Neutron Inelastic Scattering*

ROBERT M. KIEHN† AND CLARK GOODMAN
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received May 3, 1954)

Neutron inelastic scattering cross sections of Fe, Al, Cr, Ni, Pb, and Bi have been measured with ~20-kev resolution for neutron energies between 0 and 2.7 Mev. A gamma-ray spectrometer measured the mono-energetic gamma rays emitted by the excited nucleus. The cross sections are in agreement with predictions based on the Hauser-Feshbach theory. The energies of the first few excited states of the stable nuclei were found to be in good agreement with values obtained by other means.

INTRODUCTION

MEASUREMENTS of inelastic scattering[1-4] have generally employed either heterogeneous neutron sources or detectors with poor energy resolution, or both. Inelastic scattering of monoenergetic neutrons can give useful information about the compound nucleus and the target nucleus. However, the experimental problem is complicated by the lack of adequate fast-neutron spectrometers, low neutron yields from monoenergetic neutron sources, and, especially at low neutron energies, low values of the inelastic cross section itself. Threshold detectors,[1] cloud chambers,[2] photographic plates,[3] and to some extent recoil counters[4] have been used to measure the yield of inelastically scattered neutrons as compared to the incident or elastically scattered neutrons. These techniques are satisfactory for high-energy neutrons (>3 Mev) but are either inapplicable or of limited usefulness in the interesting range 0–3 Mev, which corresponds to the major yield of fission neutrons.

After several discouraging attempts[5] to measure the inelastically scattered neutrons in this energy range, it was decided instead to study the gamma rays emitted by the excited residual nucleus. It is interesting to note that this method as used by Lea[6] and by Kikuchi *et al.*[7] confirmed the earlier conclusions of Danysz *et al.*[8] and Amaldi *et al.*[9] that the change of radioactivity induced in various substances resulted from inelastic scattering of the neutrons when different scatterers were interposed between the source and the detector.

More recently there have been a number of investigations[10] of inelastic scattering by the observation of the resulting gamma radiation. However, only because of the development of sensitive, high-resolution scintillation counters is it now possible to achieve detailed information[11] such as that represented by the present work.

PRESENT TECHNIQUE

The photoelectric absorption peak in a NaI crystal was used as a measure of the yield of monoenergetic, de-excitation gamma rays.

In the energy region covered $0 \leq E_n \leq 2.7$ Mev, most nuclei with $A \leq 70$ have levels which are separated by more than 100 kev. For the heavy nuclei, except those which are magic, the level spacing is of the order of 100 kev or less. This situation imposes extreme demands upon the resolution of the gamma-ray detector. After some effort, single-crystal NaI(Tl) gamma-ray spectrometers were constructed which have a resolution of about 5 percent for 1.2-Mev gamma rays. As a result the nuclei which may be investigated by this technique are those with level spacings of 100 kev or more. Furthermore, if the element in question has several isotopes, differentiation between isotopes is difficult. Cascade gamma processes could be established by coincidence techniques, but no work of this kind has yet been done for inelastic scattering of neutrons.

* This work was supported by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Gulf Oil Corporation Fellow, now at Los Alamos Scientific Laboratory.
[1] C. H. Collie and J. H. E. Griffiths, Proc. Roy. Soc. (London) **A155**, 434 (1936); D. C. Graham and G. T. Seaborg, Phys. Rev. **53**, 795 (1938); A. Soltan, Nature **142**, (1938); Nature **142**, 252 (1938); Amaldi, Bocciarelli, Cacciapuoti, and Trabocchi, Nuovo cimento **3**, 203 (1946); Gittings, Everhart, and Barschall, Phys. Rev. **75**, 1610 (1949); W. D. Allen and C. Hurst, Proc. Phys. Soc. (London) **52**, 501 (1940); S. G. Cohen, Nature **161**, 475 (1948); Martin, Diven, and Taschek, Phys. Rev. **93**, 199 (1954). A. A. Ebel and C. Goodman, Phys. Rev. **93**, 197 (1954).
[2] H. F. Dunlap and R. N. Little, Phys. Rev. **60**, 693 (1941); Little, Long, and Mandeville, Phys. Rev. **69**, 414 (1946).
[3] P. H. Stelson and C. Goodman, Phys. Rev. **82**, 69 (1951); P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 132 (1952); Jennings, Weddell, and Hellens, Bull. Am. Phys. Soc. **29**, No. 4, 48 (1954).
[4] Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. **72**, 881 (1947).
[5] Willard, Preston, and Goodman, M.I.T. Tech. Rept. No. 45, September 27, 1950 (unpublished), p. 69; P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 132 (1952).
[6] D. E. Lea, Proc. Roy. Soc. (London) **150**, 637 (1935).
[7] H. Aoki, Proc. Phys.-Math. Soc. Japan **19**, 369 (1935); Kikuchi, Aoki, and Husimi, Nature **137**, 398 (1936); Proc. Phys.-Math. Soc. Japan **18**, 115, 297 (1936).
[8] Danysz, Rotblat, Wertenstein, and Zyw, Nature **134**, 970 (1934).
[9] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segre, Proc. Roy. Soc. (London) **149**, 522 (1937).
[10] Seaborg, Gibson, and Graham, Phys. Rev. **52**, 408 (1937); Grace, Preston, and Halban, Phys. Rev. **77**, 286 (1950); M. A. Rothman and C. E. Mandeville, Phys. Rev. **93**, 796 (1954); G. L. Griffith, Bull. Am. Phys. Soc. **29**, No. 4, 48 (1954); C. P. Swann and F. R. Metzger, Bull. Am. Phys. Soc. **29**, No. 4, 48 (1954); Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954).
[11] Grace, Beghian, Preston, and Halban, Phys. Rev. **82**, 969 (1951); R. B. Day, Phys. Rev. **89**, 908 (1952).

