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Gamma Rays from Inelastic Neutron Scattering in Chromium*

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Gamma-ray spectra from the Cr$(n,n'\gamma)$ reaction have been studied using a ring geometry for ten Li$^7(p,n)$ neutron energies ranging from 0.98 to 3.31 MeV. Isotopic assignments have been made for the observed gamma rays, and differential gamma-ray production cross sections have been obtained at $\bar{\theta}=100°$. In order to convert these to inelastic neutron cross sections, calculations using Satchler's theory have been carried out for the angular distributions of the pertinent gamma-ray transitions in Cr^{50}, Cr^{52}, and Cr^{54}. The resulting experimental (n,n') cross sections for individual levels have been compared to predictions using Hauser-Feshbach theory and various diffuse surface potentials. The use of the $(n,n'\gamma)$ reaction as a nuclear spectroscopic tool has proved to be of value, since new information has been found concerning the properties of some of the low-lying states of Cr^{52} and Cr^{53}. The relationship of these new results to other available experimental evidence and to current theoretical predictions is discussed in detail, particularly the possibility of appreciable fragmentation of the $2p_{3/2}$ and $2p_{1/2}$ single-particle states in Cr^{53}. The evidence for contributions of core excitation to Cr^{53} states is also considered. Finally, comparison of the total inelastic neutron cross section for Cr and each of its four stable isotopes has been made with theoretical predictions.

1. INTRODUCTION

FOR the study of low-lying levels of nuclei over a large region of atomic masses, the $(n,n'\gamma)$ reaction has many attractive features. First, the cross section for a level with a given energy, spin, and parity is expected to be roughly the same for most even-even nuclei. Second, in many cases the cross section rises rather rapidly above threshold. A study of the gamma-ray spectra for increasing neutron energies can reveal information concerning the position and the branching for gamma-ray decay for a number of levels in ascending order. Third, from the gamma-ray production cross sections obtained, it may be possible to extract information concerning the spins and parities of the levels excited. In order to accomplish this, attention should be paid to the gamma-ray cascades from each level, and the angular distributions of the various gamma-ray transitions. In addition, it is necessary to have available theoretical predictions for the (n,n') cross sections which are sufficiently valid to enable meaningful comparisons with experiment to be made. There are also some disadvantages to the choice of the $(n,n'\gamma)$ reaction as compared with the (n,n') reaction which have recently been discussed in detail by Lind and Day.[1]

Earlier investigations of the $(n,n'\gamma)$ reaction in Mn^{55} and Nb^{93} carried on at this laboratory[2,3] revealed considerable information for the gamma-ray branching and possible spins for many of the levels of these nuclei, from comparisons with theoretically predicted (n,n') cross sections using the diffuse surface potential of Emmerich.[4]

The success of these $(n,n'\gamma)$ experiments for monoisotopic odd-Z elements led to the initiation of a program of studies of the $(n,n'\gamma)$ reaction for even-Z elements. An obvious difficulty which would be anticipated was the usual presence of several isotopes, involving rather complicated gamma-ray spectra, which could be difficult to decompose. On the other hand, there are several compelling reasons for investigations of this nature.

(1) Studies of the systematic properties of the energies[5] and gamma-ray transition probabilities[6] of the low-lying levels of even-even nuclei indicated that the positions of the first two 2+ states could be predicted generally to about ±0.1 MeV, and that missing levels could be expected to be discovered.

(2) A systematic comparison of the observed $(n,n'\gamma)$ cross sections with theoretical predictions for levels of known spin and parity might: (a) provide a test of the statistical assumptions of the Hauser-Feshbach theory[7] by comparing ratios of cross sections for the various outgoing channels, and (b) on the basis of absolute cross sections distinguish between the various diffuse surface potentials which have been used to fit other kinds of neutron data (such as total cross sections and elastic scattering angular distributions).

(3) Provided that reasonable agreement with theory was obtained in (2) then new information should be obtainable from the observed $(n,n'\gamma)$ cross sections for those levels whose spins and parities were not known.

(4) After sufficient information is collected for similar levels in a number of nuclei, then possible effects on the cross sections depending on neutron number, proximity to closed shells, etc, may be looked for.

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This program began in 1958 with a preliminary survey of the $(n,n'\gamma)$ spectra for 14 even-Z elements (Ti to Nd) at a few selected neutron energies in the range of 1.0 to 2.7 MeV,[8] together with some theoretical calculations using the potential of Emmerich.[4] In addition, a survey was made of published data for $(n,n'\gamma)$ cross sections of even-even nuclei.[8] On the basis of this evidence, the idea of using the $(n,n'\gamma)$ reaction as a nuclear spectroscopic tool for studying the properties of low-lying levels of even-even nuclei was first proposed.[8]

The results of this initial survey appeared to be quite promising, and it was decided to concentrate on elements in the range of $Z=22$ to 42 (Ti to Mo). Several preliminary reports of this work have been given.[9,10] Three of the authors (Malik, Nath, and Rothman) of the present paper were primarily involved in this earlier phase of the program. On the basis of these results, the feasibility of using the $(n,n'\gamma)$ reaction as a nuclear spectroscopic tool was verified for several even-even nuclei.[10]

More recently, the range of neutron energies studied has been extended to 3.3 MeV for several elements, and theoretical calculations of (n,n') cross sections using transmission coefficients of Beyster *et al.*[11] have been carried out for some thirty even-even nuclei.[12] Preliminary reports of these later results have been presented,[13–15] including a discussion of the data for the Cr$(n,n'\gamma)$ reaction.[15] Finally, theoretical calculations for the angular distributions of $(n,n'\gamma)$ radiations have been made for some for the nuclei studied. This paper is the first of a series in which the results of this program will be presented.

II. EXPERIMENTAL PROCEDURE

In Fig. 1 is shown the experimental arrangement. The analyzed proton beam, with an energy resolution of about 0.1%, was provided by the Bartol-ONR Van de Graaff accelerator, with energies of from 1.8 to 5.2 MeV for this experiment. Neutrons of energies up to 3.3 MeV were produced by bombarding a lithium target mounted on a probe which could be lowered into position to receive lithium evaporated in vacuum from a small furnace. The target backing consisted of a 0.010-in.-thick tantalum sheet, riveted to a 0.035-in. copper sheet which was necessary to provide adequate cooling. During operation the target probe was cooled by liquid nitrogen. Under these conditions, it was found that the lithium target could withstand a beam of 2 to 3 μA over an area of 0.2 cm^2 without melting. During the 2-yr period during which data for the Cr$(n,n'\gamma)$ reaction were obtained, four targets with thicknesses of 40 to 50 keV for $E_p=1.88$ MeV were used, and one target of 110-keV thickness. (No noticeable difference was observed for the results obtained using the thicker target.) For the neutron energies of 1.0 to 3.3 MeV used in this experiment, the spread in neutron energy caused by a typical target thickness varied from about 35 to 20 keV. Due to the finite size of the ring scatterer, at an average angle of incidence of 13° an additional neutron energy spread of about 10–25 keV was present at these neutron energies. Therefore, the total neutron energy spread was typically about 35 keV.

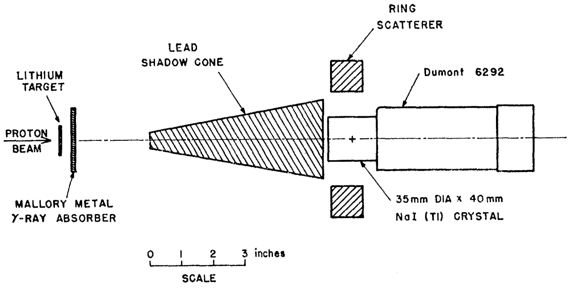

FIG. 1. Diagram of the experimental geometry for the present $(n,n'\gamma)$ investigations.

As indicated in Fig. 1, a $\frac{1}{8}$-in.-thick Mallory Metal attenuator was placed hear the neutron source to remove the 0.431-MeV gamma radiation originating from the Li$^7(p,n_1)$Be^{7*} reaction, without appreciably affecting the neutron flux. The gamma-ray detector was a cylindrical NaI crystal, 3.5 cm in diam and 4 cm long, optically coupled to a Dumont 6292 photomultiplier. The detector was shielded from direct neutrons by a Pb shadow cone, 14 cm long, and was located at a fixed angle of observation of 100°. Pulses from the detector were recorded in a 100-channel RIDL pulse-height analyzer.

Various ring scatterers were used for this experiment, each with a 3-in. i.d., a 5-in. o.d., and an axial thickness of 1 in. The chromium scatterer consisted of 912 g of fine metallic powder packed in a thin-walled Lucite container (105 g), with an average density of 4.45 g/cm^3. Background measurements were taken using a similar Lucite container containing 178 g of powdered graphite. A ring of natural iron (1511 g) of density 7.7 g/cm^3 was used to provide a standard cross-section measurement, with a background subtraction using a carbon ring (315 g).

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A. Background Subtraction

It was decided to try to take advantage of the automatic subtraction provided by the 100-channel analyzer whenever possible. This procedure, if successful, would eliminate the point-by-point normalization which has often been carried out as subtraction procedure in other similar experiments.[16,17] However, to obtain a reasonable automatic subtraction requires that the following conditions be satisfied.

(1) The background run should be taken at the same gain (generally within $\approx 0.5\%$) as the original spectrum.

(2) Time background, primarily due to the 25-min I^{128} activity produced in the NaI detector, should be the same for both runs.

(3) The background pulse distribution should not exceed the original spectrum in any channel, except for effects due to statistics.

(4) Prominent gamma-ray peaks in the background spectrum should be properly subtracted, so as to avoid negative or positive peaks in the subtracted spectrum.

At the beginning of the experiment, all of these conditions were not satisfied for some runs, and point-by-point normalization of the background runs were carried out, including gain-shift corrections. These procedures were found to be very tedious, and subject to considerable uncertainty in the regions of prominent $I^{127}(n,n'\gamma)$ radiations. It was found to be much preferable to try to achieve conditions which permitted reasonable subtracted spectra using automatic subtraction.

One unexpected initial difficulty was a gain shift of the pulse-height spectrum caused by magnetic effects on the photomultiplier when a ferromagnetic material such as iron was used as scatterer. In the case of the iron ring, this effect was enormous ($\approx 9\%$), and was attributed to the influence of the fringing field of the 90° beam-analyzing magnet. When the experiment was continued in a new target room[18] well removed from the magnet, this effect was no longer detected.

More generally, gain shifts due to changes in counting rate gave much more difficulty. Such gain shifts were minimized by the use of a low photomultiplier voltage of usually 700 V, by maintaining similar counting rates overnight by the use of radioactive sources, and by the adjustment of the intensity of the proton beam to give approximately the same counting rate for different scatterers. However, counting rate differences between the scatterer-in and background runs were usually unavoidable, in order to meet condition (2). It was sometimes necessary to adjust the gain between runs, to allow for the effect of changes in counting rate.

Precautions were taken to equalize the time background in each run. Generally, the equivalent of 1 h of continuous beam bombardment was made prior to each series of $(n,n'\gamma)$ spectra, in order to build up the I^{128} activity to approximately equilibrium. For the geometry shown in Fig. 1, the contribution of I^{128} activity to a typical background spectrum was a maximum of about 30% for $E_\gamma = 0.9-1.5$ MeV, and was relatively less for gamma-ray energies outside this range. A satisfactory subtraction of the activity was usually achieved by keeping the average beam constant to $\approx 1\%$. If for some reason the activity was not properly subtracted, this could be often detected by visual examination of the higher energy part of the subtracted spectrum above the highest prominent $(n,n'\gamma)$ radiation. If, due to an oversubtraction of I^{128} activity, predominately negative channels were observed, then these were corrected by adding in one or more minutes of time background to the subtracted spectrum.

In order to satisfy conditions (3) and (4), a suitable choice of background subtraction had to be made for each scatterer. In general, for metallic scatterers such as iron, a carbon ring of similar dimensions was found to be adequate. However, for incident neutron energies $\lesssim 1.5$ MeV, sometimes the background runs had to be shortened (up to $\approx 4\%$), in order to prevent oversubtraction in the region of the prominent 0.44-MeV group from the $(n,n'\gamma)$ reaction in Na^{23} and I^{127}. In the case of the powdered chromium scatterer, the carbon ring gave a probable oversubtraction of the 0.44-MeV gamma-ray group at $E_n = 1.41$ MeV. An undersubtraction was obtained with no scatterer present, particularly in the region of the prominent 0.63- and 0.74-MeV I^{127} $(n,n'\gamma)$ radiations.

An attempt was made to improve the background subtraction procedure for chromium. Lucite rings (127 and 190 g) of standard radial dimensions, and axial thicknesses of 0.50 and 0.75 in. were used for background subtraction at $E_n = 1.26$ MeV. Neither ring provided a satisfactory subtraction, giving too many counts for gamma-ray energies above 1.2 MeV, and too few counts in the region of the 0.63-MeV $I^{127}(n,n'\gamma)$ peak. No doubt this effect was caused by the hydrogen content of the Lucite rings, by producing an excess of slow neutrons which increased the I^{128} activity in the detector, as Freeman has pointed out.[19] A ring containing 178 g of powdered graphite was finally chosen for background subtraction, which gave a pulse spectrum similar in shape to that from the carbon ring, except that the $I^{127}(n,n'\gamma)$ peaks are possibly less prominent. A satisfactory subtraction was then obtained for most of the $Cr(n,n'\gamma)$ spectra, except for $E_n < 1.5$ MeV where

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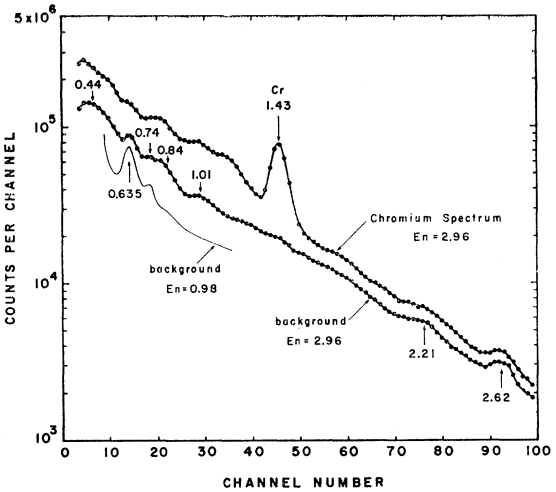

FIG. 2. Typical $(n,n'\gamma)$ gamma-ray spectra observed at an incident neutron energy of 2.96 MeV. The uppermost spectrum was obtained from a natural chromium ring before background subtraction. The run was taken for 2×10^6 neutron monitor counts, a total beam exposure of 1470 μC, an average proton beam of 0.8 μA, and an average dead time of 21% for the 100-channel analyzer, which was biased to reject pulses corresponding to $E_\gamma<0.4$ MeV. A background spectrum is also shown, which was obtained using a powdered graphite ring. The background run was taken for 1.86×10^6 monitor counts, which allowed for the difference in dead time between the two runs (21 and 14%). For purposes of comparison, the lowest curve shows a similar background spectrum at $E_n=0.98$ MeV, taken for the equivalent number of monitor counts.

occasionally there seemed to be a small undersubtraction of the 0.63-MeV $I^{127}(n,n'\gamma)$ peak.

