeV. The total energy shared by the positron and electron is equal to the energy of the incident gamma ray minus 1.02 MeV. When the positron annihilates in the crystal two 511 KeV gamma rays are emitted. If both of these gamma rays are absorbed in the crystal one obtains a peak corresponding to the full energy loss of the gamma ray. If one of the 511 KeV
gamma rays leaves the crystal without being absorbed, we obtain the so-called "one-escape" peak at 511 KeV below the full energy peak. If both of the 511 KeV gamma rays escape, one obtains a "two-escape" peak 1.02 MeV below the full energy peak. Thus, above 2 MeV the gamma ray spectrum is complicated by the presence of three peaks in the pulse height spectrum.

The ratio of the full energy peak to the total number of gamma rays detected is a function of the geometrical arrangement used in a particular experiment as well as a function of the gamma ray energy. It is important to measure the detector efficiency for the particular geometry used.

A means of measuring the absolute efficiency of the gamma detection system used in this experiment is provided by (d,pγ) reactions in which the gamma ray is emitted isotropically, as for example, from a state of spin 1/2. Let N₁ be the number of protons corresponding to excitation of a spin 1/2 level. Let N₂ be the number of gamma rays detected in coincidence with these protons. Since the gamma rays are emitted isotropically, the efficiency of the system is given by N₂/N₁.

To determine this absolute efficiency a thin carbon foil was bombarded with 4.0 MeV deuterons. Coincidences between the protons produced in the C^{12}(d,p)C^{13*} reaction leaving C^{13} in its 1/2- first excited state at 3.09 MeV and 3.09 MeV gamma rays were observed using the two dimensional analysis system as previously described. The particle detector was placed at 60° with respect to the beam axis in order to separate the first excited state proton group from the deuterons elastically scattered from C^{12}. The number of protons in the first excited state group were determined in two ways.
The first method involved setting a window around the first excited state particle group and using a scaler to measure the total number of counts in the window for a given amount of charge accumulated. In the second method, the singles particle spectrum for a given amount of charge accumulated was obtained using the Nuclear Data 1024 channel analyzer. A low beam current was used to keep the dead time of the analyzer less than 1%. The singles particle spectrum thus obtained is shown in Fig. 16. The gamma ray spectrum in coincidence with the first excited state proton group is shown in Fig. 17. From these measurements a value for the full energy peak efficiency of the detection system at 3.09 MeV gamma ray energy was calculated to be $4.6 \times 10^{-3}$ full energy gammas per proton.

Next a thicker carbon foil which contained a fair amount of oxygen was bombarded with 4.0 MeV deuterons and a particle gamma coincidence spectrum obtained for the $^{16}(d,p \gamma)^{17}$ reaction leading to the $1/2^-$ first excited state of $^{17}$ at 0.871 MeV. A singles particle spectrum for this reaction was obtained using the TMC 400 channel analyzer and is shown in Fig. 18. The gamma ray spectrum observed in a coincidence with the first excited state proton group is shown in Fig. 19. From these measurements the full energy peak efficiency of the detection system at 0.871 MeV gamma ray energy was calculated to be $9.9 \times 10^{-3}$ full energy gammas per proton.

To obtain relative efficiencies for other gamma ray energies a Bi$^{207}$ source was used. This source has gamma rays of 0.570, 1.07 and 1.77 MeV with relative intensities of 100, 87, and 8 as determined by Alburger$^{(5)}$. The Bi$^{207}$ source was placed in the target holder in the
Figure 16

Particle spectrum observed at 60 degrees when a carbon foil is bombarded with 4.0 MeV deuterons. The observed peaks correspond to excitation of levels in $^{13}$C at 3.09, 3.68, and 3.86 MeV along with the elastic deuterons scattered from $^{12}$C.
Figure 17

Gamma ray spectrum in coincidence with the protons leading to the 3.09 MeV state in $^{13}\text{C}$ in the reaction $^{12}\text{C}$(d,p)$^{13}\text{C}^*$. 
Figure 18

Particle spectrum observed at 60 degrees when a carbon foil containing oxygen is bombarded with 4.0 MeV deuterons.
Gamma ray spectrum in coincidence with the protons leading to the 871 KeV state in $^17$ formed in the reaction $^16(d,p)^17*$. 
scattering chamber in exactly the same configuration as was used in the Cr$^{52}(d,p \gamma)$Cr$^{53}$ experiment. The gamma ray spectrum obtained is shown in Fig. 20.