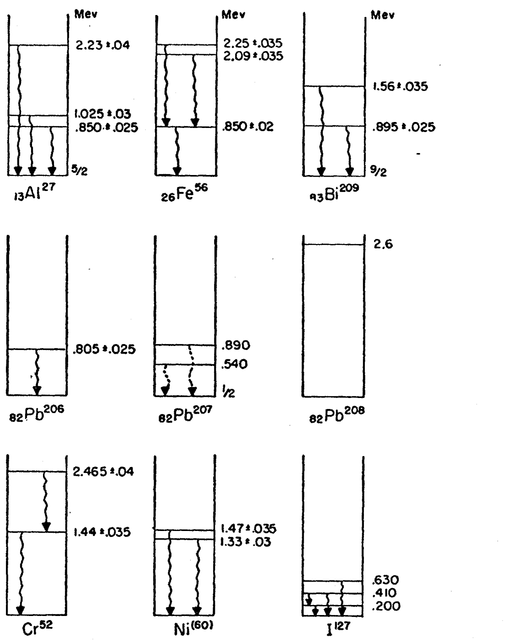

FIG. 1. Energy-level diagrams. The energies of the excited levels were determined by measuring the energy of the emitted gamma ray with a scintillation spectrometer. Utilization of the incident neutron energy and the yield of the gamma rays as two independent variables enabled the assignment of cascade processes. The gamma-ray yields, except for Pb^{207}, were studied in detail as a function of incident neutron energy. The energy assignments are in agreement with other determinations within the given experimental uncertainty. The 1.47-Mev level is probably in Ni^{58}.

The elements chosen for study were Al, Ni, Cr, Fe, Pb, and Bi. This choice illustrated the application of the technique to light, medium weight, and heavy magic nuclei, including elements with many isotopes.

After several preliminary experiments a method was evolved for examination of the inelastic neutron cross section for each of the excited levels of the target nucleus in the same detail as in total cross-section measurements. Accordingly experiments were conducted using neutron beams of $\leq$25-kev resolution for the first few Mev. Many reasonances in the yields of the individual gamma rays were observed. These are attributed to resonance formation in the compound nucleus. A summary of the experimental method has been published.[12]

RESULTS

Using neutron beams of $\leq$25-kev energy width, the gamma-ray yields for Fe, Al, Bi, Pb, Ni, and Cr were measured at 50-kev energy intervals for $0<E_n\leq 2.7$ Mev. The yield of gamma rays was calibrated in terms of the inelastic scattering cross section, σ_{in}, assuming that the observed yield is proportional to the number of inelastic events taking place in the scatterer. The measurement of the line spectrum of gamma rays insures that only inelastic events are recorded. If two or more levels are neutron excited and each emits gamma rays in transitions to the ground state, the cross section for each level excited may be determined. If the gamma rays are in cascade, the lower-level gamma ray gives the total inelastic cross section immediately, and a subtraction yields the cross section for the production of higher levels. The interpretation of the results, therefore, requires some preconception, or a preliminary determination, of the energy-level diagrams of the nuclei under consideration. The incident neutron energy and the gamma-ray energy calibration provide two independent variables by means of which the level structure may be determined for those excited states capable of being produced by neutron bombardment.