In Fig. 2 is shown a typical gamma-ray pulse distribution observed from natural chromium bombarded by 2.96-MeV neutrons without background having been subtracted. The corresponding background run was taken immediately afterwards. In order to achieve conditions for proper subtraction, the live time of the 100-channel analyzer was kept equal within 1% for the two runs, by keeping the average beam as constant as possible.

The energies of prominent gamma-ray peaks are indicated in Fig. 2 for the background spectra observed for $E_n=0.98$ and 2.96 MeV. These gamma rays can be attributed to the $(n,n'\gamma)$ reaction in Na^{23}, I^{127}, and Al^{27}, the last contribution arising from the aluminum light shield for the NaI detector. In addition for $E_n\gtrsim2.7$ MeV, a prominent 2.62-MeV gamma ray was present in the background spectra, which is attributed to the $Pb^{208}(n,n'\gamma)$ reaction in the lead shadow cone. When present, this gamma ray provided a sensitive test of the gain stability during succeeding runs, as well as a good internal gamma-ray energy calibration for the chromium spectrum. However, it did make difficult any observation of weak gamma rays in the energy region of 2.5–2.75 MeV.

Comparison of the two background spectra shown in Fig. 2 indicates that the lower energy peaks in the background spectra become more pronounced as the incident neutron energy is decreased. This effect has been exhibited in detail by Day.[16] The peaks observed in the background spectra of Fig. 2 are less prominent than in Day's spectra for the same neutron energy. As the neutron energy is decreased, difficulties with background subtraction become more severe, particularly in the region of $E_\gamma\lesssim0.4$ MeV for these experiments.

B. Neutron Monitor

A long counter[20] placed at 112 cm from the lithium target, and at 90° to the incident proton beam direction was used to monitor the neutron flux during each run. The efficiency of this counter was periodically checked by use of a Ra–Be neutron source. The neutron flux at 0° was separately measured by removing the shadow cone, ring, and detector assembly, and placing the long counter at 178 cm from the target. A small correction, which will be described later, was necessary to relate the measured flux at 0° to the flux at 13° incident on the ring scatterer. The ratio of neutron yields was measured at 0° and 90° in steps of 0.1 or 0.2 MeV for $E_n=0.5-3.5$ MeV.

Near the completion of this investigation, some deterioration of the paraffin assembly of the long counter was noticeable. The monitor was then replaced by a newly constructed long counter. Remeasurement of the ratio of neutron yields at 0° and 90° at a distance of 150 cm for $E_n=0.5-3.2$ MeV indicated agreement (within 5% on the average) with the previous measurements using the old monitor.

The observed relative yield at 0° of $Li^7(p,n)$ neutrons (versus E_n) differed for the two monitors, with that recorded by the new monitor agreeing within 3% on the average with the published results of Bair *et al.*[21] for $E_n=1.0$–3.2 MeV. This discrepancy could be explained by a possible nonlinearity in the current integration of the proton beam in the early data, or it could indicate some difference in the relative efficiencies (vs E_n) of the two long counters. The latter alternative would then require a correction of up to 10% to $(n,n'\gamma)$ cross sections measured at neutron energies other than 2.56 MeV using the old monitor. In order to examine this point, the yield of the 0.845-MeV gamma ray from the $Fe^{56}(n,n'\gamma)$ reaction was remeasured at four neutron energies from 1.0 to 2.56 MeV using the new monitor, and a lithium target of similar thickness (within 10%). On the average, the measured gamma-ray yields agreed within 2% using either monitor together with the appropriate ratio of yields at 0° and 90°. Therefore, there was no evidence for a difference in the relative efficiency versus neutron energy for the two monitors, and it was decided that no correction should be applied to the results using the old monitor.

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III. CROSS SECTION MEASUREMENTS

In these investigations the basic measurements are the relative yields of $(n,n'\gamma)$ radiations at a mean angle of observation of 100°, averaged over an angular range of approximately 40°. These yields were then compared to the yield of the 0.845-MeV gamma ray from the $\mathrm{Fe}^{56}(n,n'\gamma)$ reaction at $E_n=2.56$ MeV observed in the same geometry. The absolute differential cross section for production of this gamma ray at 95° has been measured by Day,[16] and then later revised to 4% lower.[22] To use this standard cross section, it is necessary to take account of the angular distribution of the 0.845-MeV gamma ray, which has recently been reported by Day and Walt,[22] with $A_0=79.8\pm2.4$ mb/steradian. A simplified integration was made to obtain the angular efficiency of the NaI detector for the geometry of Fig. 1. Combining this with the $\mathrm{Fe}^{56}(n,n'\gamma)$ angular distribution, the observed average yield at 100° was calculated to be 73.8 mb/steradian, or 2.6% higher than the differential cross section at 95°.

For an $(n,n'\gamma)$ radiation emitted isotropically, the following expression for the differential cross section at $\bar{\theta}=100°$ has been used:

$$\frac{d\sigma}{d\Omega}(\bar{\theta}=100°)=\frac{d\sigma'}{d\Omega}(\bar{\theta}=100°)\frac{N_p\epsilon_p'K'}{N_p'\epsilon_pK}\frac{n'}{n}\frac{\alpha't'}{\alpha t}\frac{c}{c'},\qquad(1)$$

where the primed quantities refer to the standard Fe ring scatterer, N_p is the photopeak area per 10^6 neutron monitor counts, ϵ_p is the photopeak efficiency, K is a correction factor for the self-absorption of gamma rays in the scatterer, n is the number of relevant nuclei/cm^3, α is a geometrical factor relating to the scatterer's dimensions, equal to $2\pi\ln(r_2-r_1)$, t is the axial thickness of the scatterer, and c is a factor which includes all corrections to the $\mathrm{Li}^7(p,n)$ neutron flux.

If the $(n,n'\gamma)$ radiation is not emitted isotropically, then, as has been indicated, Eq. (1) gives the observed yield at 100° averaged over a range of angles, which may differ slightly from the correct differential cross section at 100°. To obtain the total gamma-ray production cross section integrated over all angles, a further correction factor is required, which will depend on the particular angular distribution.

A. Gamma-Ray Yield

The response function of the 3.5×4.0 cm NaI detector was measured at several gamma-ray energies from 0.28 to 2.75 MeV using sources of Hg^{203}, Na^{22}, Cs^{137}, Mn^{56}, Al^{28}, Y^{88}, and Na^{24} placed opposite the side of the crystal at a radial distance of 2 in., with no ring scatterer present. Under normal conditions, the resolution for the Cs^{137} 662-keV gamma ray was 8.5%. Rather than assuming a Gaussian shape for each photopeak, several calibration curves were established for the photopeak shape, taking the separations in keV from the midpoint for various fractions of the photopeak height, each as a function of gamma-ray energy. Similar curves were established for several points below the photopeak maximum, with energy intervals of 0.05 or 0.1 MeV. A standard spectral shape could then be obtained for a gamma ray of energy $\lesssim3$ MeV by interpolation using these calibration curves.

Since it was necessary, in general, to decompose rather complex $(n,n'\gamma)$ spectra superimposed on a continuous background, a graphical procedure using linear paper was adopted. This permitted direct graphical subtractions using dividers, which is not possible for plots on semilog paper. In order to obtain a reliable estimate of the continuous background, an iterative procedure was often necessary, particularly if there were overlapping photopeaks of several gamma rays. After making an initial estimate of the photopeak heights, the spectral distributions would then be subtracted, starting with the highest energy gamma ray detected. It was then required that the remaining background vary smoothly, usually increasing for lower gamma-ray energies. This requirement would then sometimes necessitate a readjustment of the photopeak heights, and a consequent change in the spectral distributions to be subtracted.

One of the main objectives of these investigations was to look for weak $(n,n'\gamma)$ radiations which may have been missed in earlier experiments, particularly if they occurred at energies below a prominent radiation. For this reason, it was desirable to know the response function for a given gamma ray to about ±2% of the photopeak maximum. Reproducibility of the initial calibrations using radioactive sources indicated that such an accuracy was achieved. However, later it became evi-

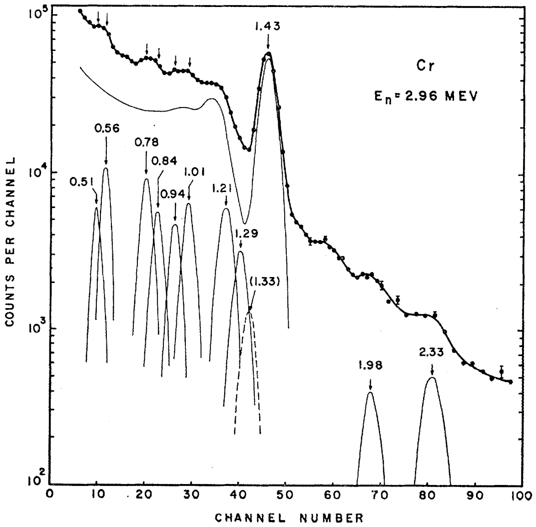

FIG. 3. Gamma-ray spectrum with background subtracted, observed from natural chromium at a neutron energy of 2.96 MeV, with the spectral analysis indicated.

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dent that the presence of the scatterer had a considerable effect on a given spectral distribution due to increased backscattering. In order to obtain a reliable response function for lower gamma-ray energies, it was necessary to approximate the geometry of Fig. 1, with sources placed at different radial positions with respect to the scatterer. The revised response function was then used for the spectral analysis of the more recent Cr data for $E_n \geq 2.68$ MeV,[15] for which the measurement of weak $\mathrm{Cr}^{52}(n,n'\gamma)$ cascade radiations required a more reliable knowledge of the spectral distribution of the prominent 1.43-MeV radiation.

In Fig. 3 are shown the results of such a spectral decomposition for a $\mathrm{Cr}(n,n'\gamma)$ spectrum at $E_n = 2.96$ MeV. The solid curve represents the spectrum remaining after subtraction of the background from the total spectrum, both of which are shown in Fig. 2. A considerable number of less prominent gamma rays are present below the intense 1.43-MeV peak. The existence of all but the 1.33-MeV gamma were verified from similar observations at lower neutron energies. Only two weak higher energy gamma rays of 1.98 and 2.33 MeV were consistently distinguishable above the continuous background.

Photopeak areas were obtained using a definite cutoff chosen to occur in the valley below each photopeak. The same cutoff procedure was used when calibrations of the photopeak efficiency of the 3.5×4.0 cm NaI detector were carried out. Since this crystal is not of standard dimensions, the efficiency calibration was obtained by comparison to a crystal 5 in. in diameter and 4 in. long. Sources of Cs^{137}, Na^{22}, Mn^{56}, and Na^{24} were placed at a standard distance from the 5×4 in. crystal, and their strengths were determined from using total efficiencies listed by Wolicki *et al.*[23] These sources were then placed opposite the side of the 3.5×4.0 cm crystal at a radial distance of 2 in., corresponding to the average scatterer-to-detector distance. Since the Mn^{56} and Na^{24} sources were extended in size, the intensities of the lowest prominent gamma rays of 0.845 and 1.37 MeV provided normalization, and the efficiency curve was extended to the higher gamma-ray energies of 1.81, 2.11, and 2.75 MeV available with these sources. In the case of Mn^{56}, the yields of the 1.81- and 2.11-MeV radiations were taken to be 28 and 16% of the intensity of the 0.845-MeV radiation, obtained from an average of the three best available measurements.[24] For the present investigations, only the relative photopeak efficiency vs gamma-ray energy is required, and it is considered to be known to be about ±5%. Near the completion of these investigations, a Y^{88} source was used to provide a check of this relative efficiency calibration, assuming that the ratio of the intensities of the 1.84- and 0.90-MeV gamma rays is 1.064 ± 0.008.[25] The result was in agreement within 5%.

Spectral decomposition of each $(n,n'\gamma)$ spectrum provided the photopeak area for each gamma ray in terms of the number of neutron monitor counts. Correction for the indicated dead time of the 100-channel analyzer was then made. The effects of neutron attenuation, multiple scattering, and gamma-ray attenuation in the ring scatterers were then considered. Since the ring geometry was reasonably similar to that used by Day,[16] it was assumed that the neutron flux was constant throughout the scatterer according to his recommendation. This assumption seems to be quite reasonable, since the present investigation involves relative, not absolute, cross-section measurements. For the same reason, a simplified correction for gamma-ray attenuation was made, by considering a two-dimensional ring geometry. The effect of the self-absorption is given by

$$K = \int_{r_1}^{r_2} e^{-\mu(r-r_1)} dr/r \Big/ \int_{r_1}^{r_2} dr/r.$$

The gamma-ray absorption coefficients used were not adjusted to take account of small-angle Compton scattering, since it was estimated that the error involved in this approximation should not exceed 3%. The total attenuation coefficients were calculated using the measured densities of the various ring scatterers.

B. Neutron Flux

Since all cross-section measurements in this investigation were made relative to Day's cross section for the $\mathrm{Fe}^{56}(n,n'\gamma)$ 0.845-MeV gamma ray at $E_n = 2.56$ MeV, simplifications result for the corrections relating to the neutron flux. As described in a previous section, the neutron flux at 0° is determined from measurements of the $N(0°)/N(90°)$ ratio using the long counter. In the geometry of Fig. 1, the neutron flux is incident on the ring scatterer at $\theta = 13°$. The angular distribution of the $\mathrm{Li}^7(p,n)\mathrm{Be}^7$ ground-state group is given by Bevington *et al.*[26] for $E_p = 2.58$–4.09 MeV, indicating that the flux at 13° is 5 to 7% less than at 0°. However, since we are concerned with measurements relative to $E_n = 2.56$ MeV, the pertinent quantity is the change in $N(0°)/N(13°)$, which for $E_n(13°) = 0.85$ to 2.38 MeV is less than 2%. For lower energies, the angular distributions of Taschek and Hemmendinger[27] for the combined (p,n_0) and (p,n_1) groups indicate that this correction exceeds 2% only for $E_n(13°) < 0.5$ MeV.

A more important correction is the effect of the presence of the $\mathrm{Li}^7(p,n_1)$ neutron group, which was not

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[23] E. A. Wolicki, R. Jastrow, and F. Brooks, Naval Research Laboratory Report NRL-4833, 1956 (unpublished).

[24] S. Sharp Cook, Nuclear Phys. **7**, 480 (1958); P. Dagley, M. A. Grace, J. M. Gregory, and J. S. Hill, Proc. Roy. Soc. (London) **250**, 550 (1959); L. V. Groschev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, Atomnaya Energ. **3**, 187 (1957) and (private communication).

[25] R. W. Peelle, Oak Ridge National Laboratory Report ORNL-3016, 1960 (unpublished), p. 110.

[26] P. R. Bevington, W. W. Rolland, and H. W. Lewis, Phys. Rev. **121**, 871 (1961).