From the observed intensities of the gamma rays from Bi$^{207}$ and the measured absolute efficiencies of the system from the $^{16}$O$(d,p \gamma)_{10}^{17}$ and $^{12}$C$(d,p \gamma)_{13}^{13}$ reactions, a curve of full energy gamma detection efficiency versus gamma ray energy was obtained as is shown in Fig. 21. By using this efficiency curve one may confirm the assignment of two gamma rays as members of a cascade and may obtain branching ratios in the case of complex decay schemes.
Figure 20

Gamma ray spectrum from a Bi$^{207}$ radioactive source.
Figure 21

Efficiency curve for the gamma detection system. The curve gives the number of counts per proton in the full energy peak of a gamma spectrum as a function of gamma ray energy.
VII. Discussion of Results

A. Experimental Results

The results of the present experiment on the level structure of \( \text{Cr}^{53} \) are summarized by the energy level diagram shown in Fig. 22. The spins and parities of the levels shown are those obtained by combining the results of the present experiment on the observed gamma decay schemes with the results of other experiments, particularly those of Sperduto, et al. \(^{(3)}\). The theoretical energy level diagram on the right is taken from the calculations of K. Ramavataram \(^{(6)}\). The numbers to the left of the gamma rays are the relative intensities of the gamma ray branches from a particular state as observed in the present experiment.

Table 1 gives a summary of the results of the determination of the relative gamma ray intensities for those states in \( \text{Cr}^{53} \) which have cascades through lower excited states. The errors indicated for the gamma ray intensities are estimated by combining the errors in determining the number of counts in the full energy peak and the possible errors in the gamma detector efficiency curve. The gamma detector efficiency curve should be good to within 10% over the gamma energy range covered in this experiment. The number of counts in the full energy peaks for the complex gamma decay schemes were obtained by graphical means. The strong gamma ray transitions in \( \text{Cr}^{53} \) at 0.56 MeV, 1.01 MeV, and 2.32 MeV, together with the 0.871 MeV transition in \( \text{O}^{17} \) and the 3.09 MeV transition in \( \text{Cl}^{13} \) were used to unfold complex gamma ray spectra. The estimated error in determining the peak intensity varied from 10 to 30% depending on the number of counts in the peak and the complexity of the decay scheme.
Figure 22

Energy level diagram of Cr$^{53}$ showing the decay schemes observed in the present experiment along with the suggested spin and parity assignments for some of the levels. The spectrum on the right is the theoretical energy level diagram calculated by Ramavataram.
<table>
<thead>
<tr>
<th>LEVEL \ ENERGY (MeV)</th>
<th>GAMMA</th>
<th>CORRECTED GAMMA INTENSITY X 10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.54</td>
<td>0.53</td>
<td>46 ± 9</td>
</tr>
<tr>
<td></td>
<td>1.01</td>
<td>41 ± 12</td>
</tr>
<tr>
<td></td>
<td>1.29</td>
<td>24 ± 7</td>
</tr>
<tr>
<td>2.69</td>
<td>0.56</td>
<td>132 ± 20</td>
</tr>
<tr>
<td></td>
<td>1.01</td>
<td>110 ± 20</td>
</tr>
<tr>
<td></td>
<td>1.29</td>
<td>74 ± 20</td>
</tr>
<tr>
<td></td>
<td>1.40</td>
<td>63 ± 20</td>
</tr>
<tr>
<td></td>
<td>1.68</td>
<td>140 ± 25</td>
</tr>
<tr>
<td></td>
<td>2.13</td>
<td>109 ± 35</td>
</tr>
<tr>
<td></td>
<td>2.69</td>
<td>62 ± 25</td>
</tr>
<tr>
<td>3.19</td>
<td>2.63</td>
<td>36 ± 15</td>
</tr>
<tr>
<td></td>
<td>0.56</td>
<td>40 ± 15</td>
</tr>
<tr>
<td>3.70</td>
<td>2.41</td>
<td>220 ± 40</td>
</tr>
<tr>
<td></td>
<td>1.29</td>
<td>210 ± 40</td>
</tr>
</tbody>
</table>
Assignment of two gamma rays as members of a cascade from a particular state requires that their energies add up to the excitation energy of the excited state in question and that their intensities are the same within the limits of experimental error.