Figure 1 portrays the results obtained for six elements. The levels in Bi^{209} have recently been observed in inelastic neutron scattering.[13] The other levels indicated have been confirmed by other means.[14]

Absolute values of σ_{in} were obtained by experimentally determining the efficiency of the detector and geometry using a known source of gamma rays distributed throughout the scatterer, and calculating the neutron flux incident upon the scatterer using the Los Alamos data for the neutron yield from the $Li^7(p,n)Be^7$ reaction.[15] This method was applied for the determination of σ_{in} for iron with an estimated uncertainty of 15 percent at $E_n\simeq 1.3$ Mev; the inelastic cross section for the other elements was then deter-

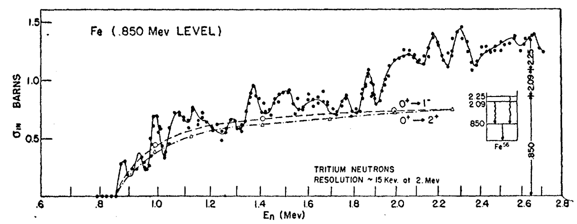

FIG. 2. The neutron inelastic scattering cross section of iron. The cross section was obtained by observing the yield of the line spectrum of gamma rays emitted from the excited state of Fe^{56}. The ordinate was calibrated by experimentally determining the counter efficiency and by computing the number of neutrons incident upon the scatterer from the measured proton current and target thickness. The absolute values for the cross sections of the other elements studied were calibrated by comparing relative gamma yields with the gamma yield from $Fe(n,n'\gamma)Fe$. The neutron energy resolution is $\sim$20 kev for all data presented in this paper. A comparison with the Hauser-Feshbach theory (see reference 17) has been made for the single level excitation for the assumed transitions $O^+\rightarrow 1^-$ and $O^+\rightarrow 2^+$ (the smooth curves). The experimental contributions of the three levels to the total inelastic cross section are given at $E_n=2.64$ Mev; note that the 850-kev level contribution falls close to the extrapolated theoretical curve.

[12] R. M. Kiehn and C. Goodman, Phys. Rev. **93**, 177 (1954).

[13] M. A. Rothman and C. E. Mandeville, Phys. Rev. **93**, 796 (1954); Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954).

[14] *Nuclear Data*, Natl. Bur. Standards Circ. 499 (U. S. Government Printing Office, Washington, D. C., 1950); Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953); Hausman, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).

[15] Hansen, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

mined relative to iron by applying first-order correction terms for self-absorption and detector efficiency, Figs. 2 to 8.

It was assumed that the anisotropy of the resulting gamma radiation was small and that "poor" geometry would average over the angular distribution. Although the scattering samples were fairly thick (1 to 1.5 mean free paths), corrections for neutron scattering were made only for single collisions, i.e., multiple scattering was neglected. Experiments are in progress to determine the effects of multiple scattering and to calibrate the elements by the source-substitution method used for iron.

The gamma rays observed were between 800 kev and 2.5 Mev in energy; lower-energy gamma transitions

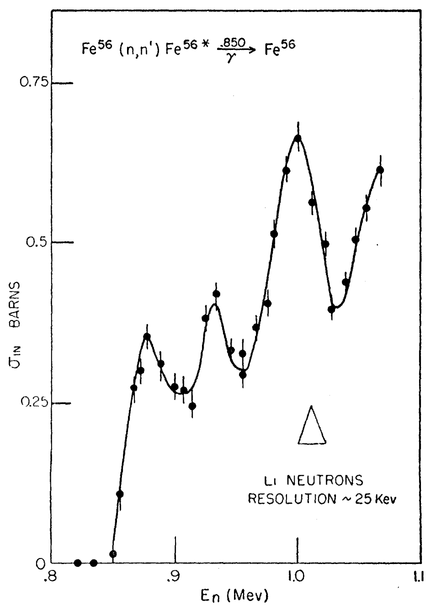

FIG. 3. Detail of the initial rise of the Fe cross section. The data represent the yield of the line spectrum of gamma rays emitted by Fe^{56}. The resonance structure in the inelastic scattering cross section, which is clearly defined in the figure, prevents the definite assignment of spin and parity to the excited state by comparison of the slope of the initial rise with the Hauser-Feshbach theory.

were either not investigated in detail or not observed. A high background radiation of 200, 410, and 630-kev gamma rays, produced by $(n,n'\gamma)$ processes in the NaI spectrometer, made determinations of low-energy gamma yields difficult. As the gammas investigated fell in the energy interval 800 kev $<E_\gamma<$2.5 Mev, no corrections for internal conversion processes were made. The transitions observed were fast (low multipole order); hence, the internal conversion corrections would be small (<5 percent) even for the heaviest elements.