[27] R. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

taken into account in our earlier investigations.[2,3] The recent work of Bevington *et al.*[26] now provides sufficient information for this correction to be made, since estimates of I_1/I_0 at 0° and 13° are needed. The results of Cranberg[28] are also needed for $E_p > 4.08$ MeV. This correction becomes most important when the (p,n_1) group is recorded by the long counter at 0°, but has not sufficient energy to excite the nucelar state in question. Without correcting for this effect, the observed (n,n') yield can be too low by as much as 12%. However, even when the (p,n_1) group is able to excite the nuclear state, some effect will remain as long as the (n,n') cross section for the (p,n_0) group is still increasing with neutron energy. In general, the correction C to the (n,n') cross section for a given level is given by

$$1/C = I(p,n_0) - I(p,n_1) \times \sigma(n,n') \text{ at } E_{n_1}/\sigma(n,n') \text{ at } E_{n_0}, \quad (2)$$

where $I(p,n_0)$ and $I(p,n_1)$ are the fractional amounts of the (p,n_0) and (p,n_1) groups present at $\theta = 13°$ and incident neutron energy E_n. The correction is more complicated for the yield of a $(n,n'\gamma)$ radiation if cascade contributions from higher levels exist. Taking this into account, the correction to the yield of the 0.845-MeV $\mathrm{Fe}^{56}(n,n'\gamma)$ radiation at $E_n = 2.56$ MeV is 1.02.

In earlier investigations,[2,3] no correction was made for the efficiency of the long counter, since it was known[29] that variations of the efficiency vs neutron energy did not exceed ±5% for the energy range of interest. However, it seemed now to be appropriate to include such a correction, based on a combination of the results obtained by Haddad *et al.*[30] for $E_n \geqq 1.5$ MeV, and Hanson and McKibben[20] for $E_n \leqq 1.5$ MeV (normalized at 1.5 MeV). A slight adjustment was needed in order to take account of the presence of the two neutron groups from the $\mathrm{Li}^7(p,n)$ reaction. Relative to the standard energy of 2.56 MeV, the correction for efficiency did not exceed ±5% for $E_n = 0.5$ to 3.4 MeV.

Since the Cr and Fe scatterers had nearly identical dimensions, no correction for a change in source-to-scatterer distance was necessary, as was the case for other scatterers investigated in this program.

C. Angular Distributions of $(n,n'\gamma)$ Radiations

One primary objective of these investigations was to compare the $(n,n'\gamma)$ cross section for excitation of a given level with theoretical predictions for (n,n') cross sections. As in many previous experiments,[1,2,31] the $(n,n'\gamma)$ yield was observed with a fixed detector, which integrated over a limited angular range. Generally in such experiments, possible corrections for angular distribution effects have been ignored in the comparisons with theory.

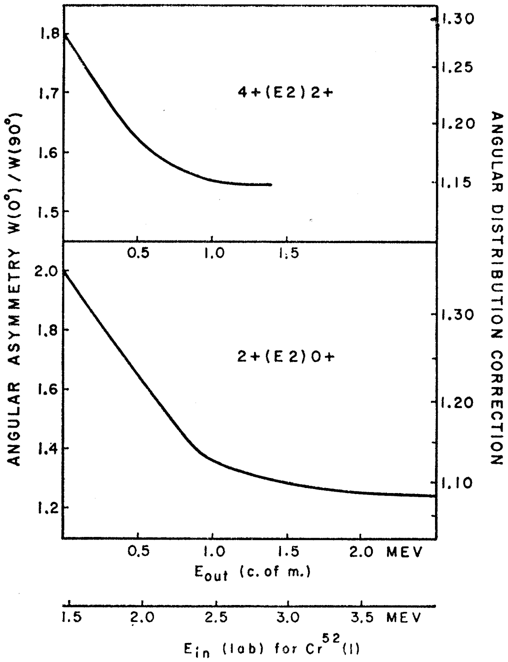

FIG. 4. Predicted angular asymmetries (0°/90°) for $(n,n'\gamma)$ angular distributions of $4+(E2)2+$ and $2+(E2)0+$ transitions in Cr^{50}, Cr^{52}, and Cr^{54} as a function of the outgoing neutron energy (c.m.). The corresponding angular corrections for the geometry of Fig. 1 are indicated on the left-hand scale for ordinates. The lower scale for abscissas gives the incident neutron energy, and applies only to the first 2+ state in Cr^{52} at 1.43 MeV.

During the course of the present program it was realized that failure to take account of angular distribution effects could result in appreciable systematic errors in some instances. Predicted angular distributions may be obtained from Satchler's compound reaction theory.[32] For example, it has been pointed out[14] that for energies sufficiently close to threshold, the angular distribution of a $2+(E2)0+$ transition should reach a limiting value given by

$$W(\theta) = 1 + 0.543P_2(\cos\theta) - 0.343P_4(\cos\theta), \quad (3)$$

provided that the statistical assumptions of Satchler's theory are satisfied. This result arises from the statistical $(2J_1+1)$ weighting of the contributions from 3/2+ and 5/2+ states in the limit of l_1(incoming) = 2, l_2(outgoing) = 0. In this case the 0°/90° asymmetry attains its maximum value of 2, as indicated in Fig. 4. For the geometry of Fig. 1, such an asymmetry corresponds to an angular distribution correction factor of 1.35; i.e., $\sigma(n,n'\gamma) = 1.35 \times 4\pi d\sigma/d\Omega(\bar{\theta} = 100°)$.

In order to obtain such predictions for neutron energies higher above threshold, explicit expressions

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[28] L. Cranberg, Los Alamos Scientific Laboratory Report LA-1654, 1954 (unpublished).

[29] R. A. Nobles, R. B. Day, R. L. Henkel, G. A. Jarvis, R. R. Kutarnia, J. L. McKibben, J. E. Perry, Jr., and R. K. Smith, Rev. Sci. Instr. **25**, 334 (1954).

[30] G. Haddad, R. L. Henkel, J. E. Perry, Jr., and R. K. Smith, quoted by J. B. Marion, *1960 Nuclear Data Tables*, Part 3 (U. S. Government Printing Office, Washington, D. C.), p. 137.

[31] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954).

[32] G. R. Satchler, Phys. Rev. **104**, 1198 (1956); **111**, 1947 (1958).

were evaluated for cascade and crossover transitions (pure or mixed) transitions from 2+, 3−, and 4+ states for $l_1 \leqq 4$, $l_2 \leqq 3$, which will be described in detail elsewhere. These expressions have been incorporated in a Univac I computer code, which also includes the angular efficiency function for the ring geometry of Fig. 1 in order to provide the required angular distribution corrections.

In principle, only the limiting value of the angular distribution [Eq. (3)] is model independent. In practice, however, it has been found that for neutron energies higher above threshold, the use of transmission coefficients, T_l, given by three different diffuse surface potentials[4,11,33] gave almost identical predictions in the case of Fe^{56}.[14] For the present investigation, the transmission coefficients of Beyster *et al.*[11] have been used, taking the values adopted for the calculation of inelastic neutron cross sections. (See Sec. IV A.)

In Fig. 4 are shown typical values for the 0°/90° asymmetry calculated for $4+(E2)2+$ and $2+(E2)0+$ transitions, plotted vs the energy of the outgoing neutron. It has been found that for a given value of the outgoing neutron energy, the asymmetry is nearly the same (within 1%), independent of the particular level being excited; this accounts for the choice of abscissas in Fig. 4. Indeed, for a fixed E_{out}, there is also only a small variation (less than 2%) in $W(0°)/W(90°)$ for different nuclei in a limited mass region (e.g., $A=50-56$). Therefore, the angular asymmetries and corrections shown in Fig. 4 are applicable to Cr^{50}, Cr^{52}, and Cr^{54}. It is noted that the predicted corrections for both types of gamma-ray transitions are quite appreciable near threshold, and diminish rapidly in the first MeV above threshold.

There is really not sufficient experimental data available for a given nucleus to provide a meaningful test of the trends predicted by Satchler's theory; i.e., an adequate series of angular distributions as a function of particle energy using the same geometry. In the case of Fe^{56}, there exist the largest amount of $(n,n'\gamma)$ angular distribution data, taken by several investigators using different geometries and incident neutron energies of 1.06,[17] 1.77,[34] 2.25 and 2.45,[35] 2.56,[22] 2.87,[36] 2.95,[37] and 4.70 [17] MeV. Comparison of these data with predictions using transmission coefficients of Beyster *et al.* indicates reasonably good agreement in most cases; however, unexplained discrepancies do remain,[34,36] particularly with respect to the recent work of Boring and McEllistrem.[36] In the case of Fe^{56}, it is possible that sufficient statistical averaging over compound states was not always achieved and perhaps a better test would be provided by choosing a nucleus near the *s*-wave resonance at about $A=150$. In any case, in view of the absence of angular distribution data for the $Cr(n,n'\gamma)$ reaction, it was decided to use these theoretical predictions for applying corrections for angular distribution effects.

D. Errors

Since these investigations were carried out over a 2-yr period, during which the ring geometry was reassembled several times, the reproducibility of the results taken under varying conditions could involve considerable uncertainty. In the case of the data for chromium, four measurements of the yield of the strong 1.43-MeV $Cr^{52}(n,n'\gamma)$ radiation were made at $E_n=2.68$ MeV. These yields agreed within ±5.4%, compared to a statistical error of ±3.5% for a typical determination of the $Cr^{52}(n,n'\gamma)$ photopeak area.

The latest value of the standard cross section for production of 0.845-MeV $Fe^{56}(n,n'\gamma)$ radiation at $E_n=2.56$ MeV given by Day and Walt[22] has an associated uncertainty of ±3.0%. For the present measurements of cross sections relative to this standard, errors associated with differences between the Cr and Fe scatterers (whose densities differed by a factor of 1.7) are of primary concern. Uncertainties related to neutron attenuation and multiple scattering, or the assumption of a constant neutron flux, were estimated to be less than 5%. Similarly, errors involved in the approximate correction for gamma-ray attenuation are not expected to exceed 3%.

The calibration of the relative photopeak efficiency of the NaI detector was considered to be accurate to ±5%. Similarly, it was estimated that the experimentally determined ratio of neutron flux at 0° and 90° was known to be ±2.5%.

The minimum error quoted for the present determinations of gamma-ray production cross sections amounts to ±10%, from a combination of the aforementioned uncertainties. This does not include any contribution associated with angular distribution corrections. Except for the intense 1.43-MeV $Cr^{52}(n,n'\gamma)$ radiation, the dominant error in the production cross section measurements arose from uncertainty in the photopeak areas due to statistics and background subtraction in the spectral analysis. For the weaker gamma rays, this error was typically 10–30%. In the case of some $(n,n'\gamma)$ cross sections for excitation of individual levels, additional errors were involved when subtraction was necessary for cascading from higher levels. For the estimate of such errors, the random error associated with photopeak areas was summed independently of the various "systematic" errors described previously.

IV. RESULTS

Gamma-ray spectra from natural chromium have been observed at a mean angle of 100° at ten neutron

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[34] J. J. Van Loef and D. A. Lind, Phys. Rev. **101**, 103 (1956).

[35] L. Cranberg and J. S. Levin, Phys. Rev. **103**, 343 (1956).

[36] J. W. Boring and M. T. McEllistrem, Phys. Rev. **124**, 1531 (1961).

[37] M. Hosoe and S. Suzuki, J. Phys. Soc. Japan **14**, 699 (1959).

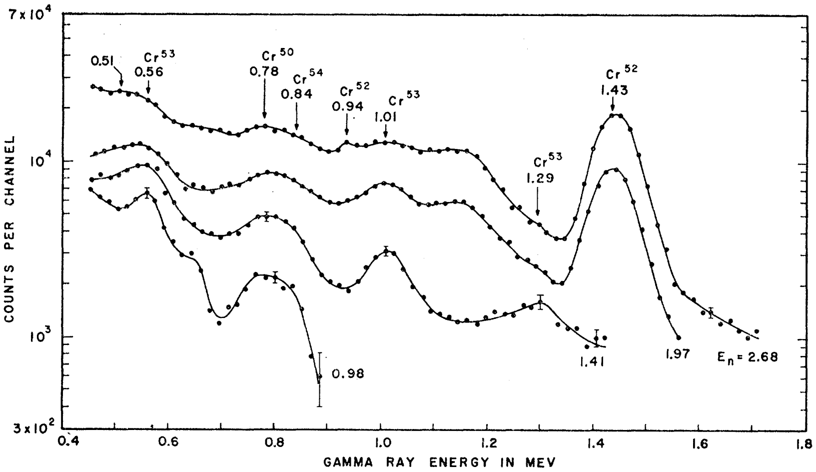

FIG. 5. Gamma-ray spectra with background subtracted, observed from natural chromium at neutron energies (lab) of 0.98 to 2.68 MeV. The isotopic assignments of the various $(n,n'\gamma)$ gamma rays are indicated

bombarding energies ranging from 0.98 to 3.31 MeV. Natural chromium consists of the following four stable isotopes: Cr^{50}(4.31%), Cr^{52}(83.76%), Cr^{53}(9.55%), and Cr^{54}(2.38%). According to the recommendation of Nier,[38] the isotopic abundances of White and Cameron[39] have been adopted. However, this choice is only of any consequence in the case of Cr^{54}, for which there is a 13% spread in the reported abundances. It is noted that for neutron energies below the threshold for $(n,n'\gamma)$ excitation of the first level in Cr^{52} at 1.43 MeV, Cr^{53} becomes the dominant isotope.

In Fig. 5 are shown typical subtracted spectra obtained during the first survey for $E_n \leqq 2.68$ MeV. Incident neutron energies were often chosen to occur between known level energies, in order to examine the gamma-ray decay of successively higher levels. For example, the spectrum at $E_n = 1.41$ MeV shows clearly a ground-state transition from the 1.29-MeV level in Cr^{53}, which at higher neutron energies becomes obscured by the intense 1.43-MeV gamma ray from Cr^{52}. Therefore, the yields of gamma rays from low-lying states in Cr^{50}, Cr^{53}, and Cr^{54} are best determined at $E_n < 1.46$ MeV.

More recent spectra observed at higher neutron energies are plotted in Figs. 3 and 6, which are all quite complex, as indicated by the spectral decomposition of Fig. 3. Many of the weak groups are assigned to cascade transitions from known levels in Cr^{52} to the 1.43-MeV state. Analysis of the two spectra of Fig. 6 indicates that three additional cascade transitions of 1.33, 1.53, and 1.73 MeV appear at $E_n = 3.31$ MeV, which were not present at $E_n = 2.77$ MeV. The former two cause an appreciable broadening of the 1.43-MeV group, although the energy of the 1.33-MeV group is not well defined because of its proximity to both the 1.29- and 1.43-MeV groups. There was also some evidence for a peak about 0.06 MeV below the 1.73-MeV gamma ray; this possibility contributed to the uncertainty in the yield of 1.73-MeV radiation. At higher gamma-ray energies, only the groups at 1.98 and 2.33 MeV consistently appear in the observed spectra. In Fig. 6, the subtracted spectrum at $E_n = 3.31$ MeV shows some rise near 2.56 MeV, which is interpreted as arising from a possible small gain shift while the total chromium and graphite background spectra were being recorded. The appearance of the strong 2.615-MeV $Pb^{208}(n,n'\gamma)$ radiation in both these spectra is indicated in the inset of Fig. 6. Since the yield of this peak is relatively intense, only a small shift of this peak could cause such a rise near 2.56 MeV in the subtracted spectrum.