Assignment of a cascade from the 1.54 MeV state through the excited state at 1.01 MeV is consistent with the agreement of the relative intensities of the gamma rays at 1.01 MeV and 0.53 MeV to within 25%.

The assignment of the cascade from the 3.70 MeV state through the level at 1.29 MeV is consistent with the observed relative intensities of the gamma rays at 1.29 MeV and 2.41 MeV.

The relative intensities of the pairs of gamma rays at 0.56 and 2.13 MeV, at 1.01 and 1.68 MeV, and at 1.29 and 1.40 MeV are consistent with the assignment of cascades from the 2.69 MeV state through the first, second, and third excited states of Cr$^{53}$ to within 30%.

An additional source of error may be the difference in the angular correlations for the different gamma rays. In general the angular correlation for a particular gamma ray depends on the multipolarity of the gamma ray transition, the spins and parities of the levels involved, and the reaction mechanism. Although a detailed knowledge of the reaction mechanism is necessary in order to obtain the angular correlation for a particular gamma ray, one can obtain an upper limit on the possible error by considering the maximum possible deviation from isotropy that a gamma ray of a given multipolarity could have. The difference between the measured gamma ray intensity and the actual gamma ray intensity for this maximum anisotropy is calculated in the Appendix for the case of magnetic dipole and electric quadrupole
transitions.

The maximum possible error in the case of an M1 transition would be 40% assuming that one has only \( m = \pm 1 \) for the \( z \) component of the angular momentum of the multipole radiation. In general, however, one has a combination of \( m = 0 \) and \( m = \pm 1 \) for a particular gamma ray depending on the population of the magnetic substates in the initial gamma emitting states. Since the \( m = 0 \) component has opposite anisotropy to the \( m = 1 \) component the effect of this combination is to reduce the anisotropy of the gamma ray. For an equal population of magnetic substates the gamma ray is isotropic. Since the angular distribution for electric and magnetic multipole radiation of the same order is the same, the above statements also hold in the case of E1 transitions.

For an E2 transition the worst possible anisotropy is obtained by considering only \( m = \pm 1 \) for the radiation. In this case a maximum error of 50 per cent is possible. However, if one includes the effect of the other components of the multipole radiation, namely the \( m = 0 \) and \( m = \pm 2 \) components, the anisotropy is reduced considerably. For an equal population of magnetic substates the distribution is again isotropic.

The agreement of the relative intensities of all the members of cascades observed in this experiment to within 30% suggests that the angular correlation effects do not cause any large deviations in the observed gamma ray intensities. This is consistent with the qualitative statement that the combination of the different \( m \) components of the radiation is such as to reduce the anisotropy considerably from
that which would result from only a single m component.
B. Theoretical

The nucleus $^{53}\text{Cr}$ is of considerable interest from a theoretical standpoint because it has a single neutron outside a closed $f_{7/2}$ neutron shell. The next three shell model states available to the neutron are the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ states. If core excitations were not important, one might expect the level structure of $^{53}\text{Cr}$ to be that of an excited single particle. Such a level structure has been observed in Ca$^{49}(7)$, in which the ground state, first excited state, and second excited state have been assigned to the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ shell model states. In $^{53}\text{Cr}$, on the other hand, considerable fragmentation of the single particle levels has been observed. Theoretical calculations of the energy levels of $^{53}\text{Cr}$ have been made by K. Ramavataram$^{(6)}$ using the unified model. The core excitations were treated as being collective in nature, arising out of the quadrupole oscillations of the even-even core. The lowest shell model states for the neutron were coupled to the phonon states of the core. The surface to particle coupling was assumed to be intermediate. The wave functions can be expanded in terms of the functions:

$$ \left| N R j ; J M \right> $$

where $N =$ number of phonons

$R =$ spin of the core state

$j =$ spin of the particle state

$J =$ total spin of the level

Free parameters used in the calculations of Ramavataram are the single particle level spacings ($p_{1/2} - p_{3/2}$) and ($f_{5/2} - p_{3/2}$), the phonon energy $\hbar \omega$ and the strength of the surface particle interaction. The
theoretical spectrum of Ramavataram is seen to be in qualitative
agreement with the results of this experiment. Further details on
the various levels observed in Cr$^{53}$ will be discussed in the next sec-
tion.
C. Conclusions