One obvious fault of the gamma-ray technique, in addition to the problems of low-energy gamma transitions, finite resolution and complex competing spectra,

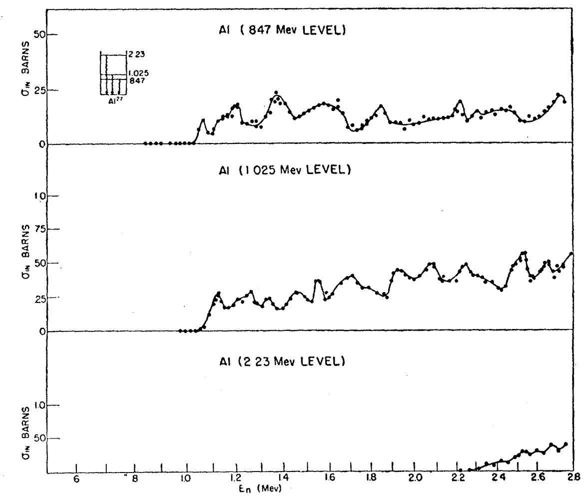

FIG. 4. The neutron inelastic scattering cross section of aluminum. The cross sections were obtained by observing the yield of the line spectrum of gamma rays emitted from the excited states of Al^{27}. The first curve is attributed to the excitation of the 0.847-Mev level in Al^{27}; the second, the 1.025-Mev level; the third, the 2.23-Mev level. The assumption has been made that no cascade processes are taking place.

is the fact that spin 0 to spin 0 transitions are not observed because this gamma transition is completely forbidden.[16]

Many resonances in the inelastic scattering cross sections of the lighter nuclei were observed. These are attributed to resonant formation of the compound nucleus. In most cases, however, the total neutron cross section has not been measured with the same degree of resolution as used in these inelastic cross section experiments. Corrections for the total cross section were based on averaged values.

For one of the major Al resonances, both the total and inelastic cross sections were measured with neutrons of the same energy. Figure 9 shows the agreement between resonance structure in both cross sections.

Several calculations based on the theory of Hauser and Feshbach[17] were made in order to compare theoretical prediction with experiment. The theoretical results, based on the assumption that the level density

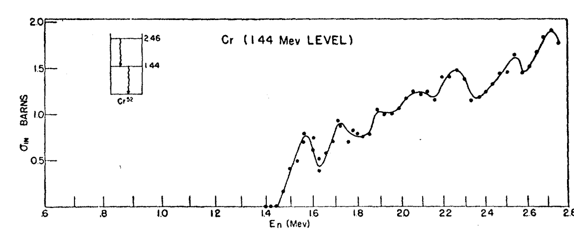

FIG. 5. The neutron inelastic scattering cross section of Cr. The cross section was obtained by observing the yield of the line spectrum of gamma rays emitted from the first excited state of Cr^{52}. The excitation of the 2.46-Mev level was not studied.

[16] J. M. Blatt and V. F. Weisskopf *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[17] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

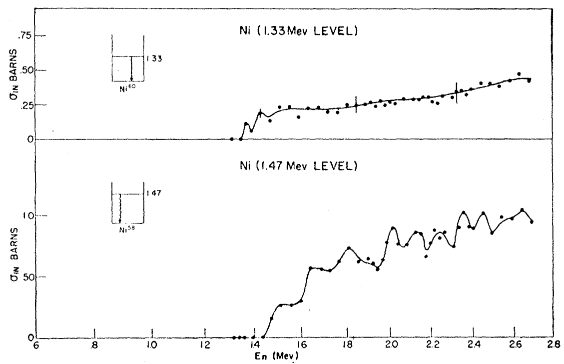

FIG. 6. The neutron inelastic scattering cross section of Ni. The cross sections were obtained by observing the yield of the line spectrum of gamma rays emitted from the excited states in Ni. The upper curve is attributed to the 1.33-Mev level in Ni^{60} while the lower curve is attributed to a 1.47-Mev level in Ni^{58}.

of the compound nucleus can be treated statistically, should be comparable to an average over the resonances in the experimental cross sections.