The results of the analyses of these spectra are listed in Table I. Thirteen gamma rays are included, of these the existence of only the 1.33-MeV γ ray was not clearly defined. In addition to the yields for these gamma rays, upper limits for the intensities of other possible transitions from some of the levels involved were obtained; these are not given in Table I. The 0.51-MeV radiation seen in the various spectra is attributed to annihilation radiation, and has not been included in Table I. The yield of the 0.56-MeV gamma ray is not given for $E_n = 1.26$ MeV, because a Lucite ring rather than a powdered graphite scatterer was used for providing background subtraction, which prevented reliable spectral analysis in the region of $E_\gamma \approx 0.6$ MeV.

In the first survey, the gamma-ray energies were determined by comparison to calibration spectra using Co^{58}(0.511, 0.805 MeV) and Co^{60}(1.172, 1.333 MeV), taken just preceding or following a $Cr(n,n'\gamma)$ spectrum. These calibrations were generally consistent with the energies well-established levels in the chromium isotopes, such as the 1.433-MeV level in Cr^{52}.[40] In the latter work at higher neutron energies, calibrations were taken using an improved procedure of superimposing a

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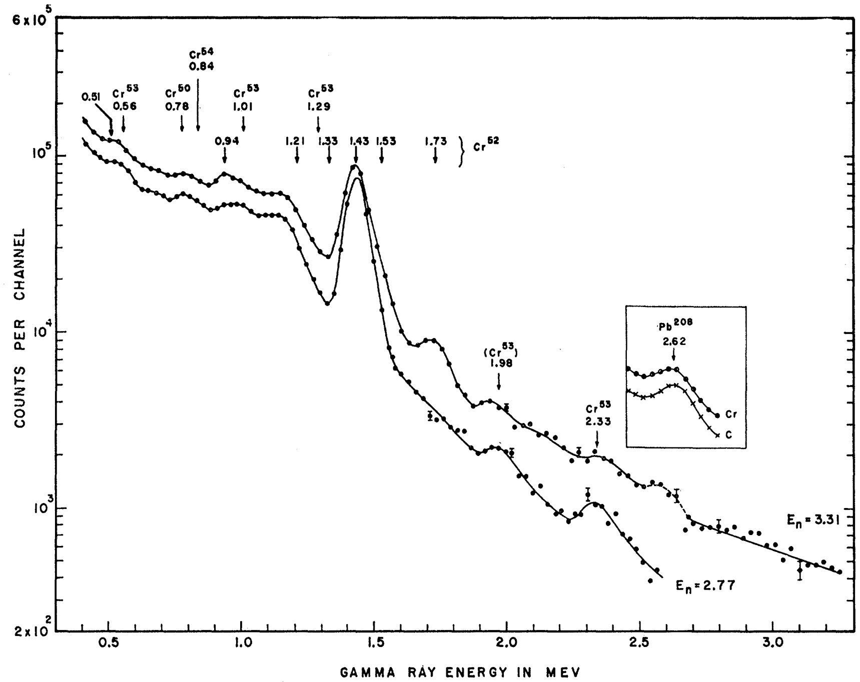

FIG. 6. Gamma-ray spectra with background subtracted, observed from natural chromium at neutron energies (lab) of 2.77 and 3.31 MeV. The isotopic assignments of the various $(n,n'\gamma)$ gamma rays are indicated. The inset shows the original spectrum before background subtraction, together with the background spectrum using a powdered graphite scatterer, plotted on the same ordinate scale, in order to show the prominence of the $\mathrm{Pb}^{208}(n,n'\gamma)$ radiation at 2.615 MeV.

Y^{88} gamma-ray spectrum (0.900, 1.837 MeV) on the $\mathrm{Cr}(n,n'\gamma)$ spectrum. These calibrations proved to be acceptable, except at $E_n = 3.31$ MeV, where a gain shift occurred, and a self-calibration was necessary using 0.511- and 1.433-MeV gamma rays in the $\mathrm{Cr}(n,n'\gamma)$ spectrum. In any case, since most of the gamma rays listed in Table I correspond to transitions from well-established states, no attempt was made to try to reduce the errors in the gamma-ray energies below 0.01 MeV.

Gamma-ray spectra from neutron bombardment of natural chromium have been reported previously by other investigators. Scherrer *et al.*[41] have listed gamma-ray energies of 0.75±0.03, 0.97±0.04, and 1.43±0.06 MeV for $E_n = 3.2$ MeV. Androsenko *et al.*[42] have observed gamma rays with energies of (0.80), 0.99±0.03, 1.42±0.04, and 1.93±0.04 MeV for $E_n = 3.0$ MeV, evidently verifying the present observation of a 1.98±0.02-MeV gamma ray. Kiehn and Goodman[31] reported 1.015- and 1.44-MeV gamma rays, and observed their thresholds. It is clear that none of these investigations revealed the complexity of the spectra as observed in this experiment.

As later discussions will reveal, almost all the gamma rays listed in Table I can be unambiguously assigned to the $(n,n'\gamma)$ reaction in a particular Cr isotope, since all but the 1.98-MeV gamma ray fit the known level schemes. The 1.98-MeV gamma ray is tentatively assigned to Cr^{53}. The assignments given in Table I

TABLE I. Gamma-ray production differential cross sections for natural Cr in mb/sr at $\theta = 100°$.

E_γ (MeV)	Isotope assign.	Neutron bombarding energy in MeV									
		0.98	1.26	1.41	1.97	2.28	2.68	2.77	2.96	3.15	3.31
0.56 ±0.01	Cr^{53}	0.9±0.3	⋯	2.0±0.5	1.8±0.3	2.1 ±0.4	1.7±0.2	1.5±0.3	1.5±0.3	1.0±0.3	1.2±0.4
0.78 ±0.01	Cr^{50}	1.4±0.3	1.6±0.2	1.9±0.3	2.7±0.5	2.4 ±0.5	2.9±0.4	2.3±0.4	2.8±0.5	1.9±0.4	2.2±0.4
0.84 ±0.01	Cr^{54}	1.2±0.2	1.7±0.3	1.4±0.3	2.1±0.3	1.4 ±0.5	2.0±0.5	1.4±0.3	2.0±0.5	1.5±0.4	1.3±0.3
0.935±0.01	Cr^{52}						1.5±0.5	2.1±0.6	2.1±0.6	4.3±0.8	4.6±0.8
1.01 ±0.01	Cr^{53}		2.2±0.3	2.5±0.3	3.1±0.4	3.7 ±0.7	3.8±0.5	2.9±0.6	3.0±0.6	4.0±0.9	2.7±0.6
1.21 ±0.01	Cr^{52}							2.6±0.9	3.9±0.9	4.3±1.1	4.6±1.2
1.29 ±0.01	Cr^{53}			1.4±0.3	1.8±0.4	1.8 ±0.4	2.2±0.6	1.9±0.7	2.4±0.9	3.2±1.0	1.9±1.0
(1.33 ±0.03)	Cr^{52}								1.0±1.0		3.2±1.6
1.43 ±0.01	Cr^{52}				32±3	37 ±4	59±6	62±6	54±6	57±6	58±6
1.53 ±0.01	Cr^{52}									8.4±1.8	10.0±2.2
1.73 ±0.01	Cr^{52}										3.5±0.8
1.98 ±0.02	(Cr^{53})					0.7 ±0.3	0.9±0.3	0.7±0.3	0.6±0.2	0.8±0.3	0.9±0.4
2.33 ±0.02	Cr^{53}						0.9±0.3	1.1±0.3	1.2±0.5	0.7±0.3	0.8±0.3

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[41] V. E. Scherrer, B. A. Allison, and W. R. Faust, Phys. Rev. **96**, 386 (1954); P. Shapiro, V. E. Scherrer, B. A. Allison, and W. R. Faust, *ibid.* **95**, 751 (1954).

[42] A. L. Androsenko, D. D. Broder, and A. I. Lashuk, Atomnaya Energ. **9**, 403 (1960) [translation: Atomic Energy (U.S.S.R.) **9**, 945 (1961)].

TABLE II. Inelastic neutron cross sections in barns for excitation of six levels in Cr^{52} (100% Cr^{52} isotope). Corrections for $(n,n'\gamma)$ angular distributions have been made assuming a spin for each level as indicated. (See text for further details.)

E_n	Cr^{52} level in MeV with assumed spin and parity					
(MeV)	1.43 (2+)	2.37 (4+)	2.65 (0+)	2.77 (4+)	2.96 (2+)	3.16 (2+)
1.97	0.59±0.06					
2.28	0.64±0.06					
2.68	0.97±0.10	0.027±0.009				
2.77	0.96±0.11	0.039±0.011	0.039±0.013			
2.96	0.79±0.09	0.037±0.010	0.059±0.013	0.02±0.02		
3.15	0 63±0.10	0.076±0.015	0.065±0.017	0.03±0.03	0.15±0.03	
3.31	0.52±0.10	0.080±0.015	0.068±0.019	0.06±0.03	0.17±0.04	0.061±0.013

agree with the $(n,n'\gamma)$ results of Sinclair[43] at $E_n=4.4$ MeV, who observed the following gamma rays using isotopically enriched scatterers: Cr^{50}, 0.787±0.010 MeV; Cr^{52}, 0.96±0.02 and 1.455±0.010 MeV; Cr^{54}, 0.849±0.010 MeV.

In Table I are listed the gamma-ray production differential cross sections for natural Cr for $\bar{\theta}=100°$ obtained from this investigation. These differential cross sections have been corrected for the presence of the $\mathrm{Li}^7(p,n_1)$ group and the variation in efficiency of the long counter. As described in Sec. III, if the particular $(n,n'\gamma)$ radiation has an anisotropic angular distribution, these cross sections would then differ slightly from the correct $d\sigma/d\Omega$ at $\theta=100°$, because of the angular integration of the NaI detector over roughly 40°. An extreme case would be near the threshold for a $2+(E2)0+$ transition, where the experimental results at $\bar{\theta}=100°$ are expected to be 8% higher than the correct $d\sigma/d\Omega$ at $\theta=100°$; but, in general this effect should be much smaller. However, these differential cross sections are the basic measurements in this experiment, assuming no knowledge of the angular distributions. Angular distribution corrections using Satchler's theory have then been applied to those gamma rays assigned to Cr^{50}, Cr^{52}, and Cr^{54} in order to obtain integrated production cross sections. In the case of Cr^{53}, no such corrections have been made; therefore, the production cross sections are obtained by multiplying the values given in Table I by 4π.

Scherrer *et al.*[41] have given production cross sections for natural Cr at $E_n=3.2$ MeV, using an NaI detector at $\bar{\theta}=90°$ which averaged over a considerable angular range. They list cross sections of 0.027±0.005, 0.10±0.02, and 0.73±0.15 for their reported gamma rays of 0.75, 0.97, and 1.43 MeV, no corrections being applied for angular distributions. These results compare favorably with the present production cross sections at $E_n=3.15$ MeV of 0.027±0.005, 0.11±0.03, and 0.72±0.07 b (corrected for angular distributions) for gamma rays of 0.78, 0.97 together with 1.01, and 1.43 MeV. However, they did not report several of the gamma rays listed in Table I, in particular, the 0.84-MeV gamma ray could have contributed to the intensity of their 0.75-MeV group.

Table I also yields information concerning the production threshold for each gamma ray, since the entries indicate the lowest neutron energy at which a particular gamma ray was observed. Thus, it is clear that the gamma rays of 0.935, 1.21, (1.33), 1.53, and 1.73 MeV all represent cascade transitions, while the remainder are ground-state transitions.

A. $\mathrm{Cr}^{52}(n,n'\gamma)$ Reaction

Accurate determinations of six low-lying states in Cr^{52} up to 3.16 MeV excitation have been reported by Mazari *et al.*[40] from an investigation of the $\mathrm{Cr}^{52}(p,p')$ and $\mathrm{Mn}^{55}(p,\alpha)$ reactions. The energies of six $\mathrm{Cr}(n,n'\gamma)$ radiations listed in Table I are in excellent agreement with their assignment to transitions from these six levels. Further, the abundances of any of the remaining Cr isotopes are not sufficient to account for the observed intensities of these six gamma rays. Except for the first 2+ level at 1.43 MeV, no ground-state transitions were observed from these levels in Cr^{52}. In the cases of the levels at 2.65, 2.96, and 3.16 MeV, upper limits for the branching ratios (crossover/cascade) of $\leqq 0.07$, $\leqq 0.03$, and $\leqq 0.08$, respectively, were estimated. No transition between the 2.96- and 2.37-MeV levels was observed with an intensity greater than 0.05 of the intensity of the $2.96 \rightarrow 1.43$ MeV transition.

In Table II are listed the present measurements of inelastic neutron cross sections for excitation of the six levels in Cr^{52}. In order to obtain these values, angular distribution corrections have been applied to the data of Table I, assuming a spin and parity for each level as indicated. For a 0+ assignment to the 2.65-MeV level, no such correction is necessary. In the case of the 2.96- and 3.16-MeV levels, the cascade transitions are assumed to be $2+(M1)2+$, in analogy to Fe^{56} where the cascade transitions from the 2.66- and 2.96-MeV 2+ states are predominately $M1$.[44]

The procedure for obtaining the $(n,n'\gamma)$ cross section for the 1.43-MeV level in Cr^{52} was more complicated, since the contributions of cascades from higher levels had to be subtracted from the observed yield of the 1.43-MeV gamma ray. First, the angular distributions of $2+(E2)0+$ transitions following cascades from higher

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[43] R. M. Sinclair, Phys. Rev. **107**, 1306 (1957).

[44] *Nuclear Data Sheets*, National Academy of Sciences (National Research Council, Washington, D. C., 1958–61).

states were calculated. The contributions of such transitions to the yield of the 1.43-MeV gamma ray could then be determined from the yields of the preceding cascade transitions. In the case of the contributions due to cascades from the 2.65-MeV level, two possible transitions were considered; i.e., $0+(E2)2+(E2)0+$ and $3-(E1)2+(E2)0+$. In the latter case, the angular distribution has an A_2 coefficient opposite in sign to that for a $3-(E1)2+$ transition; hence, the correction for cascading through the 1.43-MeV level differed considerably than for an isotropic $0+(E2)2+(E2)0+$ transition. However, this possible difference had only a minor effect of about 3% on the relatively large cross section for the 1.43-MeV level. Finally, an angular distribution correction for the direct (n,n') excitation of the 1.43-MeV level was applied.