The spin of the ground state of Cr$^{53}$ is known to be $3/2^-$ in agreement with the shell model prediction that the next major shell available for the odd neutron beyond the closing of the $f_{7/2}$ shell at $N = 28$ is the $p_{3/2}$ shell. This spin assignment is confirmed experimentally by the measurements of the magnetic moment of the ground state of Cr$^{53}$(8).

A strong $l_n = 1$ stripping pattern for the angular distribution of the protons leading to the ground state of Cr$^{53}$ has been observed in the Cr$^{52}$(d,p)Cr$^{53}$ reaction at a deuteron bombarding energy of 10 MeV(9). The angular distribution does not show a dip in the cross section at backward angles, suggesting a spin of $3/2^-$ on the basis of Lee and Schiffer's observation of the $J$ dependence of $l_n = 1$ stripping reactions in the mass region of $40 \leq A \leq 62$(10).

There is a considerable amount of experimental evidence supporting an assignment of $1/2^-$ for the first excited state of Cr$^{53}$ at 0.56 MeV. A strong $l_n = 1$ stripping pattern is observed in the Cr$^{52}$(d,p)Cr$^{53}$ reaction, indicating a spin and parity of $1/2^-$ or $3/2^-$(3),(9). The observation of a pronounced dip in the proton angular distribution at 135 degrees suggests an assignment of $1/2^-$ on the basis of the Lee and Schiffer observations. A spin and parity of $1/2^-$ is also favored on the basis of the cross section for the Cr(n,n'\gamma)Cr reaction as measured by van Patter, et al.(11). The observation by Bartholomew and Gunye(12) of an isotropic angular distribution of the 0.560 MeV gamma ray following thermal neutron capture in natural chromium suggests a $1/2^-$ assignment for the 0.560 MeV state, although, in this case isotropy could also arise from certain E2/M1 multiple mixtures in the 0.560 MeV gamma ray. The results of the present experiment provides additional evidence
for the 1/2- assignment by the failure to observe any gamma decay to
the first excited state from the levels at 1.01, 2.32, and 3.60 MeV.
All these levels decay overwhelmingly to the ground state which has a
spin and parity of 3/2- and is predominantly a p$_{3/2}$ single particle
state. If the 0.560 MeV state were also 3/2-, it would be expected to
have a strong admixture of p$_{3/2}$ in its wave function because it is
strongly excited in a stripping reaction which tends to pick out states
which have strong single particle components in their wave functions.
Hence, if the first excited state were also 3/2-, one would expect
to see significant branches from all the higher excited states which
have strong ground state transitions. The fact that none of the levels
which have strong ground state transitions have any observable branches
to the 0.560 MeV state tends to support the assignment of 1/2- to this
level.

The second excited state at 1.01 MeV decays overwhelmingly to the
ground state with no observable branch to the first excited state. The
angular distribution of the protons leading to the 1.01 MeV state in
the Cr$^{52}$(d,p)Cr$^{53}$ reaction exhibits a strong l$_n$ = 3 stripping pattern,
indicating an assignment of 5/2- or 7/2- to the 1.01 MeV state$^{(3),(9)}$.
On the basis of the shell model the assignment of 5/2- is strongly
favored because of the closing of the f$_{7/2}$ neutron shell at N = 28 in
Cr$^{52}$.

Since the f$_{7/2}$ neutron shell is filled, one cannot add an addi-
tional f$_{7/2}$ neutron by a (d,p) stripping reaction. The next shell
model single particle state available for the odd neutron to give an
l$_n$ = 3 stripping reaction is the f$_{5/2}$ shell. Therefore, it seems
highly probable that the 1.01 MeV state is $5/2^-$.