The results of the calculations for the excitation of the first excited states in Fe, Pb, and Bi are shown by dashed lines in the appropriate figures for the assumed

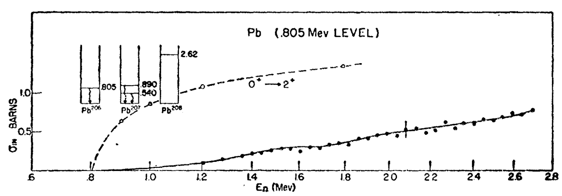

FIG. 7. The neutron inelastic scattering cross section of Pb. The cross section was obtained by observing the yield of the line spectrum of gamma rays emitted from the excited state of Pb^{206}. A theoretical curve for the assumed transition $0^+ \rightarrow 2^+$ is also shown.

spin transitions and for nuclear radii obtained from total neutron cross sections.[16] The calculations are quite sensitive to the assumed nuclear radius. The agreement between theory and experiment for Fe is probably fortuitous as the theory is expected to give shape and order of magnitude results only. The dis-

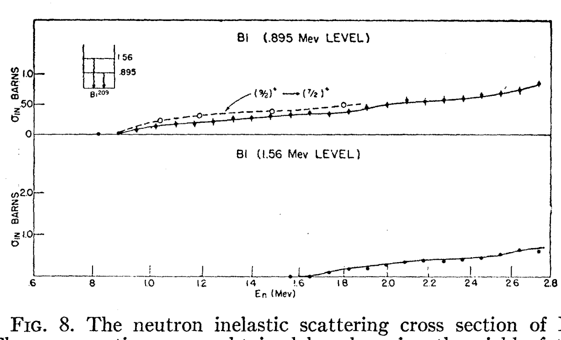

FIG. 8. The neutron inelastic scattering cross section of Bi. The cross sections were obtained by observing the yield of the line spectrum of gamma rays emitted from the first two excited states of Bi. A theoretical curve is also shown for the assumed transition of $9/2^- \rightarrow 7/2^-$ for the first excited state of Bi (incorrectly designated as + parities in the figure).

agreement between theory and experiment for Pb is probably significant. One possible explanation is that the 2+ spin assignment to the first excited state is incorrect. Another explanation would be that the statistical theory does not apply to this magic, heavy nucleus. However, fair agreement was obtained, both in shape and in magnitude, for the magic, heavy nucleus Bi^{209}.

Experiments in which the spins of the ground state and excited state of the target nucleus, and the spins of the compound levels excited are known would be very significant. Such experiments would yield information concerning a resonance theory of inelastic scattering. In the elements studied thus far, only the spins of the ground states were known.

It is to be noted that the data obtained for the individual level excitation cross sections immediately

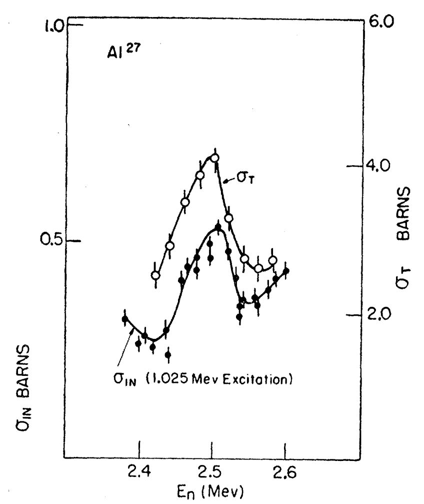

FIG. 9. Comparison of the resonance structure in the total cross section and the inelastic cross section of Al. The agreement between the resonance structure of the total neutron cross section and the inelastic neutron cross section indicates resonance formation of the compound nucleus.

give the spectral distribution, χ_{in}, of the inelastically scattered neutrons, a quantity of importance in reactor design and in neutron shielding. For each partial inelastic scattering cross section, the emergent neutron has an energy essentially equal to the incident neutron energy minus the excitation energy of the particular level excited.

We wish to acknowledge the support of the Gulf Oil Corporation fellowship program and the use of scattering samples provided by Pratt and Whitney Corporation. M. K. Salomaa helped with the electronics, T. H. Magel prepared the T-Zr targets, and C. Borkowski generously assisted by calibrating the Mn^{54} standard solution. The members of the Neutron Physics Group have given valuable assistance. Discussions with V. F. Weisskopf, R. B. Day, and H. Feshbach were particularly stimulating.