The experimental $(n,n'\gamma)$ cross sections for six low-lying states in Cr^{52} are shown in Fig. 7 as a function of incident neutron energy. For comparison, theoretical (n,n') cross sections are shown, which were obtained using Hauser-Feshbach theory[7] and transmission coefficients, $T_l(E)$, associated with various diffuse surface potentials.

Previously, it had been demonstrated that use of either of the optical potentials of Emmerich[4] or Campbell *et al.*[33] resulted in predicted total inelastic cross sections for Fe^{56} which were up to a factor of 2 higher than experiment for $E_n \lesssim 2$ MeV, while the cross sections obtained from the transmission coefficients given by Beyster *et al.*[11] for iron were in considerably better agreement.[14] This discrepancy occurred despite the fact that the parameters of the former two potentials were chosen to give "global" fits to available neutron data. In order to carry out similar calculations for the chromium isotopes, it was necessary to interpolate between values of $T_l(E)$ given by Beyster *et al.* for Ti and Fe. This interpolation procedure has been described in detail elsewhere,[12] and is subject to uncertainty (perhaps as much as ±10%), since Beyster *et al.* attempted to achieve local fits to the available cross sections for a given element. As a result, the values of a given $T_l(E)$ as a function of nuclear radius do not always vary smoothly, and have local fluctuations. Despite this disadvantage, it was anticipated that the procedure adopted to obtain T_l values would provide calculated (n,n') cross sections which would be considerably closer to experimental cross sections than those obtained by the use of any optical potential whose parameters had been chosen on the basis of a "global" fit, rather than detailed local fits. Therefore, theoretical cross sections were computed using a Univac I computer code, using such interpolated T_l values as input, and for various choices of spin of each level of Cr^{52}, as are shown by the solid lines in Fig. 7 (marked *Be*).

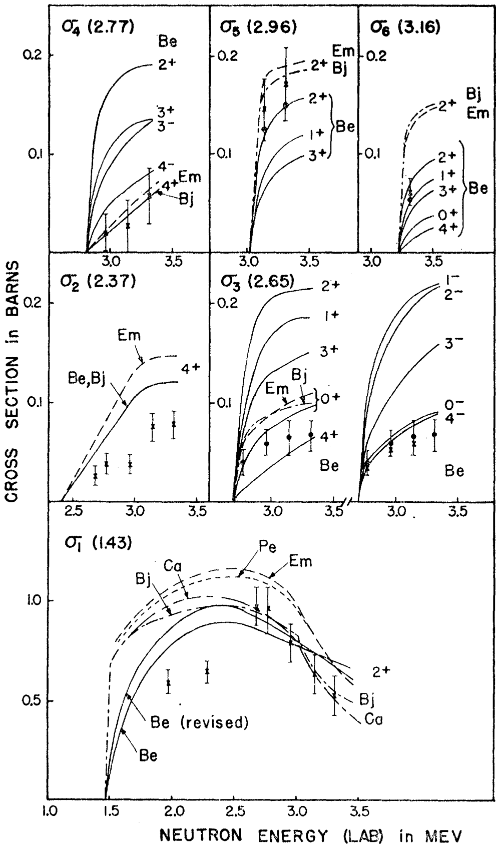

FIG. 7. Comparison of the present experimental inelastic neutron cross sections for excitation of six low-lying levels in Cr^{52} with various theoretical predictions. The theoretical cross sections shown as solid lines were obtained using the original (reference 11) and revised (reference 45) transmission coefficients of Beyster *et al.* and are indicated by *Be* and *revised Be*. The dashed lines represent predictions using the transmission coefficients of Emmerich (reference 4) (marked *Em*) and Perey and Buck (reference 46) (marked *Pe*), while the dot-dashed lines represent predictions using the potential parameters of Bjorklund and Fernbach (reference 47) (marked *Bj*) and Campbell *et al.* (reference 33) (marked *Ca*) calculated by D. T. Goldman. No angular distribution corrections have been applied to the experimental cross sections shown as closed circles, while those shown by ✕ have been corrected, as explained in the text.

Following the submission of this work for publication, we were informed[45] that recent calculations by E. H. Auerbach, Brookhaven National Laboratory, had failed to reproduce the T_l values of Beyster *et al.*[11] from the optical potential parameters which they listed. In the cases of Ti and Fe, the most significant alterations in the revised transmission coefficients are increased values of T_0(10–30%) and T_2(20–50%) $E_n \leqq 1.5$ MeV, while the values of T_1 and T_3 are relatively unaffected. Using these revised T_l values, (n,n') cross sections for levels in Cr^{52}, Cr^{53}, and Cr^{54} have been recalculated. The results are shown for the first 2+ level of Cr^{52} at 1.43 MeV by the revised Beyster curve in the lowest part of Fig. 7. In this instance, revision of the T_l values of Beyster *et al.* did not usually affect the predicted cross section by more than 10%. However, in the case of the first level of Fe^{56} at $E_n = 1.0$ MeV, the revised (n,n') cross section is increased by a factor of 1.7, thereby removing the

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[45] D. T. Goldman (private communication).

previous satisfactory agreement with experimental data.[14] In addition, the calculated compound nucleus cross section is increased from 1.3 to 2.4 b, which would then appear to destroy the local fit which Beyster *et al.* achieved originally for the total neutron cross section for Fe, which shows a minimum in the region of $E_n \approx 1.0$ MeV. Therefore, it would seem to be incorrect to use revised T_l values consistent with the optical potential parameters listed by Beyster *et al.*, since preservation of the local fits appears to require alteration of their original parameters. Without such revised parameters, in our opinion it is better to use the original transmission coefficients of Beyster *et al.*, realizing that they are not completely consistent with the potential parameters as stated. Therefore, revised Beyster curves have not been shown for other levels in the Cr isotopes.

To insure that any conclusions based on comparisons of the present experimental data with (n,n') cross sections calculated from the original T_l values of Beyster *et al.* remain unaffected, further calculations were obtained for three other optical potentials, in addition to those already calculated[12] using the potential of Emmerich. For these new calculations, one set of "best" spin values was adopted for each of the chromium isotopes, which then provides representative results for each potential chosen.

From tables of $T_l^{\pm}(E)$ provided by F. Perey for the nonlocal potential of Perey and Buck,[46] spin-independent values of $\bar{T}=[(l+1)T^{+}+lT^{-}]/(2l+1)$ were obtained according to the prescription suggested by Sheldon, in order to provide input values for our spin-independent Hauser-Feshbach code. The resulting (n,n') cross section (marked *Pe*) for the 1.43-MeV level of Cr^{52} is shown in the lowest part of Fig. 7, and is nearly identical to the predicted cross section (marked *Em*) using the T_l values of Emmerich.[4] Since this similarity persists for other levels of the chromium isotopes, for the sake of clarity of presentation the calculations based on the Perey-Buck potential have not been distinguished elsewhere from the Emmerich results.

Theoretical calculations for each of the Cr isotopes have been carried out by Goldman, at Knolls Atomic Power Laboratory, using the spin-independent potential of Campbell *et al.*[33] and the spin-dependent potential of Bjorklund and Fernbach.[47] In the latter case, parameters listed by the authors listed for $E_n = 4.1$ MeV were adopted. The results of Goldman's calculations (marked *Ca* and *Bj*) for the 1.43-MeV level of Cr^{52} in the lowest part of Fig. 7. In the curves showing cross sections for other levels, only the results for the Bjorklund-Fernbach potential are shown, since the agreement with the experimental data is usually slightly better than for calculations using the potential of Campbell *et al.*

In Fig. 7 the experimental cross sections for the 1.43-MeV 2+ level in Cr^{52} are shown to be in reasonable agreement with the various theoretical predictions for $E_n > 2.5$ MeV, and are distinctly lower for $E_n < 2.5$ MeV. As will be described in Sec. IV D, normalization of the excitation curve obtained by Kiehn and Goodman[31] indicates that this effect persists nearly down to threshold. This discrepancy is considerably reduced when the original T_l values of Beyster *et al.* are used. It is possible that some refinement of the theoretical calculations could improve the agreement in this region, such as the introduction of effects due to fluctuations of resonance widths according to Moldauer.[48] An equally substantial discrepancy is indicated in Fig. 7 for the (n,n') cross section for the known 4+ level of Cr^{52} at 2.37 MeV. As in the case of the 2.08-MeV 4+ state in Fe^{56},[14] the experimental cross sections are appreciably lower than predicted even when corrected for the expected 4+ (*E*2)2+ angular distributions. The reason for this discrepancy, which persists for all the potentials considered, is not understood.

The spin and parity of the third level in Cr^{52} at 2.65 MeV is not presently known. Theoretical predictions for various spins, and both positive and negative parities, are shown in Fig. 7. It can be seen that for nuclei in this mass region (near the *s*-wave resonance) the (n,n') cross sections are nearly parity independent. This is not always the case in other mass regions, such as near the *p*-wave resonance.[49] A choice of spin 0 for the 2.65-MeV level gives the best fit to the present $(n,n'\gamma)$ cross sections, and spin 4 seems to be clearly eliminated because of the increase in the experimental cross section near threshold. Also shown are the cross sections (marked *X*) corrected for angular distribution for the case of a 3− assignment. Although the theoretical cross sections for a 3− choice are considerably higher, it may not be possible to rule out this spin possiblity, in view of the observed discrepancy with theory for the 2.37-MeV 4+ state. The same statement applies no doubt to a 3+ choice, although the angular distribution correction for this case has not been evaluated.

At the time of the preliminary report of this investigation,[15] no information was available concerning either the spin or parity of the 2.77-MeV level, or its mode of decay. Since no ground-state transition was found in the $\mathrm{Cr}(n,n'\gamma)$ spectra, a 1.33-MeV cascade transition was then the most likely possibility. It was difficult to verify the presence of such a gamma ray because of its proximity to the intense 1.43-MeV radiation and to the weaker 1.29-MeV radiation from Cr^{53}. However, at $E_n = 3.31$ MeV, there was a clear indication of a gamma ray at about 1.33 ± 0.03 MeV. For lower bombarding energies, only a rough estimate of its yield could be obtained after subtraction for the presence of the 1.29-MeV gamma ray. Comparison of the experimental results with the theoretical predictions shown in Fig. 7 indicate that the spin of the 2.77-MeV state is $\geqq 4$.

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[46] F. Perey and B. Buck, Nuclear Phys. 32, 352 (1962).

[47] F. Bjorklund and S. Fernbach, Phys. Rev. 109, 1295 (1958).

[48] P. A. Moldauer, Phys. Rev. 123, 968 (1961).

[49] P. N. Trehan, S. M. Shafroth, and D. M. Van Patter, Bull. Am. Phys. Soc. 7, 82 (1962).

Theoretical predictions for spin possibilities of 0 to 3 are distinctly higher than the experimental cross sections.

The yield for the 1.53-MeV gamma ray from the 2.96-MeV level was substantially greater than that of any of the other cascade transitions to the 1.43-MeV first 2+ state. Similar to the predictions shown in Fig. 7 for the 2.65-MeV level, spin choices of 1− or 2± yield the largest theoretical cross sections for the 2.96-MeV level, and are not distinguishable in the present experiment. In any case, the lowest lying state of Cr^{52} which can be assigned to the second 2+ level is the 2.96-MeV state. Present knowledge of the level schemes of neighboring even-even nuclei[5] indicates that the 2+ assignment is certainly to be preferred over 1− or 2−. The assumption of a $2+(M1)2+$ transition for the 1.53-MeV gamma ray requires an angular distribution correction of about 1.15 as indicated. The assumption of pure $M1$ radiation is not critical, since taking values of δ ($E2/M1$ mixing ratio) of either ±0.2 only affects the cross section by about ∓8%.

The yield of the 1.73-MeV gamma ray assigned to the 3.16-MeV level of Cr^{52} was only observed at $E_n=3.31$ MeV. From comparison to theoretical predictions, the observed $(n,n'\gamma)$ cross section indicates possible spin assignments of 1±, 2±, or 3− for this level. As will be described in Sec. IV B (1), the available evidence for (p,p') cross sections indicates that this level has a spin similar to the 2.96-MeV level of either 1 or 2.

B. Other Evidence Concerning the Level Scheme of Cr^{52}

(1) *Inelastic Particle Scattering*

A substantial amount of the available experimental evidence concerning the properties of levels in Cr^{52} for excitation energies less than 3.9 MeV is presented in Fig. 8. The evidence for the left-hand level scheme is based on nuclear reaction data, mainly from $(n,n'\gamma)$, (p,p'), and (α,α') inelastic scattering. The gamma-ray transitions attributed to the $Cr^{52}(n,n'\gamma)$ reaction in the present investigation are shown.

A detailed examination has been made of the results of three investigations using magnetic analysis of inelastic proton groups from natural chromium at three bombarding energies of 6.5 MeV ($\theta=90°$),[40] 7.02 MeV ($\theta=75°$),[50] and 8.0 MeV ($\theta=150°$).[51] This included calculation of Q values when the information was not supplied by the authors. In addition to the six energy levels listed by Mazari *et al.*[40] their (p,p') spectrum includes other prominent groups, which, if assigned to Cr^{52}, would correspond to levels at 2.93, 3.42, 3.47, and 3.64 (±0.01 MeV). The intensity of the 2.93-MeV group is not quite sufficient to rule out the possibility of its assignment to a low spin state in Cr^{50}; hence it has been shown as an uncertain level in Fig. 8. The remaining three groups appear to be too strong to be assigned to any isotope except Cr^{52}. Evidence for these three groups (Q values agreeing within ±0.01 MeV) is also found in Seward's (p,p') spectrum at $E_p=7.02$ MeV,[50] as well as for another group corresponding to a level near 3.79 MeV. Comparison of relative intensities clearly indicates that these groups are to be associated with the (p,p') groups observed by Hausman *et al.*,[51] who reported corresponding level energies of 3.46, 3.51, 3.65, and 3.80 MeV. (As has been pointed out by Mazari *et al.*,[40] the level energies of Hausman *et al.* tend to be too high by 0.01 to 0.06 MeV.) This evidence is summarized in the left-hand level diagram for Cr^{52}.

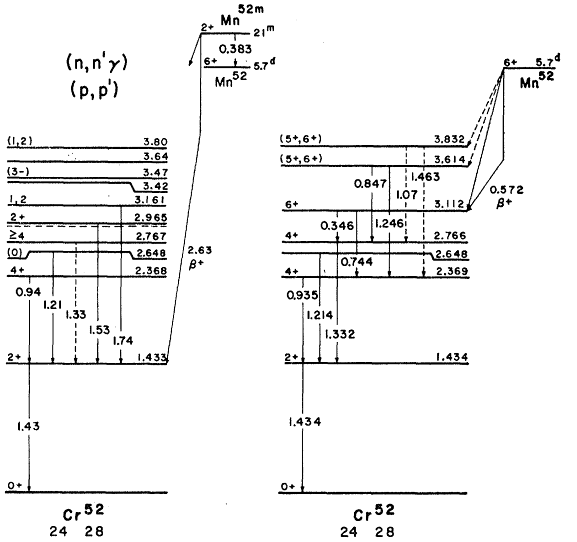

FIG. 8. Level schemes for Cr^{52}. The left-hand diagram includes information obtained from various nuclear reactions, while the right-hand diagram shows the results of Wilson *et al.* (reference 53) for the decay of 5.7-day Mn^{52}.