The next excited state at 1.29 MeV decays primarily to the $3/2^-$
ground state and to the $5/2^-$ state at 1.01 MeV but not to the $1/2^-$
state at 0.56 MeV, suggesting an assignment of $5/2^-$ or $7/2^-$ to this state.
The assignment of $5/2^-$ would give an M1 (or mixed M1 and E2) transition
to the ground state and an M1 transition to the 1.01 MeV state while re-
quiring an E2 transition to the 0.56 MeV state. An assignment of $7/2^-$ to
the state at 1.29 MeV would require the transition to the ground state to
be E2 with an M1 gamma ray transition to the 1.01 MeV state. A means of
choosing between these possibilities is provided by the fact that the
3.70 MeV state decays almost entirely to the 1.29 MeV state. The level
at 3.70 MeV has been observed by Sperduto, et al.\(^{(3)}\) to have an $l_n = 4$
stripping pattern in the Cr\(^{52}\)(d,p)Cr\(^{53}\) reaction, and hence is believed
to be a $g_{9/2}$ single particle state, giving a spin and parity of $9/2^+$
for the 3.70 MeV state. An assignment of $7/2^-$ to the 1.29 MeV state
would allow an E1 transition from the 3.70 MeV state to the 1.29 MeV
state, while the transition from the 3.70 MeV state to the 1.01 MeV
state ($5/2^-$) would be a much slower M2 transition, in agreement with
the observed gamma decay scheme. A $5/2^-$ assignment for the 1.29 MeV
state would require an M2 transition from the 3.70 MeV state in which
case one might expect the 3.70 MeV state to have a significant branch
to the 1.01 MeV state. The 1.29 MeV is most probably the $7/2^-$-level
predicted by Ramavataram at 1.39 MeV. The principal configuration of
this state is that of $p_{3/2}$ neutron coupled to a $2^+$ one phonon vibra-
tional core to give a spin and parity of $7/2^-$. If this state has such
a configuration, one would expect a collective enhancement of the E2
transition probability to the ground state. One of the features of
the unified model is the prediction that the reduced transition probability, \( B(E2) \), to the ground state from any of the four levels of spin \( 7/2^- \), \( 5/2^- \), \( 3/2^- \), and \( 1/2^- \) formed by coupling a \( p_{3/2} \) neutron to a 2+ vibrational core should be enhanced by the same factor as the corresponding transition in the adjacent even-even nucleus. In other words, the \( B(E2) \) for the decay of the 1.29 MeV state should be enhanced over the single particle transition probability by the same factor as the transition from the 2+ first excited state of \(^{52}\text{Cr} \) to the ground state of \(^{52}\text{Cr} \). This transition in \(^{52}\text{Cr} \) is observed to have a value of \( B(E2)^{13} \) which is about 10 times the single particle estimate. The decay of the 1.29 MeV state primarily to the ground state is consistent with such an enhancement.

The level at 1.54 MeV has its principal decay to the 5/2- level at 1.01 MeV with a lesser branch to the 7/2- level at 1.29 MeV. An assignment of 7/2- to the 1.54 MeV state would permit M1 transitions to both of these states while requiring an E2 transition to the ground state. The failure to observe any significant decay to the ground state indicates that the 1.54 MeV state is not primarily a collective vibrational state or else one would observe an enhanced E2 transition to the ground state. A study of the \((p,d)\) reaction on natural Cr by J. C. Legg\(^{14}\) indicates a particle group corresponding to excitation of a level at about 1.59 MeV in \(^{53}\text{Cr} \) with an angular distribution characteristic of \( l_n = 3 \) pickup. This level is presumably formed by the pickup of an \( f_{7/2} \) neutron from the core in \(^{54}\text{Cr} \). A combination of the results of the \((p,d)\) reaction with the present results indicates that the 1.54 MeV level is a 7/2- core excitation level. Since
this level is formed by excitation of one of the \( f_{7/2} \) core neutrons, it would not be included in the theoretical levels predicted by Ramavataram.

The presence of two \( 7/2^- \) levels in \( \text{Cr}^{53} \) at 1.29 MeV and 1.54 MeV is consistent with recent work done on the \( \text{Fe}^{56}(p,d)\text{Fe}^{55} \) at Princeton\(^{(15)} \). Since \( \text{Fe}^{55} \) also has one neutron outside a closed \( f_{7/2} \) shell, one might expect a similar level structure. The angular distribution of the deuterons in the \( \text{Fe}^{56}(p,d)\text{Fe}^{55} \) reaction shows a strong \( l_n = 3 \) pickup reaction to a 1.41 MeV state in \( \text{Fe}^{55} \). This represents the pickup of an \( f_{7/2} \) neutron from the \( \text{Fe}^{56} \) core and is similar to the 1.54 MeV state in \( \text{Cr}^{53} \). A much weaker pickup is observed in another \( 7/2^- \) state in \( \text{Fe}^{55} \) at 1.33 MeV. This state may be similar to the 1.29 MeV state in \( \text{Cr}^{53} \) but the 1.33 MeV state in \( \text{Fe}^{55} \) must contain a small admixture of the core excitation state in order to show an \( l_n = 3 \) pickup angular distribution.

The level at 1.97 MeV decays primarily to the ground state. Since this level is not strongly excited in the \((d,p)\) reaction and does not show a characteristic stripping angular distribution, it may well be one of the collective states formed by coupling the \( 2^+ \) core to a \( p_{3/2} \) neutron. The decay principally to the ground state would then be due to a collective enhancement of the E2 transition probability. This level may be the \( 5/2^- \) level predicted by Ramavataram at 1.89 MeV, but this assignment is not definite.

The level at 2.32 MeV is strongly excited in the \( \text{Cr}^{52}(d,p)\text{Cr}^{53} \) reaction with a proton angular distribution characteristic of an \( l_n = 1 \) stripping reaction, giving possible spins and parities of \( 1/2^- \) or \( 3/2^- \). The assignment of \( 3/2^- \) is favored because of the absence of
a pronounced dip in the angular distribution of the protons at back angles\(^{(3),(9)}\). The assignment of \(3/2^-\) is also favored by the Cr \((n, n' \gamma)\) Cr cross section measurements\(^{(11)}\). This assignment is confirmed by the observed anisotropy of the 2.32 MeV gamma ray following thermal neutron capture in \(\text{Cr}^{52}\)\(^{(12)}\). The observation in the present experiment that the 2.32 MeV state decays to the ground state with no observable branch to the 0.560 MeV state tends to support the assignment of \(3/2^-\) for the 2.32 MeV state as may be seen from the following simple arguments. Since the 2.32 MeV state, the 0.560 MeV state and the ground state of \(\text{Cr}^{53}\) are all strongly excited by a \((d,p)\) stripping reaction, they all must have significant neutron single particle components in their wave functions. The ground state has the odd neutron in a \(p_{3/2}\) state while the 0.560 MeV state has the odd neutron in a \(p_{1/2}\) state. If the 2.32 MeV state is assumed to have a strong single particle component due to an odd neutron in a \(p_{3/2}\) state, the gamma ray decay to the \(p_{3/2}\) ground state can proceed by means of a "parity-favored" M1 transition, whereas the decay in the first excited state would be a "parity-unfavored" M1 transition\(^{(16)}\). The distinction between these two types of M1 transitions lies in the fact that a "parity-unfavored" transition requires a spin flip of the intrinsic spin of the odd nucleon while a "parity-favored" transition does not require a spin flip. In the present case of the odd nucleon in a \(p_{3/2}\) state the orbital angular momentum \(l = 1\) and the intrinsic spin \(s = 1/2\) are lined up parallel to each other. A transition to a \(p_{1/2}\) configuration would require the intrinsic spin to be lined up antiparallel to the orbital angular momentum; in other words, a spin flip would
have to take place. The transition to the $p_{3/2}$ configuration does not require a spin flip and hence would be expected to be favored over the transition requiring a spin flip. If one assumes that the gamma ray decay of the 2.32 MeV state is predominantly of a single particle character, the observation of the strongly favored transition to the $3/2^-$ ground state with no observable branch to the $1/2^-$ first excited state suggests an assignment of $3/2^-$ for the 2.32 MeV level.