The measurements of Seward[50] reveal that in the region of $E_p=6.5$ to 7.0 MeV, for the $Cr^{52}(p,p')$ group with $Q=-1.43$ MeV, the differential cross section at 90° is nearly constant, and the angular distribution is almost isotropic. For the three bombarding energies where (p,p') spectra have been measured, it appeared to be useful to compare the intensities of the various (p,p') groups by normalizing to the yield of the most intense group ($Q=-1.43$ MeV) in each spectrum. It was observed that in general the intensities of the (p,p') groups increase in a similar fashion as the incident proton energy increases from 6.5 to 8.0 MeV. [The one outstanding exception is the $Cr^{52}(p,p')$ group with $Q=-2.65$ MeV, which is relatively much weaker at $E_p=7.02$ MeV than either 6.5 or 8.0 MeV.] Also it was clear that some (p,p') groups were consistently more prominent than others, taking the excitation energy of the final states into account.

These observations indicated that compound reaction theory might be reasonably valid, and that it might

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[50] F. D. Seward, Phys. Rev. **114**, 514 (1959); and Ph.D. thesis, University of Rochester, 1958 (unpublished).

[51] H. J. Hausman, A. J. Allen, J. S. Arthur, R. S. Bender, and C. J. McDole, Phys. Rev. **88**, 1296 (1952).

provide predictions of the relative (p,p') cross sections which could be somewhat quantitative in nature. In order to examine this point, a detailed Hauser-Feshbach calculation was made for $E_p = 8.0$ MeV, including fifteen levels in Cr^{52} up to 3.83-MeV excitation. The validity of this calculation was somewhat limited by the use of transmission coefficients from a blackbody potential.[52] However, it did reveal that if this theory is correct, then the highest (p,p') cross sections should occur for states with spins and parities of 1± or 2±, and that the cross sections should diminish rapidly for spins of >4. Comparison of the theoretical results with the experimental relative intensities of (p,p') groups indicated that each of the 2.96-, 3.16-, and 3.80-MeV levels should have a low spin of 1 or 2. The yields of the less prominent groups with $Q=-3.42$ and -3.64 MeV appeared to be more similar to the yields of the (p,p') groups corresponding to the known 4+ levels at 2.37 and 2.77 MeV. Finally, there remain two prominent (p,p') groups corresponding to levels at 2.65 and 3.47 MeV. The 3.47-MeV level appears to be the present best choice for the 3− octupole level reported at 3.6 MeV by Crut *et al.*[53] from inelastic scattering of 30-MeV alpha particles, although the (p,p') spectra were not observed at angles sufficiently forward, nor incident energies sufficiently high to show a strongly enhanced cross section for this level. The Nuclear Data group have recently reached the same tentative conclusion.[54] The prominence of the (p,p') group corresponding to the 2.65-MeV level indicates a state of low spin ($\leqq 3$), but its nonuniform yield prevents any tentative spin assignment being made. Some of these tentative assignments are indicated in Fig. 8.

(2) *Decay of 21-min* Mn^{52m}

An investigation of the decay of 21-min Mn^{52} by Katoh *et al.*[55] has revealed the presence of several weak gamma rays with approximate energies of 0.70, 0.94, 1.02, 1.15, 1.37, and 1.52 MeV. Since the 21-min isomeric state in Mn^{52} is now known to be 2+,[54] its decay should primarily involve low spin states in Cr^{52}. Unfortunately, the gamma rays of interest were not well defined in the spectra observed by Katoh *et al.*,[55] and it may be unwise to draw any definite conclusions from their results. However, the possible presence of 1.52-MeV radiation may indicate decay to the 2.965-MeV state, which is consistent with our assignment of 2+ for this state. However, there was no evidence for a similar transition to the low-spin 3.16-MeV state.

Katoh *et al.*[55] suggest the possibility of a new level at 3.67 MeV, in order to account for the presence of 0.70- and 1.02-MeV gamma rays. This seems to be an unlikely possibility from the present analysis of the available evidence from the (p,p') reaction, since there is no convincing evidence for a low spin state at this excitation. A more acceptable suggestion has been offered by Wilson *et al.*[56]; i.e., that transitions occur to a level in Cr^{52} at 3.80 MeV, which could account for the presence of 1.02- and 1.15-MeV radiations. As has been described, there is evidence from the (p,p') reaction for such a low spin state at this energy. Wilson *et al.* also suggest the possibility of assigning the 0.70-MeV gamma ray to the decay of the 3.47-MeV state, which would then require a beta transition from Mn^{52m} to this state with a $\log ft$ value of roughly 4.4. This assignment would seem to be in contradiction to the possibility that the 3.47-MeV state may be the 3− octupole state. Since it does not seem likely that any of these weak gamma rays from Mn^{52m} can presently be assigned with certainty, they have not been shown in the left-hand scheme of Fig. 8.

(3) *Decay of 5.7-day* Mn^{52}

The results of a recent study of the 5.7-day decay of $Mn^{52}(6+)$ by Wilson *et al.*[56] are summarized in the right-hand scheme of Fig. 8. As expected, this decay involves primarily high spin states in Cr^{52}. There is one puzzling feature about their results which concerns the 2.648-MeV state in Cr^{52}. Although they find no evidence for beta transitions to this level, a gamma ray ($E2$ or $M1$) of 1.214±0.001 MeV is observed, which appears to originate from the decay of the 2.648-MeV state to the first 2+ level. As they point out, this observation seems to eliminate the possibility of spin 0 for the 2.648-MeV state, as indicated by the present $(n,n'\gamma)$ results. The only spin choice for the 2.648-MeV state which now seems to be compatible with both investigations is 3+. For the Mn^{52} decay, such a choice would require gamma-ray feeding of this state from a state of higher energy (and spin). Wilson *et al.* suggest the possibility of feeding from the 2.766-MeV level by an observed 0.118-MeV gamma ray. In addition, they had some evidence for a weak gamma ray of 2.65 MeV of about 0.03 of the intensity of the 1.214-MeV gamma ray. This cannot be ruled by the present $(n,n'\gamma)$ results, since an upper limit of $\leqq 0.08$ was found for a possible ground-state transition form the 2.65-MeV level. However, the observed $(n,n'\gamma)$ cross section for this state definitely eliminates the possibility of 2+ suggested by Wilson *et al.*

A possible weak gamma ray of 1.72 MeV reported in the decay of Mn^{52} by Katoh *et al.*,[55] was not confirmed (nor ruled out) in the more recent and detailed measurements of Wilson *et al.*[56] Katoh *et al.*[55] assign this gamma ray to the decay of the 3.16-MeV level, which

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[52] H. Feshbach, M. M. Shapiro, and V. F. Weisskopf, Atomic Energy Commission Report NYO-3077, Nuclear Development Associates Report 15B-5, 1953 (unpublished).

[53] M. Crut, D. R. Sweetman, and N. S. Wall, Nuclear Phys. **17**, 655 (1960).

[54] K. Way, N. B. Gove, C. L. McGinnis, and R. Nakasima, *Energy Levels of Nuclei, A=21−212*, edited by K. H. Hellwege (Springer-Verlag, Berlin, 1961).

[55] T. Katoh, M. Nozawa, Y. Yoshizawa, and Y. Koh, J. Phys. Soc. Japan **15**, 2140 (1960).

[56] R. R. Wilson, A. A. Bartlett, J. J. Kraushaar, J. D. McCullen, and R. A. Ristinen, Phys. Rev. **125**, 1655 (1962).

TABLE III. Inelastic neutron cross sections in barn for excitation of levels in Cr^{53} (100% Cr^{53} isotope).

E_n (MeV)	Cr^{53} level in MeV 0.56	1.01	1.29	1.98	2.33
0.98	0.12 ± 0.04				
1.26	···	0.29 ± 0.04			
1.41	0.26 ± 0.06	0.33 ± 0.04	0.18 ± 0.03		
1.97	0.24 ± 0.03	0.41 ± 0.06	0.24 ± 0.05		
2.28	0.28 ± 0.05	0.49 ± 0.10	0.24 ± 0.05	0.09 ± 0.03	
2.68	0.23 ± 0.03	0.51 ± 0.07	0.29 ± 0.08	0.11 ± 0.03	0.13 ± 0.04
2.77	0.20 ± 0.04	0.39 ± 0.07	0.25 ± 0.09	0.10 ± 0.03	0.14 ± 0.04
2.96	0.20 ± 0.04	0.39 ± 0.07	0.32 ± 0.12	0.08 ± 0.03	0.16 ± 0.06
3.15	0.14 ± 0.04	0.53 ± 0.12	···	0.10 ± 0.04	0.09 ± 0.04
3.31	0.16 ± 0.05	0.35 ± 0.08	0.26 ± 0.13	0.11 ± 0.04	0.11 ± 0.04

would require a spin of 3 or 4 for this state. It is felt that the evidence from $(n,n'\gamma)$ and $(p,p'\gamma)$ favor spin possibilities of 1 or 2, while a spin of 3 is unlikely, and a spin of 4 is ruled out.

C. $Cr^{53}(n,n'\gamma)$ Reaction

Five of the $Cr(n,n'\gamma)$ radiations listed in Table I are assigned to ground-state transitions in the Cr^{53} isotope (9.55%). The energies of the gamma rays of 0.56, 1.01, 1.29, and 2.33 MeV agree within ±0.01 MeV with known energy levels of Cr^{53}, as indicated in the level scheme of Fig. 9. The energies listed for these states are best values obtained from magnetic analysis of charged particles from the $Cr^{53}(p,p')Cr^{53}$, $Cr^{52}(d,p)Cr^{53}$, and $Mn^{55}(d,\alpha)Cr^{53}$ reactions.[57,58] The 1.98-MeV gamma ray is tentatively assigned to a new 1.98-MeV level in Cr^{53}, since according to present knowledge about the systematics of energy levels of even-even nuclei,[6] it is unlikely that such a ground-state transition should occur in Cr^{50}, Cr^{52}, or Cr^{54}.

The measured inelastic neutron cross sections for excitation of Cr^{53} levels are listed in Table III. No corrections have been made for cascading from higher levels or for $(n,n'\gamma)$ angular distributions, for it is expected that these should be small compared to the uncertainties associated with the gamma-ray intensities.

In Fig. 10 the experimental cross sections are compared with theoretical predictions. As in the case of Cr^{52}, the theoretical calculations are generally too high for $E_n \lesssim 2.0$ MeV but give a satisfactory fit for $E_n \gtrsim 2.5$ MeV, as illustrated in the case of the 0.56-MeV level. The original T_l values given by Beyster *et al.* provide the best over-all agreement.

It is well established from $Cr^{52}(d,p)Cr^{53}$ stripping data that the 0.56-MeV state has a spin and parity of either 1/2− or 3/2−.[59] As indicated in Fig. 10, the theoretical (n,n') cross sections for these two possibilities differ by nearly a factor of 2, so that, in principle, it seems that measurement of the $(n,n'\gamma)$ cross section should provide a definitive result. The present experimental data clearly favor the 1/2− assignment. However, it should be noted that the yield of the 0.56-MeV radiation could be subject to considerable systematic error because of improper background subtraction in the vicinity of the prominent 0.44-MeV $I^{127}(n,n'\gamma)$ group. Nevertheless, it is difficult to imagine that this yield could have been underestimated by nearly a factor of 2, particularly since the yield remains reasonably constant at higher neutron energies where the difficulties in background subtraction tend to diminish.

An equally important question is the reliability of the present theoretical calculations, in view of the discrepancies observed for the first two levels in Cr^{52}.

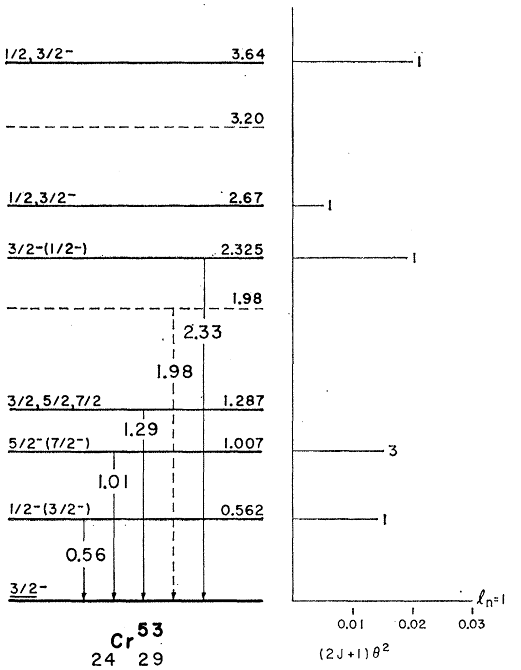

FIG. 9. Level scheme for Cr^{53}, including information concerning (d,p) stripping widths obtained by Dalton *et al.* (reference 61) according to the method of presentation adopted by the Nuclear Data Group (reference 51).

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[57] W. C. Porter, D. M. Van Patter, M. A. Rothman, and C. E. Mandeville, Phys. Rev. **112**, 468 (1958).

[58] M. Mazari, W. W. Buechner, and A. Sperduto, Phys. Rev. **112**, 1691 (1958).

[59] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

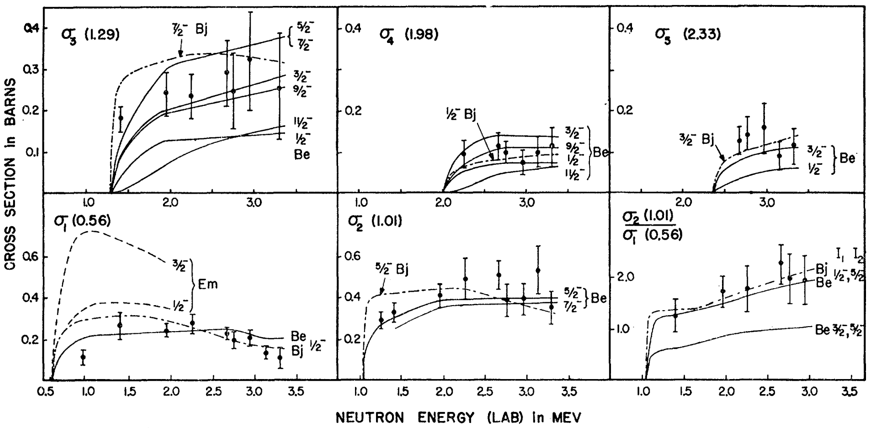

FIG. 10. Comparison of the present experimental inelastic neutron cross sections for excitation of five low-lying levels in Cr^{53} with theoretical predictions using the transmission coefficients of Beyster *et al.* (reference 11) (solid lines: *Be*) and Emmerich (reference 4) (dashed lines: *Em*) and the potential parameters of Bjorklund and Fernbach (reference 47) (dot-dashed lines: *Bj*). In addition, in the lower right is shown a similar comparison for the ratio of the (n,n') cross sections of the first two levels of Cr^{53}, with choices of 1/2- and 3/2- for the spin of the first level at 0.56 MeV. The theoretical predictions for either spin choice appear to be nearly independent of the choice of optical potential (references 4, 11, and 46). The experimental cross sections have not been corrected for $(n,n'\gamma)$ angular distributions.