The observed "level" at 2.69 MeV which exhibited such a complex decay scheme has been shown by recent high resolution studies using a broad range magnetic spectograph to consist of three closely spaced levels at 2.669, 2.681, and 2.723 MeV(3). Measurements by Sperduto, et al. of the angular distribution of the protons from the $\text{Cr}^{52}(d,p)\text{Cr}^{53}$ reaction indicate that the lowest of the three levels has an $l_n = 3$ stripping pattern. Presumably, the gamma rays observed in the present experiment as cascades to the 1.01 MeV state ($5/2^-$) and the 1.29 MeV state ($7/2^-$) originate from this level. The observed gamma decay would be consistent with a $5/2^-$ assignment which is suggested by the $l_n = 3$ stripping pattern as previously discussed in the case of the 1.01 MeV state. The next two levels in this group have angular distributions characteristic of $l_n = 1$ stripping. The observation of a strong cascade to the $1/2^-$ first excited state suggests that at least one of these levels has spin $1/2^-$, thus allowing a "parity-favored" M1 transition to the first excited state. Since the three levels were not resolved in the present experiment, these spin assignments must be regarded as tentative.

The level at 3.19 MeV is only weakly excited in the $(d,p)$ reaction and very little information is available concerning it. The observation
that the principal decay mode is a cascade through the $1/2^-$ first excited state suggests the possibility that the 3.19 MeV level has spin and parity $1/2^-$ but this is far from certain.

A number of weakly excited levels have been observed between the group of levels at 2.69 MeV and the level at 3.62 MeV by recent high resolution studies using magnetic spectographs at Copenhagen$^2$ and at M.I.T.$^3$. Although there is definitely some indication in the present experiment of the existence of other levels in this region they are too weakly excited and too closely spaced to obtain any significant information on their decay schemes.

The next strongly excited state at 3.60 MeV has been observed to have an $l_n = 1$ stripping angular distribution$^3$. The fact that this level exhibits a strong ground state transition with no observable branch to the 0.560 MeV state suggests an assignment of $3/2^-$ as previously discussed in the case of the 2.32 MeV level. This assignment is consistent with the absence of a dip at back angles in the proton angular distribution as observed in the $^{52}\text{Cr}(d,p)^{53}\text{Cr}$ reaction$^3$. An assignment of $3/2^-$ is also in agreement with the tentative assignment of Bartholomew and Gunye from the angular distribution of the gamma rays following thermal neutron capture in $^{52}\text{Cr}$.$^{12}$

The state at 3.70 MeV has been previously discussed in reference to the 1.29 MeV level. The angular distribution of the protons from the $^{52}\text{Cr}(d,p)^{53}\text{Cr}$ reaction indicate an $l_n = 4$ stripping pattern for the 3.70 MeV level, indicating a spin and parity of $9/2^+$ or $7/2^+$. A $9/2^+$ assignment is favored from shell-model considerations since one would expect the first $g_{9/2}$ single particle state to lie below the
first $g_{7/2}$ single particle state. An assignment of $9/2^+$ is also favored on the basis of the present experiment by the absence of any observable decay to the $5/2^-$ level at 1.01 MeV. A $7/2^+$ assignment to the 3.70 MeV level would permit a strong E1 transition to the 1.01 MeV state in contrast to the experimentally observed decay scheme. The failure to observe any decay from this level to the level at 1.54 MeV is an indication of the fact that the 1.54 MeV state is predominantly a core excitation state with very little admixture of any other configuration. One would expect a greatly reduced gamma ray transition to any state which would require an excitation of a core nucleon.

The gamma decay schemes obtained in the present experiment when combined with the results of previous experiments suggest the following assignments for the spins and parities of excited states of Cr$^{53}$:

ground state, $3/2^-$; 0.56 MeV state, $1/2^-$; 1.01 MeV state, $5/2^-$;
1.29 MeV state, $7/2^-$; 1.54 MeV state, $7/2^-$; 2.32 MeV state, $3/2^-$;
3.70 MeV state, $9/2^+$. A tentative assignment of $3/2^-$ for the level at 3.60 MeV would seem most consistent with the observed gamma decay.

There is also some indication that one of the group of levels at 2.69 MeV is a $1/2^-$-level.
APPENDIX

The angular distribution for a pure multipole radiation of angular momentum \( \ell \) and \( \ell \) component \( m \) is given by (17)

\[
Z_{\ell, m}(\theta, \phi) = \frac{1}{2} \left[ 1 - \frac{m(m+1)}{\ell(\ell+1)} \right] |Y_{\ell, m+1}|^2 + \frac{1}{2} \left[ 1 - \frac{m(m-1)}{\ell(\ell+1)} \right] |Y_{\ell, m-1}|^2 + \frac{m^2}{\ell(\ell+1)} |Y_{\ell, m}|^2.
\]

For the case of dipole radiation, one has \( \ell = 1 \) and \( m = 0, \pm 1 \).

The angular distribution for each of the \( m \) components can be obtained from the above expression and are given by:

\[
Z_{1, 0}(\theta, \phi) = \frac{3}{8\pi} \sin^2 \theta
\]
\[
Z_{1, \pm 1}(\theta, \phi) = \frac{3}{16\pi} \left( 1 + \cos^2 \theta \right)
\]

The maximum possible anisotropy is obtained by considering a transition involving only one of the \( m \) components. In order to determine the effect of this anisotropy on the observed gamma ray intensity, one must integrate this angular distribution over the solid angle subtended by the NaI crystal. The fraction of the gamma rays striking the NaI is given by

\[
f_{\ell} = \frac{\int_{0}^{2\pi} \int_{0}^{\pi} Z_{\ell, m}(\theta, \phi) \sin \theta \, d\theta \, d\phi}{\int_{0}^{2\pi} \int_{0}^{\pi} Z_{\ell, m}(\theta, \phi) \sin \theta \, d\theta \, d\phi}
\]

For a dipole transition this is just

\[
f_{1} = \frac{\int_{0}^{\pi} (1 + \cos^2 \theta) \sin \theta \, d\theta}{\int_{0}^{\pi} (1 + \cos^2 \theta) \sin \theta \, d\theta}
\]

where \( \Theta = 37^\circ \) for the case of the NaI crystal directly on top of the chamber.
Carrying out the above integration one obtains

\[ f_1 = 0.14 \]

For an isotropic distribution of the gamma rays, the fraction of the gamma rays striking the crystal is

\[ f = \frac{\int_0^{37^\circ} \sin \theta d\theta}{\int_0^{37^\circ} \sin \theta d\theta} = 0.10 \]

The maximum possible deviation from isotropy in the extreme case of only \( m = \pm 1 \) radiation is 40%. In an actual case one has a combination of \( m \) components and the anisotropy is reduced. In the case of equal population of magnetic substates, one has

\[ \sum Z_{l, m}(\theta, \phi) = Z_{1, 0} + Z_{1, 1} + Z_{1, -1} = \frac{3}{4\pi} \]

The resulting gamma ray is seen to be isotropic. Since the angular distribution of electric and magnetic radiation is the same for a particular multipole order, these results are valid for M1 and E1 radiation.

For quadrupole transitions one has the possibility of \( m = 0, \pm 1, \pm 2 \).

The angular distributions for the different \( m \) components are

\[ Z_{2,0} = \frac{5}{6\pi} \sin^2 \theta \cos^2 \theta \]
\[ Z_{2,\pm 1} = \frac{5}{16\pi} - \frac{15}{16\pi} \cos^2 \theta + \frac{5}{4\pi} \cos^4 \theta \]
\[ Z_{2,\pm 2} = \frac{5}{16\pi} - \frac{5}{16\pi} \cos^4 \theta \]

A sketch of the radiation patterns for these components is shown below:
Integrating the expression for the $m = \pm 1$ case gives

$$f_2 = \frac{\int_0^{37^\circ} (1 - 3 \cos^2 \theta + 4 \cos^4 \theta) \sin \theta \, d\theta}{\int_0^{37^\circ} (1 - 3 \cos^2 \theta + 4 \cos^4 \theta) \sin \theta \, d\theta}$$

$$f_2 = 1.15$$

Thus the maximum error in the case of the quadrupole transition is 50%. Once again, however, if one includes the other $m$ components, the anisotropy is reduced. If all the magnetic substates are equally populated, then the gamma ray distribution is isotropic as can be seen by summing the five possible $m$ components.
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