Examination of the results for the 1.01-MeV second level in Cr^{53} provides some reassurance, since this state is known to be either 5/2− or 7/2− from observation of $l_n=3$ stripping in the $Cr^{52}(d,p)$ reaction, with 5/2− being preferred from shell-model considerations.[59] The experimental $Cr^{53}(n,n'\gamma)$ cross sections are in satisfactory agreement with either possibility. It should also be noted that this result indicates that the 1.01-MeV state in Cr^{53} decays predominantly to the ground state, since any contribution from cascades would increase the experimental cross section. As is indicated in the lower right of Fig. 10, the theoretical predictions for the ratio of the (n,n') cross sections for the first two levels of Cr^{53} are nearly identical for the various potentials used.[4,11,47] The experimental values of this ratio clearly favor a spin choice of 1/2 for the 0.56-MeV level.

A further verification of the dependability of the present theoretical calculations is provided by the results of theoretical calculations by Moldauer,[60] who used the potential of Campbell *et al.*[33] plus a spin orbit term, together with corrections for level width fluctuations. He obtained (n,n') cross sections for the 0.56-MeV level in Cr^{53} of 0.19 and 0.21 b at $E_n=0.8$ and 1.0 MeV, which agree within 10% with the present values of 0.17 and 0.21 b for a 1/2− spin assignment using the potential of Beyster *et al.* Therefore, it appears that the present investigation provides the first available evidence which can distinguish between the 1/2− and 3/2− possibilities for the 0.53-MeV state. Since the reliability of this nuclear spectroscopic method has not been tested for many odd-*A* nuclei in this mass region, the present assignment of 1/2− cannot be regarded as being completely certain.

The 1.29-MeV level in Cr^{53} has not been seen in the $Cr^{52}(d,p)Cr^{53}$ reaction,[59] and a recent investigation of the (n,γ) reaction for enriched Cr isotopes by Kane *et al.*[61] has revealed a similar negative result for the $Cr^{53}(n,\gamma)$ reaction. The only published evidence for this level was obtained by Porter *et al.*[57] from observation of a weak (p,p') group from an enriched Cr^{53} target. Examination of (p,p') spectra from natural chromium obtained in other investigations at $E_p=5.43$,[50] 6.5,[40] and 7.02 MeV[50] reveals a weak group occurring within ±0.01 MeV of the expected energy. This information concerning the $Cr(p,p')$ reaction does not eliminate the possibility that such a group could arise from a level in Cr^{54}. A possible level in Cr^{54} at about 1.31 MeV has been reported by Elwyn and Shull[62] from the (d,p) reaction on an enriched Cr^{53} target. However, Kane *et al.*[61] did not find any evidence for such a Cr^{54} state in their recent investigation of the $Cr^{53}(n,\gamma)Cr^{54}$ reaction.

The most convincing argument that the 1.29-MeV gamma ray observed in this $Cr(n,n'\gamma)$ experiment cannot be assigned to Cr^{54} arises from its observed yield, which is roughly the same as the yield of the 0.84-MeV gamma ray from the first 2+ state of Cr^{54} (see Table I). If the 1.29-MeV gamma ray were assigned to Cr^{54}, the experimental total inelastic cross section for Cr^{54} would be approximately doubled, and would then be in serious disagreement with theoretical predictions. (See Sec. IV D.) Therefore, it seems clear that the 1.29-MeV state in Cr^{53} is now firmly established. The present results indicate that this state decays predominantly to the 3/2− ground state, thereby limiting the range of possible spins to from 1/2 to 7/2, because of the availability of the 1.01-MeV state. Because of the considerable uncertainty in the experimental $(n,n'\gamma)$ cross sections, comparison to theory only eliminates the spin 1/2 possibility, as can be seen in Fig. 10.

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[60] P. A. Moldauer (private communication).

[61] W. R. Kane, N. F. Fiebiger, and J. D. Fox, Phys. Rev. **125**, 2031 (1962).

[62] A. J. Elwyn and F. B. Shull, Phys. Rev. **111**, 925 (1958).

TABLE IV. Total inelastic neutron cross sections in barns for Cr and each of its four stable isotopes.

E_n (MeV)	Natural Cr	Cr^{50} (100%)	Cr^{52} (100%)	Cr^{53} (100%)	Cr^{54} (100%)
0.98	0.055±0.008	0.55±0.10		0.12±0.04	0.87±0.16
1.26	0.102±0.013	0.59±0.09		0.52±0.08	1.11±0.18
1.41	0.125±0.015	0.67±0.12		0.77±0.11	0.94±0.21
1.97	0.65 ±0.07	0.87±0.15	0.59±0.06	0.89±0.12	1.22±0.20
2.28	0.70 ±0.07	0.79±0.15	0.64±0.06	1.10±0.16	0.79±0.27
2.68	1.02 ±0.10	0.93±0.13	0.99±0.10	1.27±0.16	1.14±0.28
2.77	1.02 ±0.10	0.72±0.12	1.04±0.10	1.07±0.17	0.78±0.19
2.96	0.93 ±0.09	0.90±0.16	0.90±0.09	1.14±0.19	1.13±0.27
3.15	0.95 ±0.10	0.63±0.13	0.94±0.10	1.13±0.20	0.88±0.22
3.31	0.95 ±0.10	0.71±0.15	0.96±0.10	0.99±0.19	0.74±0.19

The experimental cross sections shown in Fig. 10 for the tentative 1.98-MeV level in Cr^{53} are really lower limits, since other possible gamma-ray transitions from this level would have probably been unobservable in this investigation. Therefore, no conclusion has been drawn concerning possible spin assignments for this level.

It is now well established from $Cr^{52}(d,p)Cr^{53}$ stripping data[63,64] that the only two spin possibilities for the 2.33-MeV state are 1/2− or 3/2−. The suggestion of Macfarlane and French that the earlier stripping data[59] might be fitted with $l_n=2$ appears to be no longer tenable. Kane *et al.*[61] have found from their investigation of the $Cr^{52}(n,\gamma)Cr^{53}$ reaction that this level decays predominantly by a ground-state transition. Therefore, the $(n,n'\gamma)$ cross sections obtained from the yield of the 2.33-MeV gamma ray should be reasonably correct. Possible cascades from higher levels should not affect the yield at $E_n=2.68$ MeV, and the observed excitation curve for the 2.33-MeV gamma ray shows no sign of such contributions. Although the experimental cross sections have large uncertainties, the present $(n,n'\gamma)$ results shown in Fig. 10 clearly favor a spin of 3/2 rather than 1/2 for the 2.33-MeV state. As in the case of the 0.56-MeV level, this is the first available evidence in which some distinction between the 1/2− and 3/2− spin possibilities has been made.

D. Total Inelastic Neutron Cross Sections

In Table IV are listed the total inelastic neutron cross sections for natural chromium, as well as for each of its four stable isotopes, obtained in the present experiment. The values listed for Cr^{52} and Cr^{53} result from the addition of the cross sections for individual levels listed in Tables II and III. The values listed for Cr^{50} and Cr^{54} are based on the observed yields of 0.78- and 0.84-MeV gamma rays, assigned to the first 2+ level of each of these isotopes. It is assumed that higher levels decay primarily by transitions to the first 2+ level, as has been found for Cr^{52}. Angular distribution corrections include the effect of cascades from the first 4+ levels, assuming these to be located at 1.89 MeV (Cr^{50}) and 1.83 MeV (Cr^{54}).[44] The total (n,n') cross sections for natural chromium are then obtained by summing the contri-

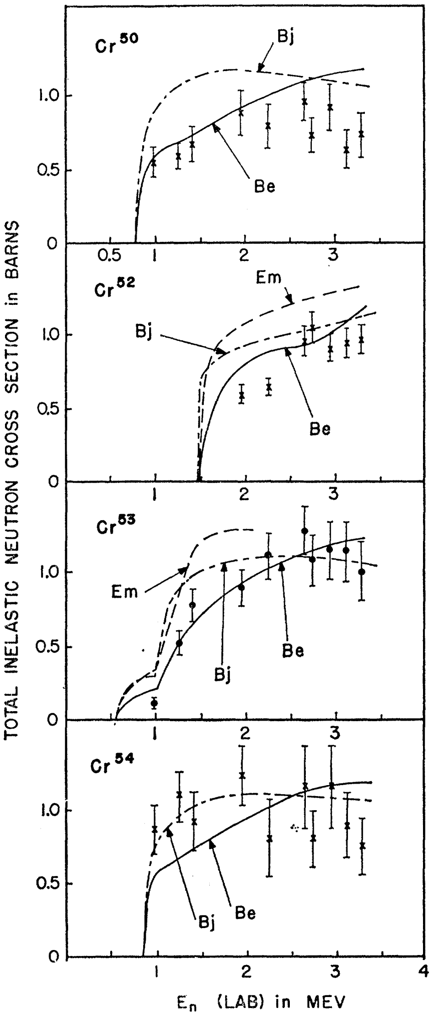

FIG. 11. Comparison of the present total inelastic neutron cross sections for each of the stable isotopes of chromium with theoretical calculations using the transmission coefficients of Beyster *et al.* (reference 11) (solid lines: *Be*) and Emmerich (reference 4) (dashed lines: *Em*) and the potential parameters of Bjorklund and Fernbach (reference 47) (dot-dashed lines: *Bj*).

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[63] F. A. El Bedewi and S. Tadros, Nuclear Phys. **19**, 604 (1960).

[64] A. W. Dalton, G. Parry, and H. D. Scott, University of Liverpool Report ULDP-5, 1961 (unpublished).

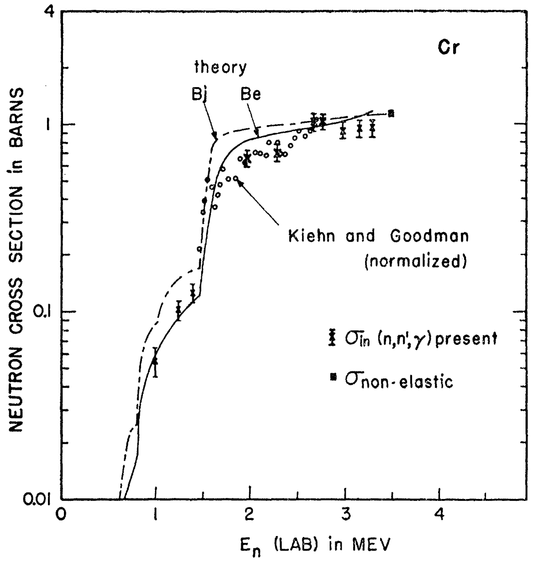

FIG. 12. Total inelastic neutron cross sections for natural chromium, compared with theoretical predictions using the transmission coefficients of Beyster *et al.* (reference 11) (solid line) and the potential parameters of Bjorklund and Fernbach (reference 47) (dot-dashed line). The normalized $(n,n'\gamma)$ excitation data of Kiehn and Goodman is also included (see text for explanation), as well as one nonelastic cross section reported by Taylor *et al.* (reference 65).

butions from the four stable isotopes. Present knowledge concerning the level schemes of these isotopes indicates that it is unlikely that any appreciable contribution to the $\mathrm{Cr}(n,n')$ cross section was neglected by the lack of observation of gamma-rays with energies below 0.5 MeV.

In Fig. 11 the experimental total inelastic cross sections for each Cr isotope are compared with theoretical predictions, which were obtained taking the best available choice of spin assignments for the levels of each isotope. The first 4+ level in both Cr^{50} and Cr^{54} was included in these calculations; however, the questionable level in Cr^{54} at about 1.2 to 1.3 MeV[62,63] was omitted.

It can be seen in Fig. 11 that the theoretical cross sections using the Emmerich (*Em*) or Bjorklund-Fernbach (*Bj*) potentials are higher than the experimental results for Cr^{50}, Cr^{52}, and Cr^{53} for $E_n \lesssim 2.5$ MeV, while the original transmission coefficients of Beyster *et al.* provide generally good agreement. The extent of the agreement and the similar cross sections for the different isotopes at $E_n \approx 2.5$ MeV imply that the isotopic identification of nearly all of the observed $\mathrm{Cr}(n,n'\gamma)$ radiations must have been correct. Further, we conclude that the available information concerning the modes of gamma-ray decay for the various levels must have been essentially correct; e.g., that the low-lying levels of Cr^{53} up to 2.33-MeV excitation decay primarily to the ground state. Only the 2.67-MeV state is known to have a more complex decay.[61]

The present results for the total inelastic neutron cross section of natural chromium are compared in Fig. 12 with theoretical predictions based on the original transmission coefficients Beyster *et al.* and the Bjorklund-Fernbach potential parameters. The sharp rise in the theoretical curves at $E_n > 1.46$ MeV can be easily understood. For 0.57 $E_n <$ 1.46 MeV, only the isotopes Cr^{50}, Cr^{53} and Cr^{54} (total abundance 16.2%) contribute to the cross section, while for $E_n > 1.46$ MeV the predominate Cr^{52} isotope is also involved.

The experimental cross sections for $E_n < 1.46$ MeV are in excellent agreement with the predictions based on the original T_l values of Beyster *et al.* However, because of a gap in the present measurements between incident energies of 1.41 and 1.98 MeV, the expected sharp rise above the threshold of the 1.43-MeV state in Cr^{52} is not clearly demonstrated. In order to show this more clearly, a curve based on the normalized results of Kiehn and Goodman[31] has been included in Fig. 12. They observed the yield of 1.43-MeV radiation from natural chromium at $\bar{\theta} = 93°$. While their geometry did extend over a considerable angular range, corrections for $(n,n'\gamma)$ angular distributions cannot be neglected. After making a simplified numerical integration to obtain the angular efficiency of their geometry, angular distribution corrections ranging from 1.25 to 1.09 were calculated for $E_n = 1.46$ to 2.75 MeV, assuming the theoretical $(n,n'\gamma)$ angular distributions presented in Fig. 4 for a $2+(E2)0+$ transition. A normalizing factor of 0.41 was then required to reduce their absolute cross sections to obtain agreement with the present imeasurements. The expected contributions of the remaining Cr-isotopes were then added to obtain the total (n,n') cross sections for Cr, shown as a dashed curve in Fig. 12. The combined experimental data now indicate the expected threshold for the 1.43-MeV level in Cr^{52}, although they remain generally lower than the theoretical predictions for $E_n \cong 1.6$–2.5 MeV.

Taylor *et al.*[65] have measured a nonelastic cross section of 1.14±0.04 b for natural chromium at $E_n = 3.5$ MeV. This provides a test of the reliability of the present total (n,n') cross sections, as indicated in Fig. 12. It is unfortunate that similar nonelastic measurements are not available for incident neutron energies $\leqq 3.3$ MeV for comparison with the results of the present investigation.

V. DISCUSSION

A. Energy Levels of Cr^{52}

The present investigation of the $\mathrm{Cr}(n,n'\gamma)$ reaction has resulted in new information concerning the spins of several states in Cr^{52}. A check on the reliability of this nuclear spectroscopic method is provided by the recent assignment of 4+ to the 2.766-MeV state from a study of the 5.7-day Mn^{52} decay by Wilson *et al.*,[56] which con-

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[65] H. L. Taylor, O. Lonsjo, and T. W. Bonner, Phys. Rev. **100**, 174 (1955).

firms the present result of a spin of $\geqq 4$. In addition, the available evidence from the Cr(p,p') reaction supports the identification of low spin states at 2.965 and 3.161 MeV. A study of the decay of Cu^{58} by Sutton *et al.*[66] has revealed a low spin state in Ni^{58} at 2.90 MeV, which has been tentatively identified as the second 2+ level.[54] It seems reasonable to make a similar identification of the 2.965-MeV level in Cr^{52}, as indicated in Fig. 8. There still remains an unresolved question concerning the spin of the 2.648-MeV state.[66a] The decays of V^{52} and 21-min Mn^{52m} should be re-examined in order to obtain independent information about these levels in Cr^{52}.

Wilson *et al.*[56] have given a comprehensive discussion of the various theoretical predictions for the energy levels of Cr^{52}, including a level scheme selected from the shell-model calculations of Edmond and Flowers[67] for an $(f_{7/2})^4$ configuration. For their choice of the range parameter $a/a_0=1.4$, the 4+ state of seniority 4 lies above the 4+ state with seniority 2; however, the order is reversed for $a/a_0=2.0$. A more recent calculation by Talmi[68] indicates that the lower 4+ state at 2.369 MeV should have seniority 4, and the 2.766-MeV 4+ state should have seniority 2. In addition, Talmi calculates the 2+ state with seniority 4 at 3.5 MeV, which should preferentially decay to seniority-2 states (rather than seniority $v=0$, 4). The nearest low-spin states are at 3.16 and 3.80 MeV. As discussed previously in Sec. IV B (2), there is some evidence that the 3.80-MeV state may be populated by the 21-min Mn^{52m} decay. In this case, the 1.02-MeV gamma ray could be a transition to the 2.766-MeV state of $v=2$; however, a 2.37-MeV transition to the first 2+ state ($v=2$) would also be expected. As will be discussed below, it is more likely that the 2.965-MeV level can be described by the collective model, and therefore it probably should not be considered as a possible seniority-4 state.

Shakin and Kerman[69] have recently carried out calculations for Ni^{62} by considering collective vibrations, including expansion of the Hamiltonian to cubic terms. In order to fit this theory to Cr^{52}, Wilson *et al.*[56] found it necessary to identify the levels at 2.766 and 2.965 MeV as the 4+ and 2+ two-phonon states, which would then require the 2.648-MeV state to be the 0+ two-phonon state. In addition, a three-phonon 2+ state is predicted near 3.8 MeV where a low spin state is now known to exist. Therefore this calculation provides the best agreement with the present results concerning spin assignments. It is noted that the observed branching of $\leqq 0.03$ (cross-over/cascade) for the 2.965-MeV level in Cr^{52} is similar to that of 0.024 ± 0.003 measured for the second 2+ level in Fe^{56}.[6] Therefore, there is no evidence which contradicts the choice of the 2.965-MeV level as the second 2+ state.

B. Energy Levels of Cr^{53}

The present investigation has provided new information concerning the spins of low-lying states in Cr^{53}. The most significant results are the possible choices of spins of 1/2− and 3/2− for the 0.56- and 2.33-MeV states, since such spin assignments relate to the question of the energy spacing of the $2p_{3/2}$ and $2p_{1/2}$ single-particle levels, which is of current theoretical interest.[70] Since the available information on this matter comes mainly from stripping reactions, it is worthwhile discussing the current experimental situation for Cr$^{52}(d,p)$Cr^{53} stripping results, together with possible interpretations and consequences.

Macfarlane and French[59] have offered three possible explanations of the relative stripping widths measured by Elwyn and Shull[62] for the Cr$^{52}(d,p)$Cr^{53} reaction. Since then, similar relative measurements have been reported by El Bedewi and Tadros.[63] As indicated in Fig. 9, the recent absolute cross-section determinations of Dalton *et al.*[64] at $E_d=8.9$ MeV provide values of $(2J+1)\theta^2$, the ratios of which are in reasonable agreement with the previous relative values. If spins of 3/2− and 1/2− are assumed for the ground and 0.56-MeV states, then these new results give values of θ^2 of 0.007_5 and 0.007 for (d,p) transitions to these states. These values are considerably lower than the values of the single-particle reduced width $\theta_0^2(2p)$ shown in Fig. 58 of the review article of Macfarlane and French,[59] which average about 0.022. Even if the 0.56-MeV state were also to be considered a $2p_{3/2}$ fragment, the total sum for both states would only be $\theta^2=0.011$.

If the procedure described by Macfarlane and French for extracting values of $(2J+1)\theta^2$ by Butler analysis can be relied upon, then the obvious conclusion is that the ground and 0.56-MeV states in Cr^{53} do not have nearly the full single-particle $2p_{3/2}$ and $2p_{1/2}$ reduced widths, and that both single-particle states are considerably fragmented. This conclusion would be consistent with the observation of several prominent $l_n=1$ transitions in Cr^{53} up to 3.64-MeV excitation, and provides an alternative solution to the three suggested by Macfarlane and French. It should also be noted that the new results of Dalton *et al.*[64] yield a stripping width ($l_n=3$) for the 1.01-MeV state (assumed to be $1f_{5/2}$) of $\theta^2=0.002_5$, which is also lower than earlier estimates[59] for the reduced width of the $1f_{5/2}$ single-particle state.

The present evidence for spin assignments of 1/2− and 3/2− for the 0.56- and 2.33-MeV states of Cr^{53}, together with the new results for absolute stripping widths, indicates that considerable overlapping of the $2p_{3/2}$ and $2p_{1/2}$ fragments is likely in Cr^{53}. It follows that without

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[66] D. C. Sutton, H. A. Hill, and R. Sherr, Bull. Am. Phys. Soc. 4, 278 (1959).

[66a] *Note added in proof.* Preliminary evidence for a 0+ assignment from the Cr$^{52}(p,p'\gamma)$ reaction has been presented recently by G. Kaye and J. C. Willmott, Abstracts of the Conference on Low Energy Nuclear Physics, Harwell, 1962, p. 13.

[67] A. R. Edmonds and B. H. Flowers, Proc. Roy. Soc. (London) **A215**, 120 (1952).

[68] I. Talmi, Phys. Rev. **126**, 1096 (1962).

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experimental evidence which can distinguish between the 1/2− and 3/2− spin possibilities for all prominent $l_n=1$ transitions, any estimates of the $(2p_{3/2}-2p_{1/2})$ energy spacing are open to suspicion. Further, the interpretation of Schiffer *et al.*[71] of the gross structure $l_n=1$ peaks in their low resolution studies should be reconsidered, at least in the case of the $\mathrm{Cr}^{52}(d,p)\mathrm{Cr}^{53}$ reaction. Even in high resolution studies, an estimate of the $(2p_{3/2}-2p_{1/2})$ energy spacing is often obtained from the sum rule for the fragments of a single-particle state.[59] The validity of this procedure should be examined in those cases where there are many $l_n=1$ transitions spread over an appreciable energy range, and definite spin assignments of either 1/2− or 3/2− are not available for most of the states.[72] These remarks point to the value of experiments which are capable of making such a distinction, such as determinations of cross sections for inelastic neutron scattering, particularly using enriched isotopes.

Now that there is evidence that possibly none of the low-lying levels in Cr^{53} may be considered as essentially pure single-particle states, it is worth examining the possibility that some of these levels may include contributions from core excitation. McGowan *et al.*[73] have recently observed the Coulomb excitation of the 0.56-MeV state, with a reduced $E2$ transition probability for excitation of $(1.18\pm0.08)\times10^{-50}e^2$ cm^4. It follows that the ratio of the reduced $E2$ transition probability for decay to the reduced $E2$ single-particle transition probability is either 10 or 20, for a spin assignment of either 3/2 or 1/2. This result can be compared to a value of $B(E2)_d/B(E2)_{\mathrm{sp}}=10\pm1$ for the $E2$ decay of the 1.43-MeV first 2+ state of Cr^{52}, obtained from an average of three recent lifetime determinations.[73–75] It appears likely, therefore, that the 0.56-MeV state exhibits some collective properties.

According to the model of de-Shalit,[76] a multiplet of four states (spins 1/2− to 7/2−) could occur in Cr^{53} due to the coupling of the $p_{3/2}$ neutron with the Cr^{52} core, excited to a 2+ state. The $B(E2)_d$ values for the ground-state transitions from such a multiplet should equal the $B(E2)_d$ values for the $2+(E2)0+$ transitions in neighboring even-even nuclei, provided that the core state in the odd-nucleon nucleus is identical with the corresponding state in the even-even nuclei. In the present case, $B(E2)_d=1.2\times10^{-50}e^2$ cm^4 for the $2+(E2)0+$ transition in Cr^{52}, compared to either 1.18 or 2.36 $\times10^{-50}e^2$ cm^4 for the 0.56-MeV state in Cr^{53}, assuming a spin of 3/2 or 1/2. If taken seriously, this comparison could indicate that a spin of 3/2 is preferred, contrary to the present assignment of 1/2 from the $(n,n'\gamma)$ cross section measurements. The observation that all the Cr^{53} levels up to 2.33-MeV excitation decay predominantly to the ground state may be an indication of enhanced $E2$ ground-state transitions expected from core excitations.

The core excitation states considered by de-Shalit are more general than the configurations considered earlier by Lawson and Uretsky[77] on the basis of the j-j coupling shell model; however, in the case of Cr^{53} they become equivalent. In addition to their center-of-gravity theorem, Lawson and Uretsky made further assumptions in order to obtain the following explicit energy predictions for each of the four states of the predicted multiplet in Cr^{53}: 0.46(3/2), 1.41(7/2), 1.83(5/2), and 2.34(1/2) MeV. If one takes their sequence of spins, together with the new tentative level at 1.98 MeV, then the experimentally determined states of 0.56(3/2), 1.29(7/2), 1.98(5/2), and 2.33(1/2) MeV have a center of gravity of 1.45 MeV, in excellent agreement with 1.43 MeV, the energy of the first 2+ level of Cr^{52}. The spin assignments for the 0.56- and 2.33-MeV levels would then be contrary to the present $(n,n'\gamma)$ results.

Macfarlane and French[59] have pointed out the general validity of the center-of-gravity theorem of Lawson and Uretsky. However, the more detailed additional assumptions adopted for their predictions for Cr^{53} are possibly less valid. In the case of either of the nuclei Cu^{63} and Cu^{65}, a multiplet of four states is expected, produced by the coupling of a $p_{3/2}$ proton with the 2+ core state of either Ni^{62} or Ni^{64}. Lawson and Uretsky[77] found that the center of gravity of each quartet agreed very well with the energy of the corresponding 2+ level, after choosing states with a spin sequence of 1/2, 5/2, 7/2, and 3/2. The existence of these core states seems to be clearly demonstrated in the recent (α,α') studies of Saudinos *et al.*[78] It is not yet clear whether or not the spin sequence given by Lawson and Uretsky is correct for both Cu^{63} and Cu^{65}, since there is some evidence consistent with a spin sequence of 1/2, 7/2, 5/2, and 3/2 for Cu^{65}.[79] On the other hand, a 7/2− spin assignment for the 0.96-MeV second level of Cu^{63} seems to be ruled out.[44]

The present $\mathrm{Cr}^{53}(n,n'\gamma)$ results would favor a spin sequence of 1/2, 5/2, 7/2, 3/2 (or 1/2, 7/2, 5/2, 3/2) over the spin sequence for Cr^{53} given by Lawson and Uretsky. Selecting the same four Cr^{53} levels as previ-

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ously considered, then the center of gravity would exceed 1.6 MeV for either spin sequence. Therefore, there still remains the need for further identification of the members of this possible quartet, and the further possibility that such core excitations may be fragmented, as indicated by the recent calculations of Bouten and van Leuven for the odd-mass Cu isotopes.[80]

While the possibility of contributions from core excitations remains promising for the low states in Cr^{53}, considerably more experimental information is needed, particularly concerning their decay modes and spin assignments. The latter information will also aid the understanding of the $2p_{3/2}$ and $2p_{1/2}$ energy spacing and fragmentation in this nucleus.

C. Final Remarks

Van Patter *et al.*[8,10] first pointed out the feasibility of using the $(n,n'\gamma)$ reaction as a nuclear spectroscopic tool to study the properties of low-lying states of even-even nuclei—in particular, to obtain information concerning the spins of these states. This method of detailed comparisons between experimental cross sections and theoretical Hauser-Feshbach predictions has been applied recently to Pb^{206} by Lind and Day.[1] Day and Walt[22] have also suggested that a more sensitive method for spin determinations might be the comparison of $(n,n'\gamma)$ angular distributions with theory. As an example, they showed predicted angular distributions (which differed considerably) for ground-state transitions from a state whose spin was varied from 1+ to 4+. However, a state with spin 3+ or 4+ will generally occur above the first 2+ level, and will not decay to the ground state. Therefore, a more typical problem would be to distinguish between angular distributions of transitions such as $2+(M1,E2)2+$, $3+(M1,E2)2+$, $4+(E2)2+$, some of which may have a considerable variation for different choices of the $E2/M1$ admixture. Hence, the general applicability of this latter method is not obvious, and the first method of comparing experimental cross sections or cross sections ratios with theoretical predictions still appears to be the most useful for obtaining information about spins.

The amount of information extracted from this present investigation of the $Cr(n,n'\gamma)$ reaction exceeds considerably that obtained in any previous experiment for natural chromium. It has been possible to observe a total of 13 gamma rays, and to assign each of them to one of the four stable isotopes of chromium. As a result, the total inelastic neutron cross sections for each isotope have been measured up to 3.3 MeV and found to be in satisfactory agreement with theoretical predictions. Except for differences associated with threshold energies, the expected similarity of the (n,n') cross section for each isotope was also verified. It was found that the results concerning spin identifications of the various levels considered do not depend critically on the choice of nuclear potential used for the theoretical Hauser-Feshbach calculations. However, some questions remain to be clarified concerning the agreement between experiment and theoretical predictions for excitation cross sections of individual levels, particularly in the case of the 2.37-MeV 4+ state in Cr^{52}. While future refinements in both experiment and theory would undoubtedly improve the reliability of the $(n,n'\gamma)$ method, even in its present stage of development this nuclear spectroscopic tool has proved to be of considerable value.

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